Manual for the design and implementation of a regenerative agri-food model:

the Polyfarming system

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Prologue

We are immersed in a moment of change. There is no doubt. In all areas of society, including, very explicitly, the field of agriculture, forestry, and ecology. This change is accompanied by a growing interest in seeking new ways of thinking, conceiving and relating to the environment and, in particular, to the land that is home to the resources used for productive purposes.

This search for new production models drive the Polyfarming project and, with it, the 'Manual for the design and implementation of a regenerative agri-food model: the Polyfarming system' that I am pleased to present. This extensive document explains the various agricultural, livestock and forestry management options that can be applied holistically in agroforestry farms in the Mediterranean climate.

The road is open; it has started with strength and determination. The Manual captures new ideas and includes broad and diverse content on the regenerative model, resulting from the fusion of different forms of knowledge, both from the academic, empirical, and popular world. Forms that result from resistance or marginality become the centre and, probably, one of the few solutions to an unprecedented environmental crisis.

Essays, observations, and trial/error experiences give the Manual credibility, dimension and rigour. It is clear that the formalisation of this new form of management is a matter of great complexity, and, indeed, for its large-scale application to be possible, a transversal network of actors will be needed to make it possible.

These actors include other disciplines with which it will be necessary to build bridges with intelligence and generosity. Including the field of urbanism, since land planning of the human ecosystem, of which agriculture is also a part, can no longer be done without their voice. It is time to give content to what many understand as the void, or the green because the void or the green is a complex system, which has attributes and potential. Furthermore, as the document makes clear, the future of our civilisation lies specifically in the void or green.

The paradigm shift will lead to important spatial changes and this will surely be your best asset to ensure that it is fully assimilated and understood. The landscape will once again be continuous, bare ground will disappear, as will the geometries produced by the impact of large machines.

A new continuity will appear; it will consider all living systems and allow a new fruitful cohabitation, never experienced before. Ultimately, the regenerative model will integrate all forms of life, including our own, that of humans in their full glory.

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Preface

The current agri-food model is based on a way of producing, distributing and consuming that is closely related to the environmental crisis that we are suffering. One of its most devastating consequences is the loss of soil fertility and soil degradation, the source of our food and the largest carbon stock on Earth. In this unsustainable panorama, a change in the agriculture and livestock model is urgently needed, so that these sectors, fundamental to our survival, go from being part of the problem to contributing to its solution. With this objective in mind, the **Polyfarming** system is being developed, **a pioneering project in Catalonia,** funded by the LIFE programme of the European Commission and coordinated by the CREAF research centre. Polyfarming proposes **a truly sustainable regenerative production model** that contributes to mitigating climate change, increasing soil fertility and biodiversity, recovering agro-silvo-pastoral activity in abandoned Mediterranean mountain areas and claiming food sovereignty. The project has been fully implemented at the Planeses farm (Girona) since 2016 in order to become **a real and demonstrative example** that can be replicated locally and globally.

Along these lines, the **'Manual for the design and implementation of a regenerative agri-food model: the Polyfarming system'** aims to provide knowledge so that anyone interested can learn about the regenerative model, enjoy learning about it and replicate it on their own farm. This material is the result of an exhaustive work of documenting, analysing and evaluating the real experience of applying the Polyfarming system at the Planeses farm, as well as the result of interactions with other researchers and producers and a review of the literature for aspects that have not yet been measured in the pilot farm.

The manual comprises different sections that explain the regenerative system from the perspectives of soil, forest, pasture, livestock and crops. It describes specific regenerative agriculture and livestock techniques and details how to combine and integrate them into an agri-food production model. In addition, it includes a section with the costs involved in putting it into operation, both the different techniques separately and the total balance at farm level and another section on the environmental, productive and economic benefits involved in applying it. Thus, the manual comprises six sections that, in total, contain **72 sheets** that can be read as a unit, but also individually. The sections are the following:

- **INTRODUCTION.** This section describes the most relevant environmental changes that the Mediterranean region has suffered in the last century and contextualises the importance of the regenerative model in comparison with the conventional model.

- **BASES OF A REGENERATIVE PRODUCTION SYSTEM.** This section begins by explaining what aspects of the soil should be considered to start a regenerative model. It then describes the management of the different uses: the forest, pasture and animals that graze in it and the crops, from a regenerative perspective.

- **THE POLYFARMING SYSTEM.** This section describes the different agricultural, livestock and forestry techniques that make up the Polyfarming system. Then it analyses how this system works, explains the synergies established between the components, the complementarity of products and labour and the integration of the different elements at farm level. It ends by explaining the lessons learned after putting it into practice..

- **COSTS AND KEY POINTS OF THE DIFFERENT ACTIVITIES.** This section specifies the costs and key points that must be considered when implementing the different components that make up a regenerative model. In addition, it includes the total balance of costs and income of the Polyfarming system of a pilot farm.

- **ENVIRONMENTAL, PRODUCTIVE AND ECONOMIC BENEFITS.** This section outlines the environmental and socio-economic improvements involved in implementing a regenerative model, such as Polyfarming.

- **CONCLUSIONS.** This section summarises the reasons why we must address a regenerative future, as well as some initiatives, institutions and organisations that promote the regenerative model from various fields and countries.

Introduction

– General context

Introduction

General context

- Changes in the mediterranean region in the last century
- The conventional production model and its consequences
- The regenerative production model: a proposal to overcome the environmental and climate crisis

Changes in the mediterranean region in the last century

Global environmental change in the Mediterranean region manifests itself mainly in three types of impacts: climate change, with an increase in temperature and a decrease in precipitation; imbalance of biogeochemical cycles, with an increase in greenhouse gases and eutrophication of water; and loss of biodiversity. At landscape level, there has been a rural exodus that has caused a very significant decrease in the area devoted to crops and an increase in the area of forests. This rural depopulation has led to the abandonment of traditional farms, and the increasing concentration of intensive agriculture and livestock in the plains.

Global environmental change in the Mediterranean region

Europe, and in particular the Mediterranean region, **is one of the places in the world where global environmental change is occurring with the greatest intensity**. This environmental change manifests, among others, in three main impacts:

(a) Climate change. Europe is warming faster than the global average. It is especially true in the Mediterranean region, where climate change has extreme consequences: the period of extreme heat increases, rainfall and river flow are reduced, and this increases the risk of droughts and, with it, the risk of forest fires. That is why all southern European countries have declared a state of climate emergency. In Spain, the outlook is even worse: the average Spanish temperature has increased by more than **0.5°C every decade since the beginning of the 20th centur**y (Gómez-Cantero 2015). Added to this is a decrease in rainfall since 1950. The temperature and precipitation forecasts for the end of the century (2100) are even more negative (**Figure 1**).

(b) Transformation of biogeochemical cycles. Since the industrial revolution and due to the exponential growth in the use of fossil fuels and fertilisers associated with intensive agriculture, there has been an **imbalance in the biogeochemical cycles** of almost all the elements, mainly of the three most important: C, N and P (Enrich-Prast et al. 2018). Especially relevant is the increase in the atmospheric concentration of CO_2 (from 285 ppm in 1850 to more than 400 ppm today), as a consequence of burning fossil fuels, and the loss of reserves due to **deforestation** of forests in tropical regions and **degradation of the soils** of the entire planet. The large amount of N added to the soil annually in the form of fertilisers to improve agricultural production increases the eutrophication of aquifers and aquatic ecosystems and causes an increase in nitrous oxide (N_2O) emissions into the atmosphere (Enrich-Prast et al. 2018). Similarly, the **high use of phosphates in intensive agriculture** has also contributed to the eutrophication of natural systems and has altered the P cycle.

(c) Loss of biodiversity. The Mediterranean region is one of the biodiversity **hotspots** on the entire planet (Myers et al. 2000). Specifically, **the biodiversity of Spain is one of the highest**, with around 85,000 species of animals and plants and 30% of European endemisms. However, **this biodiversity is in danger**, since a significant proportion of these species, 14%, are under threat in Europe. The main direct causes of biodiversity loss are changes in land use, unsustainable use of natural resources such as water, abandonment of traditional livestock and agricultural uses, pollution, climate change and invasive species (OSE 2010).

A. Change in annual temperature (°C) **B. Change in annual precipitation (%)**

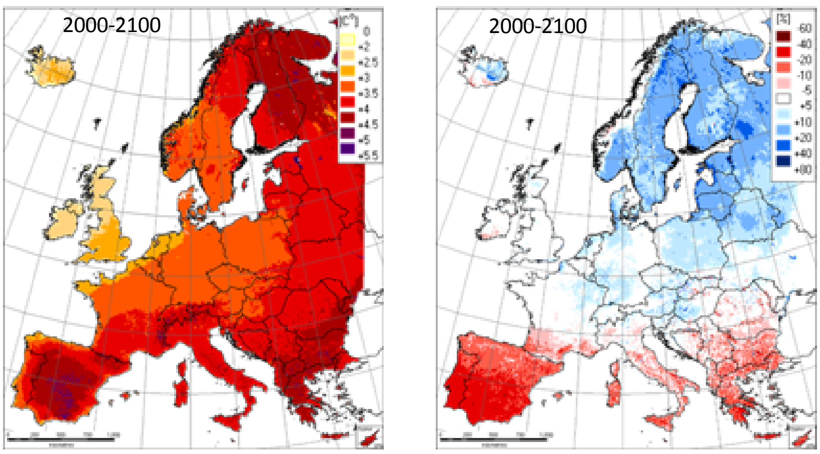


Figure 1. Expected changes in the 21st century in (a) annual temperature (° C) and (b) annual precipitation (%) in Europe. Maps produced in the European project PRUDENCE PESETA I results - Change in mean annual temperature and precipitation by the end of the century. Credit: European Commission Joint Research Centre (JRC). Copyright: European Union - Joint Research Centre (JRC).

Rural exodus and its consequences on the landscape: changes in land uses

Studies of the Mediterranean region (e.g., Mazzoleni et al, 2004) and, in particular, of the Iberian Peninsula, show that since the middle of the 20th century the abandonment of rural areas and the establishment of successional plant communities are two of the most important transformation processes. **The**

areas affected by this rural exodus (**Figure 2**) in the latter part of the 20th century cover almost a third (29%) of the natural vegetation systems (Hill 2008). The spatial pattern of this rural exodus reflects the main demographic trends in Portugal and Spain, which are characterised by **strong urbanisation trends and population concentration along the coasts and in the main cities**, in contrast to the decline of the population in the interior. These changes, which have led to industrial and tourist development, are also reflected in the proportion of people dedicated to different socioeconomic sectors (Pausas 2004), with an increase in the industrial and service sectors and a decrease in the primary sector.

This pattern of rural exodus has led to a very significant decrease in the area devoted to crops and **an increase in the forest area throughout the 20th century** (**Figure 3**). Spain is one of the countries with the most depopulated rural areas in Europe. This rural depopulation means that these forests, despite increasing, are not cared for, and livestock do not consume the understory. For this reason, **a large part of today's forests is at high risk of fires** which, in turn, can cause desertification in many areas.

Figure 2. Abandoned farm recolonised by the forest in Catalonia. Photo: AVVideo.

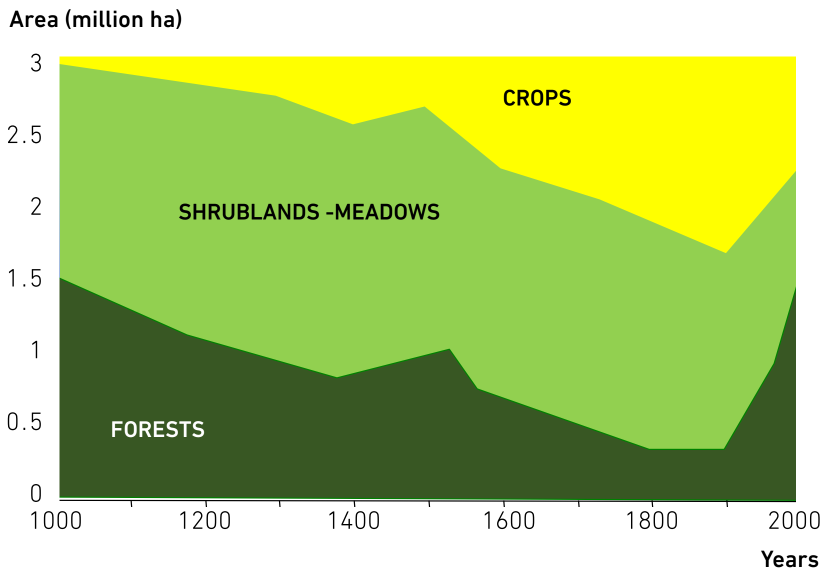


Figure 3. Changes in the main land uses in the last 1000 years in Catalonia. Information prepared by Jordi Peix, unpublished.

Abandonment of traditional farms and concentration of production on the plains

Rural depopulation has led to the abandonment of traditional farms, especially in the mountains, where the lack of profitability has made most small farms where a traditional agro-silvo-pastoral survival management used to be carried out unviable. These Mediterranean mountain farms have **very low profitability related to three main factors:** (i) **difficult environmental** conditions linked to the Mediterranean climate; (ii) **mechanisation difficulties** due to the steep slopes and small terraces; (iii) **soil degradation** as a result of old harvesting that has left poor soils with a very low organic matter content.

This traditional management has been replaced by the increasing concentration of large oligopolies in the plains. According to updated data from the Ministry of Agriculture, in Spain there are **1 million farms, but 42% of the total production is obtained in only 6.6% of all of them**. The open and extensive areas of the plain are normally easily machinable and, in general, they opt for obtaining large productions in small spaces. It is common for them to focus on a single product, deriving all the resources for its exploitation. To do this, they exploit the means of production to the maximum and **intensify agriculture and livestock**, increasing inputs (synthetic fertilisers, chemical pesticides, water), and the **capitalisation of companies and labour**. Although the result is a large increase in food production, this type of agriculture and livestock has important environmental consequences such as soil degradation, vulnerability to climate change and loss of biodiversity, and socio-economic consequences, since it generates territorial imbalances and the abandonment and loss of productive capacity of a large part of the territory.

The conventional production model and its consequences

Conventional agriculture and livestock are intensive production systems that use large-scale technologies to fully exploit the means of production. Pesticides, fertilisers and other agrochemicals and a high amount of fuel in intensive agriculture, or a high overcrowding of livestock in intensive livestock are elements that increase the productivity of the system. But at the same time, this model causes significant negative consequences, including the excessive use of synthetic agrochemicals, an increase in greenhouse gases, the contamination of aquifers and the depletion of water resources, as well as numerous health and food system problems.

Characteristics of conventional agriculture and livestock

The traditional agriculture and livestock that operated until the **1960s** were characterised by having **very little technology** and a very low use of machinery. Their purpose was a small-scale production mainly for their **own consumption** that depended on internal resources, the recycling of organic matter and the weather associated with each season. Production was ensured by planting **more than one crop in space and time to reduce the impact of severe weather**. Nitrogen fertilisation was achieved with legume crop rotation, and crop rotations suppressed or reduced pests and diseases. Livestock often lived on the land where the crops were to use the manure as compost. Therefore, **both the performance and the optimisation of resources** to obtain better products **were low**. But, in turn, the environmental impact produced by the farms was also low.

Nowadays, conventional agriculture and livestock are **intensive production systems** characterised by the large-scale use of technologies that allow the means of production to be exploited to the maximum. This intensive use of the different elements favours large farms, specialisation of production, **monocultures** (**Figure 1**) and **mechanisation**. The use of pesticides, fertilisers and other agrochemicals and a high amount of fuel in intensive agriculture, as well as overcrowding of livestock in intensive livestock farming, are essential to increase the productivity of the system. The main advantage of this system is that **the productivity of companies is greatly increased** and this allows them to respond to the needs of the market by trading thousands of tonnes of food at national and international level at an affordable price. However, **this production model has also been shown to have significant negative consequences**, such as the excessive use of synthetic agrochemicals, increased greenhouse gases, contamination of aquifers and depletion of water resources, as well as multiple health and food system problems.

Figure 1. Intensive monoculture lettuce plantation. Photo: Pxfuel, CC0.

Figure 2. Intensive chicken farm. Photo: Larry Rana, public domain, via Wikimedia Commons.

Mechanisation, energy costs and incorporation of agrochemical inputs

In the conventional agricultural system, the plant feeds mainly on soluble nutrients that are provided by means of **external fertilisers**, and pest control is carried out with increasingly powerful **synthetic agrochemicals**. In this type of agriculture, the habitat conditions necessary for the growth of plants are not achieved with the formation of a soil, but by working the land with **increasingly heavy machinery**. In the same way, in intensive livestock (**Figure 2**) animal production is maximised with increasingly processed feed and many antibiotics to prevent any disease. In both cases, **a system dependent on the increasing consumption of external energy** (machinery, fertilisers, herbicides and insecticides) is created which, without this important input of energy, collapses and stops producing.

The current model is marked by large companies, which manufacture the machinery necessary to drive the system, synthetic fertilisers to replace the nutrients removed from the soil, the seeds that allow the production of high-yield plants and the pesticides that are used to control adventitious plants, pests and diseases. The costs of these products are the highest production costs. To maintain profitability, the farmer or rancher has a **continuous increase in external costs**, as they are dependent on large industry to produce and sell. Many small farmers cannot afford these costs and end up closing.

Greenhouse gas emissions

Intensive agriculture and livestock make a significant contribution to anthropogenic greenhouse gas emissions.

• **Carbon dioxide (CO_2)** is the gas that contributes the most to global warming. Two of the main causes that cause the release of CO_2 into the atmosphere are the **excessive consumption of fossil fuels** to maintain very intensive agricultural systems, and the destruction of the soil structure, which favours the mineralisation of organic matter and the release into the atmosphere of the carbon that was retained in it.

• **Methane (CH_4)** is the second most important greenhouse gas, with a heat retention power 21 times higher than that of CO_2 (Steinfeld et al. 2006). The role of livestock in methane emissions has long been well known, as **35-40%** of global CH4 emissions come from the decomposition of fertilisers and animal manure.

• **Nitrous oxide (N_2O)** is the third greenhouse gas with the greatest potential for global warming, with a reduced concentration in the atmosphere, but a heat retention capacity 296 times higher than that of CO_2 (Steinfeld et al. 2006). **More than 65% of the total N_2O of anthropogenic origin is produced through intensive livestock and agriculture**. Most of it is released during storage and application of organic manures and nitrogen fertilisers.

Soil and water pollution and depletion of water resources

Large-scale monoculture farms and intensive livestock farms are among the main sources of soil and water pollution. Thus, **agriculture releases large amounts of manure, fertilisers and pesticides** into water sources. Agrochemicals pollute the environment due to their excessive application and the fact that crops use them inefficiently. Similarly, **livestock is also a major cause of water contamination** with microorganisms, parasites and antibiotics that are massively administered to livestock. This contamination of water by agricultural production causes a loss of its value for the supply and contributes to the depletion of the resource (Steinfeld et al. 2006). Today in many industrialised countries drinking untreated water is a hazard. In Catalonia, for example, 41% of the underground water bodies are contaminated, mainly by slurry.

In addition to the impoverishment of water quality, conventional agriculture and livestock are also contributing to a **depletion of water resources**. Intensive agriculture promotes water losses mainly because it destroys the structure of soils that, consequently, lose a large part of their water retention capacity because they have practically no organic matter. In addition, **conventional agriculture** uses inefficient irrigation techniques and makes poor crop selection, which also contributes to water loss. Intensive livestock farming also has a high-water consumption, which exceeds the volume of water used for human needs, mainly destined for the production of feed, by 8%. As a result, most of the largest aquifers are at serious risk of depletion, as water is being withdrawn at a rate that exceeds its capacity to replenish.

Environmental and food system problems

The intensification of food production through conventional agriculture and livestock is mainly responsible for the current environmental crisis that we are suffering. The main environmental problems that are increasing in recent decades are:

• The **loss of biodiversity** due to the increasing pollution and degradation of natural ecosystems due to the current production system.
• The **erosion and loss of soil fertility**, due to the intensive agricultural practices applied.
• **Pollution of waters** by toxic chemicals released to improve production from intensive agriculture and livestock.
• The **greater susceptibility of crops to pests**, linked to the adoption of extensive monocultures and the elimination of natural enemies of pests.
• The spread of **foodborne illnesses and drug-resistant bacterial infections** to humans.
• The **expansion of zoonoses**, since intensive activities facilitate pathogens being passed from wild animals to farm animals and, from these, to humans.

The regenerative production model: a proposal to overcome the environmental and climate crisis

The regenerative model includes a whole series of practices that promote soil health and, with it, that of all the elements that make up the system. It is based on integrating agriculture, livestock and forestry as the axis of a sustainable food system that reproduces natural patterns and processes. It differs from the conventional model in that it allows the accumulation of organic matter in the soil, integrating the animals into the functioning of the system and reducing the inputs needed to produce food. In this way, it has important advantages over the conventional model in order to overcome the current environmental and climatic crisis.

Origin and sources of the regenerative production model

The regenerative model was first defined in the early 1980s, when the **Rodale Institute** defined the term "regenerative agriculture" as a real environmental and economic alternative to conventional agriculture. Since then, with the Australian Darren Doherty as the initial promoter of its introduction in many parts of the world, the regenerative production model has expanded and spread throughout the world.

The regenerative model is not a unique concept but includes a whole series of practices that promote **soil health** and, with it, that of all the elements that make up the system: **crops, animals, forests and people**. The sources on which the regenerative model is based are diverse (**Table 1**), including different agricultural alternatives (natural agriculture promoted by Masanobu Fukuoka in Japan, organic agriculture, carbon agriculture or pasture cropping), agroforestry or a combination of trees with crops or livestock, the design of key lines to retain water, programmed intensive grazing (through holistic management or rational Voisin grazing) or Polyface farms where living soil, plants and animals are integrated.

Objective and bases of the regenerative model

The objective of the regenerative model is to integrate agriculture, livestock and forestry as the axis of a **sustainable food system** that reproduces natural patterns and processes and establishes a global vision of the productive system that includes environmental, economic and social aspects. **The regenerative model is a way of producing with the objective of being:**

• **Ecologically regenerative**: it promotes practices that do not degrade the soil, but rather regenerate it and thereby improve the services provided by ecosystems, animals, plants and the humans who live in them.

TECHNIQUE	DESCRIPTION
Natural farming	Based on intervening as little as possible in the system to let natural processes do their work. It proposes the rotation of crops within the same year and looks for the right moment to carry out each action.
Organic agriculture	Cultivation system based on the optimal use of natural resources, without using chemical products and promoting the production of biofertilisers and native microorganisms.
Carbon agriculture	It consists of leaving the soil unploughed, since tilling the fields can alter the natural structure of the soil and release the stored carbon into the atmosphere.
Pasture cropping	It involves sowing winter cereals directly onto perennial meadows that are active in summer.
Agroforestry	Cropping system that combines trees with crops or livestock In the same area to increase synergies between them.
Keyline design	System that allows water storage, distributing it homogeneously along key lines according to the topography of the ground.
Holistic management	Based on planning how to use very high livestock densities in small spaces, but with very long recovery periods, following a predetermined schedule.
Rational Voisin grazing	System based on a combination of the knowledge of the ecophysiology of the resprouting of grass and needs and animal welfare, in order to choose the most suitable plot at all times for the grass and for the livestock.
Polyface farms	They are resilient agro-silvo-pastoral farms that integrate living soil, plants and animals, increasing the fertility of the system.

Table 1. Main techniques on which the regenerative production model is based.

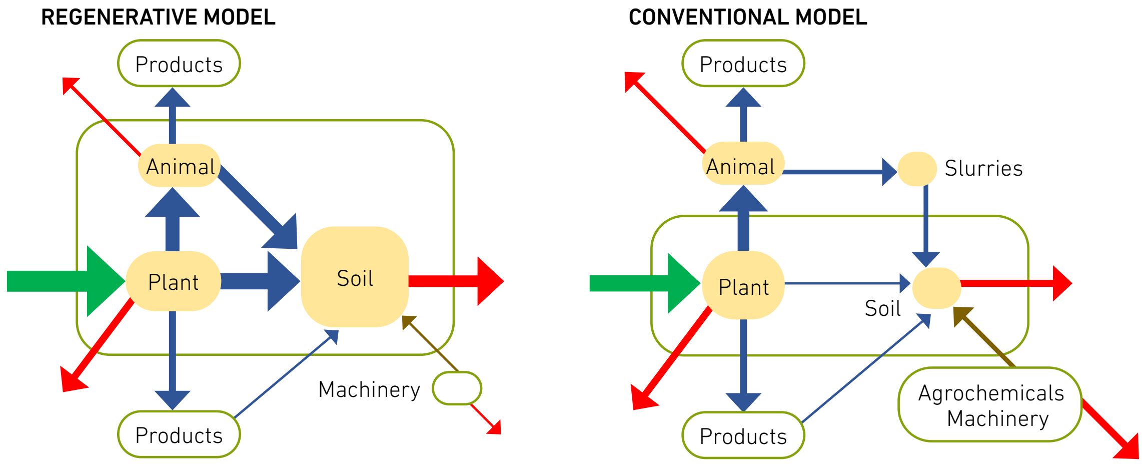


Figure 1. Flow diagrams of the regenerative production model and the conventional one. The large green square corresponds to the agri-food system considered in each case (with or without animals). The boxes represent compartments and the arrows represent flows. The size of the boxes is proportional to the amount of energy stored in each compartment. The thickness of the arrows is proportional to the magnitude of the flow. Green arrows: energy inputs by photosynthesis; red arrows: energy outputs per breath; blue arrows: energy flows between compartments; brown arrows: energy inputs from external inputs.

• **Economically profitable**: it aims to make farms profitable by drastically reducing costs and increasing yields.
• **Socially sustainable**: it allows the creation of employment and local wealth and is committed to the sustainable and healthy management of food production that can be available to any farmer.

There are **five elements of the production system** in which it is possible to intervene and which are the bases for a regenerative production model: (i) the diversity of plants; (ii) the return of plant materials to the ground; (iii) interventions that block the functioning of soil biological processes; (iv) the functioning of the soil and the carbon cycle; and (v) water as a limiting factor in the productivity of the system. These five elements are described in the sheet "Analysis of a productive system from a regenerative perspective".

Advantages of the regenerative model over the conventional one to overcome the environmental and climate crisis

The regenerative and conventional models differ in some very important aspects that make them show very contrasted schemes (**Figure 1**). Thus, the **regenerative model is based on** (i) **accumulating organic matter in the soil**, which makes it possible to maintain the trophic web and reduces carbon losses; (ii) **integrating animals** into the functioning of the system, which reduces the system's outputs and allows the internal cycle to be enhanced; (iii) **reducing the inputs** needed to produce food, since it does not use agrochemicals and uses little heavy machinery. On the other hand, the **conventional model** is characterised by: (i) **accumulating little organic matter in the soil**, because it is lost by respiration; (ii) keeping the animals out of the agricultural system, so that their excrement cannot contribute to improving the soil until the slurry is distributed in the fields; (iii) using large amounts of inputs in the form of synthetic agrochemicals and fossil fuels to run heavy machinery.

There are several **advantages** of regenerative agriculture over conventional agriculture in order to overcome the current environmental and climate crisis:

• **Positive balance of the conversion of atmospheric CO_2 into soil organic carbon.** With the regenerative model, more CO_2 is removed from the atmosphere and stored in the soil, since soils do not lose carbon, they store it. In this way, the production system has a positive carbon sequestration balance, something that does not happen with the conventional model.

• **Reduction of CO_2 emissions by the productive sector.** Destroying the soil releases all the carbon it contains. The regenerative model, through not tilling and covering the soil with plants, reverses this process. Greenhouse gas emissions are also reduced by not requiring the manufacture of synthetic fertilisers and pesticides and by requiring much fewer fossil fuels for the use of heavy machinery.

• **No synthetic agrochemical inputs are required.** Regenerative agriculture does not require synthetic fertiliser and pesticide inputs to produce high-yield crops. These agrochemicals have a high cost to human health and the environment, so regenerative systems generate healthier environments.

• **Increase in the water retention capacity of soils.** With the regenerative method, soils are richer in organic matter, which increases their water retention capacity and helps plants to better resist climate change.

Bases of a regenerative production system

- The soil from a regenerative productive perspective

- Forest management from a regenerative productive perspective

- Management of the meadow and the animals that graze in it from a regenerative productive perspective

- Crop management from a regenerative productive perspective

Bases of a regenerative production system

The soil from a regenerative productive perspective

- Nourish and preserve the habitat of the soil food web: the principles of a regenerative production system
- High diversity of plants: maximum production and variety of food for the soil trophic web
- The return of plant materials to the soil: balance between mineralisation and humification
- Interventions that block the functioning of soil biological processes
- Soil functioning and the carbon cycle: carbon inputs, outputs and stocks
- Water, the limiting factor of the productivity of the system
- Indicators of soil health
- Analysis of a productive system from a regenerative perspective

Nourish and preserve the habitat of the soil food web: the principles of a regenerative production system

The soil food web is the set of organisms that live in the soil. The nutrition of the food web and the preservation of a favourable habitat for the life of these organisms are the basis of a sustainable production system. A system managed following these criteria results in high soil fertility and health and, therefore, high plant productivity.

A healthy soil harbours a complex **trophic network** (**Figure 1**), ranging from microorganisms (bacteria, fungi, protozoa, nematodes), to the soil macrofauna (worms, insects, reptiles and mammals). Under natural conditions, **efficient plant feeding** occurs as a result of the biological activity of this trophic network. The functioning of this biological activity requires two basic conditions: 1) the supply of food for the soil trophic network and 2) the maintaining of suitable habitat conditions for the different organisms. Compliance with these conditions defines the bases of a sustainable production system.

Relations between the soil food web and plants

Maintaining the relationships established between the organisms of the soil food web and plants is the basis of a sustainable production system. These relationships occur in both directions:

• **Plants feed the soil food web**. Under natural conditions, all the carbohydrates produced in photosynthesis, which have not been consumed by plant respiration, end up being incorporated as organic materials to feed the food web of the soil. An important part of this incorporation is performed by the **roots (Figure 2)**. Through them, the plant directly feeds ecto and endomycorrhizal fungi and releases exudates to favour the presence and activity of beneficial microorganisms in its environment (rhizosphere). **Dead roots are an important contribution of organic material** for feeding the trophic web of the soil. When a plant dies, the plant tissues of the aerial part are also incorporated as organic materials that nourish the trophic network of the soil, either directly or through herbivore excrements.

• **The food web of the soil feeds the plants**. The activity of the soil trophic network generates complex processes that make it possible to make the nutrients available to the plant in the most appropriate place and time. Soil ecto and endomycorrhizal fungi help the plant to more efficiently prospect for nutrients and water from the soil. The biological activity that favours the plant in the root environment generates biochemical changes that release cations retained in the soil and make them available to it. The activity of **nitrogen-fixing bacteria** is also favoured. In addition, the roots can also directly absorb amino acids and proteins from **organic materials incorporated into the soil** and partially decomposed by the activity of the soil's food web.

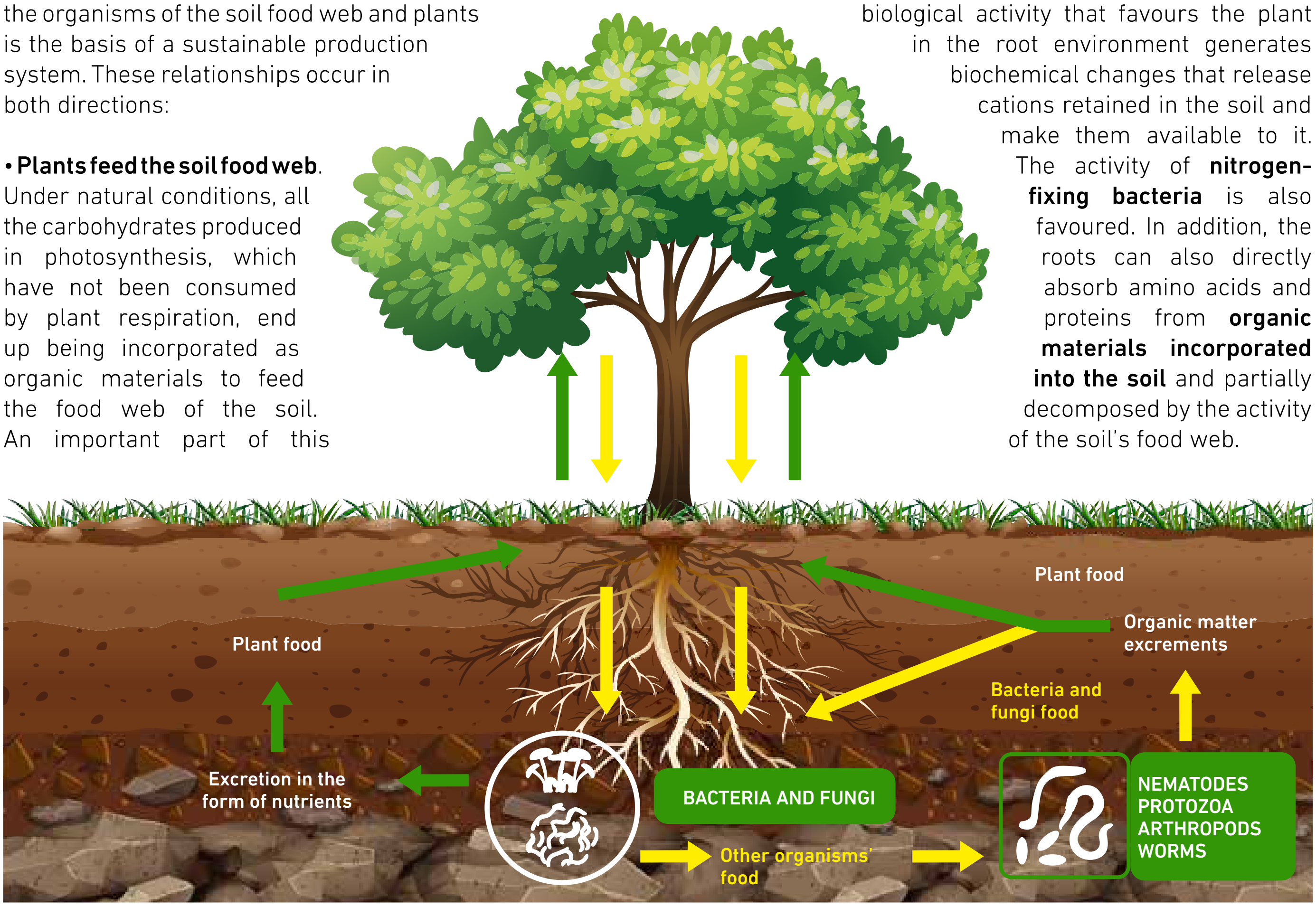


Figure 1. Chain of relationships between soil and plants. Yellow arrows: the plants feeding the soil, green arrows, the soil feeding the plants.

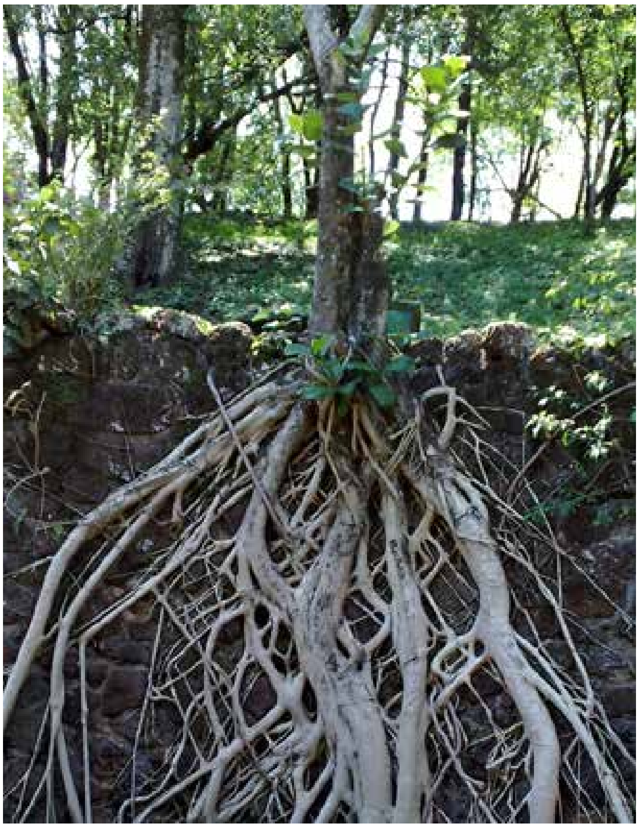


Figure 2. Roots play a fundamental role in feeding the soil food web. Photo: Pxfuel. Creative Commons Zero - CC0.

Figure 3. Earthworms play a fundamental role in soil aeration. Photo: iStock.

Habitat conditions necessary for the life of the soil

The functioning of the biological processes of the soil requires habitat conditions (micro and macro pores) that allow the **movement of air in the soil, the movement and retention of water**, and the necessary conditions for the movement and shelter of the different components of the food web. The main thing responsible for maintaining these habitat conditions is **Soil Organic Matter** (SOM). An important component of this SOM is humus, which is a stable phase of the degradation process of organic material incorporated into the soil by the trophic web. Another important component of SOM is organic chains, which are produced by fungi and are responsible for creating stable agglomerates of mineral particles. The **activity of the soil macrofauna**, such as worms or ants, creates tunnels that improve the conditions necessary for the functioning of the entire trophic network (**Figure 3**).

The regenerative production model is based on the natural feeding of the plant

The regenerative production model is based on knowing the factors that **naturally nourish a plant** and only uses the soil's resources to feed it. This model is based on feeding the **soil food web** and maintaining the habitat conditions necessary for its functioning, specifically regarding SOM and soil structure. As a result, the regenerative production system, well managed, obtains a large production of food with high nutritional quality and in a sustainable way.

The conventional agricultural system, on the contrary, does not consider the importance of the biological processes of the soil trophic network, and the plant is mainly fed by soluble nutrients provided by **external fertilisers**. In this type of agriculture, the habitat conditions necessary for root growth (penetrability, aeration and infiltration), are achieved by working the land with increasingly powerful machinery. In this way, a system dependent on the increasing consumption of external energy (machinery, fertilisers, herbicides and insecticides) is created. Without this important input of external energy, the system collapses and stops producing.

High diversity of plants: maximum production and variety of food for the soil trophic web

A great diversity of plants allows the maximum amount of organic materials to feed the trophic web of the soil to be provided. Mixing species to achieve greater diversity can be achieved in time or space. In time, it is achieved mainly using rotations. In space, the greatest diversity is obtained with the association of plants that can have a joint use, using companion plants or maintaining the margins with high diversity.

Maintaining a high diversity of plants

The plant is the engine that directs the functioning of the ecosystem from the organic materials synthesised in photosynthesis. These organic materials are the basis for feeding the soil food web and creating the necessary habitat for it to function. **The objective of productive management is to make the system work to the maximum** to maximise solar energy capture and carbon sequestration by plants (through photosynthesis). For this, we must know how to manage a diversity of plants that allows us to maintain the maximum contribution of organic materials to feed the trophic network of the soil throughout the year (**Figure 1**). This can be achieved in a number of ways:

1. With the presence of active roots at different depths and throughout the year. The incorporation of organic materials from plants to the soil occurs mainly through the roots. We must know how to manage a diversity of plants that guarantees a good presence of roots throughout the year and with most of the space occupied, with special attention to the presence of roots at different depths.

2. With complete ground cover. We must manage a diversity of plants that allows us to create complete coverage throughout the year, whether with green material or dead material.

3. With growing plants throughout the year (when the area allows it). It is essential to be able to obtain the maximum possible growth all year round to maintain the maximum biological activity of the system and the maximum contribution of organic materials to the soil.

4. Providing varied plant material. The more varied the organic material provided by the plants, the better the feeding of the soil food web.

5. **Collecting plants at the time of the plant growth cycle** in which they have introduced the greatest amount of carbon into the soil and have the highest reserve content in the roots.

Figure 1. A high diversity of plants (both in the aerial and underground parts) allows the trophic network of the soil to be fed throughout the year. Photo: Stock

Figure 2. Crop rotation. Photo: Markus Winkler, CC-BY (Unsplash).

Figure 3. Orchard with different types of crops (polyculture). Photo: MJ Broncano.

Figure 4. Agroforestry. Photo: National Agroforestry Center, CC-BY.

How to get a high plant diversity

When designing the mixture of different species we must consider different criteria, apart from our own production criteria, such as the depth of the roots, the ability to produce biomass or the ability to control their growth. The mixing of these species can be achieved in time or space (or both).

• **In time**. The diversity of plants in time is achieved using **rotations** (**Figure 2**). It is important that there are no seasons of the year without cultures (although for climatic reasons the cultivation is stopped). If for climatic reasons there is a time of year without cultivation, we must ensure that the soil is covered so that the biological activity of the soil is limited as little as possible.

• **In space**. We can increase the density of roots in space through the **association of plants** that allow a joint use (polyculture) (**Figure 3**) or through the use of **companion plants** that do not have a direct use, but that improve the production of the plants that are intended to be collected. A similar effect can also be achieved by **maintaining margins** with high diversity. A specific case of great interest is the combination of herbaceous and tree production in different systems that are included in **agroforestry (Figure 4)**.

The regenerative production model: competition versus collaboration

In the **conventional production system** plants **compete** for the soluble nutrients of the fertilisers provided for their nutrition. On the other hand, in the regenerative productive system, all the plants that coexist in the same space **collaborate** in feeding and maintaining a favourable habitat for the soil food web. As a result, there is an overall improvement in the fertility of the site. Thus, the more diverse the production system is, and the more it produces, the more we can increase the production potential of our location.

Competition for light is the main limiting factor that must be controlled to favour the species we are interested in producing. In relation to **competition for water**, we must bear in mind that its use is optimised in structured soil and with a complete soil food web. In dry seasons, however, water limits the system. In this case, water control should not be by interventions in the soil (tillage) but by controlling the aerial part (evapotranspiration control). Thus, we must always maintain complete coverage (alive or dead) of the soil that protects against the direct impact of sun and rain.

The return of plant materials to the soil: balance between mineralisation and humification

The organic matter incorporated in the surface provides nutrients and plays an important role in covering the soil surface. The way in which organic plant materials are incorporated into the soil can vary greatly in each ecosystem depending on environmental conditions. The main factors that regulate the balance between mineralisation and humification of these materials are the C/N ratio of the organic material, the degree of lignification, the level of crushing and the microenvironmental conditions of the place.

Incorporation of organic matter into the soil surface

A production system based on feeding the soil food web and maintaining the **habitat conditions** necessary for it to function is defined by the type, quantity, and way in which organic materials are incorporated into the soil. Although the most important incorporation occurs through the roots, the incorporation of the aerial part is the one that we can manage the easiest, therefore, it is what characterises our system. The **organic matter incorporated in the surface**, in addition to providing nutrients, plays an important role in covering the soil surface. The value of this organic matter depends on the speed at which it decomposes. The way in which organic materials from the aerial part of plants are incorporated is a **characteristic of different natural systems:**

• In the **forest**, incorporation occurs mainly by **leaves** falling, which accumulate on the ground (**Figure 1**). The interior microclimate of the forest makes it easier for these leaves to **decompose** and, in this way, they are the basis of organic matter for the functioning of the food web.

• In **grazed grasslands**, the incorporation of organic matter occurs mainly through **manure and urine** from animals that graze on the grassland. Manure is a partially decomposed organic material **rich in microorganisms.** For effective incorporation into the soil, especially at depth, manure requires the activity of its **own set of insects** such as dung beetles (**Figure 2**), among others.

• In **non-grazed plant systems**, the incorporation of plant material from the aerial part of the plants requires some type of intervention (such as cutting or trampling leaves and branches) that allows this material to be lowered to the ground. If the **material does not reach the soil** it degrades without being incorporated into the soil (standing oxidation), so that a significant part of the material is not used by the food web (**Figure 3**).

Balance between mineralisation and humification

When bacteria very quickly consume the plant materials provided on the surface, this produces a rapid supply of nutrients, in a process called **mineralisation**. If this happens, plant materials disappear quickly and cannot play any role in soil cover. On the contrary, when decomposition is slow, plant materials create a soil cover that protects against direct attacks from the sun, rain and wind, it encourages water infiltration, creates the necessary habitat for important elements of the food web, and is responsible for forming a stable surface humus. It is a process called **humification**.

Figure 1. Holm and cork oak forest with ground covered by a layer of leaves. Photo: MJ Broncano.

Figure 2. Dung beetle on cow excrement. Photo: MJ Broncano.

Figure 3. Tractor crushing the plant aerial part that remains on the ground and can be used by the soil food web. Photo: MJ Broncano.

To prioritise the process that is of most interest each time, it is necessary to know the factors that regulate the **balance** between mineralisation and humification. Modifying these factors can control the balance and therefore the role that the incorporated materials perform in the creation and function of the soil. **The main factors that regulate the balance** between mineralisation and humification of plant matter are:

• **C/N ratio**. To satisfy their needs, bacteria require an optimal **C/N ratio close to 24**, which is what they need to breathe and build up their organism. When the relationship moves away from this value, two different things happen:

- If the **C/N ratio of the organic materials is less than 24** (high nitrogen content), in relation to their needs, there is a lack of carbon, in order to consume all the nitrogen, the bacteria look for additional carbon in their environment. This leads to a rapid loss of organic matter, leading to a loss of soil structure and cover on the surface.

- If the organic material has a **C/N ratio greater than 24** (low nitrogen content), the bacteria look for more nitrogen to adjust this ratio to their needs, consuming a large part of the nitrogen available around them. In this case decomposition of the materials is slow and **can lead to a lack of available nitrogen for plants**.

Working with green manures, it must be considered that the nitrogen content varies throughout the life of the plant: in **young plants** the content is high for all species. When they **start flowering**, the C/N ratio is usually over 24. This is a good point to incorporate green manure superficially because microbes can quickly consume the material, but part of carbon remains, allowing slower decomposition. In the **plant's maturity** phase there is a drop in nitrogen content that can vary greatly depending on the species.

• **Degree of lignification**. There are several substances, such as lignin or suberin, that have a complex structure that makes it difficult for bacteria to break down. These complex substances must be broken down by actinomycetes and fungi. Therefore, materials with a **high lignin content**, such as forest debris from trunks and branches, decompose more slowly than other plant debris, and therefore **give rise to a more stable humus**.

• **Level of crushing of plant materials**. For the same material, the more crushed it is, the more easily it is attacked by detritivore organisms that make it more accessible to microorganisms, so that its decomposition is faster.

• **Micro-environmental conditions**. Environmental conditions largely determine the rate of decomposition of organic matter. **The activity of microorganisms and fungi** increases with the right humidity conditions, temperature and the presence of oxygen. Otherwise, in conditions of lack of water, low temperatures and anoxia (lack of oxygen) the decomposition rate of organic matter is reduced.

The regenerative production model is based on knowledge of natural processes

The proposal for a sustainable regenerative production model should not be confused with the return to a productive system of the past. The approach to a sustainable production model is possible thanks to **scientific advances in knowledge of natural processes, which allows us to know** how the natural nutrition of plants works and its technical application in a controlled way in the field. Efficiently controlling the return of organic materials to the soil and the mineralisation/humification balance allows improved production per unit area of fields. In this way, the environment's resources are used in a **real circular economy model**. This increase in production does not depend on external resources and makes it possible to recover the profitability of small farms in which the current model, strongly dependent on oil and agrochemicals, is not profitable. At the same time, **this new model is a scalable one**, i.e. it can adapt to any type of condition and offers a real alternative to the dependent and unsustainable system that we have at present.

Interventions that block the functioning of soil biological processes

Some management practices destroy biodiversity and therefore do not favour the food web of the soil. These include: (i) tillage: it breaks down the suitable habitat for the soil food web; (ii) the increase of bare soil: it allows the direct impact of the sun and rain on the soil surface; (iii) soil compaction: it destroys the habitat by altering the porosity of the soil; (iv) the use of chemical fertilisers: they directly feed the plants without feeding the trophic web of the soil; (v) the use of insecticides, fungicides and herbicides: they reduce the soil's biological activity.

All agricultural practices that negatively affect the soil food web or that destroy the habitat, cause the blocking of biological processes and, as a result, the natural fertility of the soil is lost. In this situation, farms depend on external factors such as the use of tillage (oil) and agrochemicals (more oil) to continue producing. The following **interventions have the greatest impact on the loss of soil fertility**:

• **Tillage**. Tilling the soil (**Figure 1**) breaks the hyphal systems of the fungi that help the roots to increase the prospecting of the soil, **breaks the agglomerates** that participate in the creation of the suitable habitat for the soil food web and facilitates the mineralisation of the organic substances that are responsible for maintaining these conglomerates. At the same time, tillage increases the temperature and aeration of the soil, favouring the activity of opportunistic bacteria and the mineralisation rate of soil organic matter. This means that tilling the soil has an initial effect of increasing fertility (mineralisation), but the final effect is a **decrease in the total content of organic matter in the soil**, and its consequences are the worsening of the habitat conditions for the soil food web and the nutrient and water retention capacity.

Figure 1. Turned soil after tillage. Photo: Núria Anglada.

• **Increase in bare soil**. The increase in bare soil is an important effect of tillage or overgrazing (**Figure 2**). The bare ground **causes a direct impact of sunlight,** with a direct effect on the life of the first few centimetres of the ground. At the same time, it allows the impact of rain and wind on the soil surface, which causes **erosion and loss of superficial organic matter,** compaction and a decrease in the infiltration rate.

• **Soil compaction**. Compaction is usually the result of the use of heavy machinery or poor grazing management (overgrazing) (**Figure 3**). It is usually linked to bare ground. This compaction **breaks the micro- and macro-porosity of the soil**, destroying the habitat of the soil trophic network and preventing the infiltration of rainwater. This does not mean that machinery cannot be used. For extensive productions it is necessary to use a tractor for the direct sowing and harvesting of products. But you should always use the lightest possible machinery and avoid times when damage to the ground can be more significant, such as when the ground is very wet.

• **Use of chemical fertilisers**. Chemical fertilisers directly feed the plants, which, having soluble nutrients available, do not invest in feeding the soil food web. In addition, the **increase in nitrogen in the soil causes bacteria to consume more carbon**, which they obtain from the soil organic matter (SOM). This increases the mineralisation rate and causes the disappearance of SOM and the loss of habitat for the soil food web, so that the natural diet of plants stops working and it becomes increasingly dependent on external inputs. **When the biological activity of the soil is lost, feedback is generated with a negative effect**: the plants become increasingly malnourished. This makes them more easily attacked by

Figure 2. Tilled field with the soil exposed. Photo: Pxhere, CC0.

pests, which requires the use of multiple products (such as insecticides, fungicides or herbicides) to protect them; in turn, these biocides further reduce the biological activity of the soil.

• **Use of insecticides, fungicides and herbicides**. All these products directly affect the life of organisms and, therefore, all the biological activity and functioning of the soil. These products are closely related to chemical fertilisers, since they make plant nutrition increasingly dependent on the soluble nutrients provided. In this way, and as we have said, **a circle of growing dependence** between chemical fertilisers and insecticides is generated.

The regenerative production model: production is put in the farmer's hands

The conventional production model depends on the big companies that manufacture the machinery and agrochemicals necessary for the system to function. The costs of this machinery and these agrochemicals are the highest production costs and continuously increase. To maintain profitability, the farmer must produce more and more, entering a **circle of dependence on large industry to produce and sell**. The small farmer usually cannot afford these costs and must close down.

A model that considers the natural feeding of the plant is based on knowledge, which is accessible to everyone, and does not depend on oil. With this model, production costs related to external inputs are reduced or disappear (there are no agrochemicals, there is no soil work).

There is also an economy of scale: as it does not require external inputs, it is a model applicable to smaller scales. The difference in costs when working at reduced scales is manageable and can be compensated by local sales strategies. **This creates the opportunity for quality food in the hands of farmers and consumers**.

Figure 3. Uncovered soil compacted by overgrazing. Photo: MJ Broncano.

Soil functioning and the carbon cycle: carbon inputs, outputs and stocks

Soil functioning in any ecosystem depends directly on its characteristic carbon cycle. The cycle has dynamic stocks between the different components of the system: plants, other organisms that intervene in the cycle, organic materials and organic matter in the soil. This carbon cycle is modified by a series of factors: the mineralisation/humification balance, the export and import of organic materials, and disturbances. The applied agricultural, livestock or forestry management model can intervene on the carbon cycle by modifying these factors in one direction or another.

System components and their relationship with carbon stocks

Soil is the main element of terrestrial biological systems. The soil requires carbon (organic materials) to maintain all the biological processes that characterise it. Thus, managing a terrestrial biological system can be understood as managing the carbon cycle, which starts from the CO_2 fixed by the photosynthesis of plants until it reaches the ground. Each terrestrial biological system presents a characteristic **carbon cycle**, in which dynamic stocks of carbon are established that are temporarily retained in the **different components of the system**. The quantity and stability of these carbon stocks determines the functioning of the system and its capacity **to sequester carbon from the atmosphere**.

a) Plants. The carbohydrates that the plant produces and that are not used in respiration are the basis of the carbon cycle. Part of these carbohydrates is released directly by the roots in the form of exudates to feed the soil food web. Another part becomes part of different structures of the plant (reserve, support, reproductive) and finally, they also end up joining the carbon cycle of the system. In some cases these structures represent small and not very stable carbon stocks (such as the aerial part of annual grasses), but in other cases these structures can represent very important carbon stocks with great stability, as is the case of the wood of the forests.

b) Organisms involved in the cycle. Before reaching the soil, the organic matter produced by the plant can pass through different organisms (herbivores, carnivores, decomposers). Every time a new organism intervenes in the cycle, part of the carbon is used to obtain energy for respiration and released into the atmosphere in the form of CO_2. Another part of the carbon is eliminated in the form of excrement and the rest becomes part of the different structural elements of the body of organisms until they die.

c) Organic materials. These materials are provided mainly by the roots and remains of the aerial part of the plants, as well as by the excrement and dead bodies of the different organisms that intervene in the cycle. They are not very stable materials, they are rapidly degraded by microorganisms, thereby losing about 90% of their composition. The fact that they degrade rapidly means that these organic materials represent an insignificant stock within the system.

d) Soil organic matter (SOM). This corresponds to humified organic materials. SOM presents greater stability than the organic matter it comes from and represents a very important stock within the system. In fact, it is the main terrestrial reservoir of organic carbon. Thus, at least 10 kg of organic materials are needed to form 1 kg of SOM, which in turn fixes 3.7 kg of CO_2. 1% of SOM in the soil represents 27 t SOM/ha, which is more than 90 t/ha of CO_2 sequestered.

Factors that modify the system's carbon stocks

There are a series of factors that modify the carbon cycle, and especially the dynamics of carbon in the soil, and that, therefore, affect the system's function and carbon storage capacity.

- **Mineralisation/humification balance of organic materials in the soil.** The soil is the component with the highest carbon retention capacity in the system. Therefore, all the factors that favour greater mineralisation and loss of soil organic matter reduce the total carbon stock of the system. These include the factors that regulate the balance between mineralisation and humification of plant matter and, in general, the different interventions that reduce soil organic matter.

- **Export of organic materials outside the system** (**Figure 1**). If part of the carbohydrates produced by the plant are removed from the system (for example, by agricultural, livestock or forestry use), this produces an overall loss of the carbon stock. When this export is small, the system can recover naturally. But if the export is significant, an overall loss of carbon from the system occurs, especially in the soil, which affects the stock and the biological activity of the soil and causes a gradual impoverishment of the system.

- **Import of organic materials external to the system.** The current agricultural system depends on the external carbon

Figure 1. Wood extraction is a way of exporting organic matter out of the system. Photo: MJ Broncano.

Figure 2. Tractor spreading manure. Photo: José Cárceles, CC-BY-NC. Source: Flickr.

input linked to the use of oil (**fuel and agrochemicals**), without which the system would not function. There are also important external inputs based on **slurry** (**Figure 2**). In both cases, these are costly external inputs and they do not represent any improvement in the productive capacity of the system itself (it does not feed the soil food web or create soil habitat) or the carbon stock. In other cases, external organic materials are imported with the aim of **incorporating organic matter to improve the habitat and feed** the soil food web, increasing the soil's carbon stock. This is the situation that occurs, for example, when there is a transition from conventional to regenerative agriculture.

• **Disturbances.** Disturbances typically represent an abrupt loss of carbon from the system. The clearest case is fires (**Figure 3**). Gross carbon emissions from **fires are huge**, equal to 25% of global annual emissions from fossil fuels. The **impacts of other disturbances** such as extreme droughts or floods on the carbon stocks of the system are less, since the direct release of CO_2 is less or lasts longer over time.

Carbon cycle and management model

The agro-silvo-pastoral management model intervenes on a natural system modifying the carbon cycle in its different phases: producing **carbon extraction** (outcomes), modifying the **conditions of return to the soil and the capacity to store carbon** in the soil, and making a contribution of external carbon to the system

Figure 3. State of the forest after the 1994 fire in Bages and Berguedà (Barcelona). Photo: Josep Maria Espelta / Javier Retana.

(oil and agrochemicals). In general, the **conventional model** creates long cycles, with carbon outputs and inputs that are not connected, and **eliminates the most important stocks: soil and large trees. A regenerative management model** must ensure that the outcomes do not significantly affect the biological processes of the soil and, therefore, its productive potential, while minimising external contributions and maintaining the main carbon stocks.

The regenerative model: carbon stocks and climate change

All plants sequester carbon in photosynthesis, whether this sequestered carbon influences reducing atmospheric CO_2 will depend on the cycle that this carbon follows and on whether it becomes part of stable stocks. **The most important potential carbon stock in regenerative systems is soil**. The conventional system destroys the soil structure and favours the mineralisation of soil organic matter, releases the carbon that was retained in the soil into the atmosphere (i.e. it increases the effect of climate change) and eliminates the role of carbon reservoir that the soil has in natural conditions. In addition, this model consumes a large amount of oil linked to the use of machinery and agrochemicals. **The regenerative system preserves the structure of the soil and feeds the soil food web reduces carbon from the atmosphere and introduces it into the soil**, turning the soil back into a large carbon reservoir. In fact, according to the Rodale Institute, if we managed all the world's croplands and pastures according to the regenerative organic model, we could sequester more than 100% of current annual CO_2 emissions.

Water, the limiting factor of the productivity of the system

Water is the main limiting factor in terrestrial ecosystems. The increase in the organic matter content of the soil soil organic matter linked to a regenerative system makes the soils have a better structure, be more porous and present greater infiltration, while guaranteeing greater water storage that can be used by the plants. In dry or seasonal climates, whenever possible it is good to have systems that improve and increase the water supply. Irrigation obviously stands out among them, as do terraces, contour systems or small reservoirs.

Figure 1. In healthy soils the organic matter content is high, as is the associated water retention. Photo: Marc Gràcia.

Water is the main limiting factor in a terrestrial environment

In terrestrial ecosystems the main limiting factor is water. It is not distributed equally in all ecosystems. There is a direct and very high relationship between the water available in **ecosystems and their productivity**: the lack of water limits the growth of plants and, indirectly, of animals in many ecosystems, while in those with a large amount of water, productivity is very high.

In general, conventional agriculture notably increases **water losses** due to the use of the flood irrigation technique, the destruction of the soil structure and poor crop selection. For this reason, most aquifers are being considerably reduced, since water is being extracted at a rate that exceeds their capacity to replenish them.

Maintaining the coverage and structure of the soil with a higher content of organic matter linked to a **sustainable agriculture system is the main way to improve the infiltration and water retention capacity in the soil**. The increase in organic matter in soils improves their characteristics related to their ability to retain nutrients and water for plants. Thus, when the organic matter content of the soils is higher (**Figure 1**), they have a better structure, are more porous and present greater infiltration, a fact that reduces the volume of runoff water and the risk of erosion. In addition, the organic fraction of the soil is highly hydrophilic, **it can retain between 4 and 6 times more water** than its own weight, thus guaranteeing good storage of useful moisture for the plants.

Additional water supply systems

In dry climates, seasonal climates during the summer or in areas of intensive use such as vegetable gardens, water continues to be a limiting factor for agricultural production, even if the soil conditions in terms of organic matter content are adequate. Therefore, whenever possible, it is good to have systems that improve and increase the water supply. This contribution should respect the principles of soil function to increase the productive potential defined by the climatic conditions of each area.

• **Irrigation**. The possibility of watering is **conditioned by the availability of water and the cost of its application** (start-up investment and operating costs) (**Figure 2**). There are interesting technologies available today to improve the efficiency of its use. The quality of the water to be used must always be taken into account, together with the impact that its use may have on the water sources, since if the resource is depleted, the investment will be lost.

• **Terraces**. This is the traditional system in mountain areas (**Figure 3**). Terraces **improve water infiltration and soil depth on steep slopes**. Traditionally terraces have been supported by stone walls. Where these walls are still standing, their use is very convenient, taking into account that, if the wall is lost, gullies and erosion phenomena can occur. The **construction of new stone terraces** is very expensive and usually cannot be carried out.

• **Runoff retention systems following contour lines**. There are systems that cost less to make than terraces to slow down the movement of water and facilitate its infiltration. At each site, various techniques adapted to the site can be used. One option is to **create small barriers** following contour lines using logs and remnants of forest harvesting. The **Keyline system** proposes a very complete system for landscape design in order to distribute water in a homogeneous way and turn the system into a large water store that is distributed along key lines according to the topography of the land.

• **Systems of small reservoirs to collect rainwater in the upper parts of the land**. This system requires planning and prior design. There are many examples of the construction of relatively low-cost small rainwater collection reservoirs with earthen dikes. **They require a water extraction system and distribution channels**. These systems represent a way to create water reserves that can be used for downstream use. For many areas with water problems, this can be an important goal.

Figure 2. Irrigation with sprinklers. Photo: CC0.

Figure 3. Terraces supported by stone walls. Photo: Parc Natural dels Ports distribution license under CC BY-ND 2.0.

The regenerative production model optimises the use of water

The conventional model is based on tilling the soil that breaks its structure and any plant cover. At the same time, **it causes the waste of water** because the soils in this type of agriculture do not have a retention capacity. As a result of this type of agriculture, water resources are depleted and overexploitation occurs as water is withdrawn at a rate that exceeds its replenishment capacity.

Instead, **the regenerative model agriculture protects water sources** and reduces the need for them. This type of management, in contrast to the conventional one, is based on maintaining the soil structure and therefore, the humus layer. **Humus improves the water cycle on small and large scales**. Humus determines the infiltration capacity of water, the recharging of aquifers and the prevention of floods and droughts. The water stored in the humus is transported to the deepest layers of the soil and finally, to the aquifers. A soil rich in humus can absorb 150 l/m^2 in an hour, which will be distributed like a system of sponges. This ability to absorb water makes it possible to mitigate the effect of floods and erosion caused by heavy rains.

Permanent ground cover is another characteristic of the regenerative model as it protects against wind and water erosion. The vegetation cover also prevents the excessive evaporation of water from the soil, by exerting a regulating role of its temperature and reducing the loss of water by evaporation.

Indicators of soil health

A series of qualitative indicators, which do not require laboratory analysis, make it possible to quickly assess, on the ground, the state of soil health. These indicators can be grouped into three types: a) from the visual analysis of a section of the soil (identifying organic material, roots, soil organic matter, macro-fauna, aggregates and pores); b) indicators by physical tests (penetrability, infiltration, aggregate stability); and c) through the smell of the soil.

Indicators to monitor soil quality

There are a large number of indicators to monitor the quality of soils and the changes that occur in them. These include **indicators of the physical properties of the soil**, such as depth, texture, infiltration potential or water retention capacity. Others are **chemical indicators**, such as organic matter or carbon content, pH, or electrical conductivity. Finally, there are also **biological indicators**, such as microbial biomass, respiration or, more recently, soil biodiversity. However, all of them require complex sample collection and laboratory analysis. The way to interpret them and the methodology to measure them are widely described in any soil science manual.

However, there are other indicators that do not require laboratory analysis and that allow a quick assessment of soil health in the field. Although they are mostly **qualitative indicators** that do not allow making certain comparisons, they do **allow us to quickly identify possible problems in the soil,** and to have a reference for monitoring the change over time of the soil. We can group these indicators into three groups: indicators from a visual analysis of a section of the soil, indicators through physical tests, and indicators of soil odour.

Figure 1. Section of healthy soil. Photo: Marc Gràcia.

Visual analysis of a soil section

Some indicators can be obtained directly from the visual analysis of a **soil section** (**Figure 1**). To do this, a hole is dug in the ground or, more quickly, a **soil sample of the first 10-15 cm** is removed with a knife or shovel. The elements that can be observed visually are the following:

• **Cover of dry organic material**. Look at the soil surface for dry organic matter cover. A balance between good cover and a certain degree of decomposition of organic matter is an indicator of healthy soil.

• **Abundance of roots**. Roots grow in all directions and root density is a sign of healthy soil. At the same time, in plants with taproot roots, the fact that the main roots grow vertically downwards is a sign that there is no horizontal impermeable layer as a result of tillage.

• **Dark colour of soil organic matter**. In well-structured soil, a gradient is usually appreciated that begins with a darker colour on the surface that gradually lightens with depth. Depending on the type of soil, in well-structured soils the top may have a darker layer of humus.

• **Macro-organisms in the soil**. The aim is to identify macro-organisms in the soil, which can be arthropods or other groups (with adequate soil moisture and if the sample is large enough, worms should be found). They are easier to see under the cover of organic material, and a good number of them indicate healthy soil.

• **Aggregates and pores**. Looking closely at a sample in your hand, you can observe aggregates of different sizes. A soil without aggregates and with an amorphous structure is a soil without pores and with very little aeration, which prevents the movement and life of the components of the food web.

Figure 2. Elements for the infiltration test. Photo: Marc Gràcia.

Figure 3. Dry soil samples from a regeneratively cultivated agricultural field (left) and a conventional agricultural field (right) submerged in water. Photo: MJ Broncano.

Soil physical tests

There are simple physical tests that give us good indications about the health of the soil. With these tests we can observe how the soil changes as measures are taken to improve it.

• **Penetrability**. In this test, a knife or machete is stuck to check the resistance offered by the soil. It should be done in conditions of minimal humidity. The machete marks the limit beyond which it is difficult to nail. In a healthy soil it should be easy to drive the knife deeper than 15 cm.

• **Infiltration**. To carry out this test, a tall metal ring (it can be a can open at both ends) is driven into the soil at a depth of 3-5 cm. The ring is filled with a fixed amount of water and the time it takes to infiltrate is observed, so that if it is a short time it is considered that the soil has a good infiltration (**Figure 2**).

• **Stability of the aggregates.** A sample is taken from the top layer of the soil. It is left in the air to dry. Once dry, it is immersed in a glass jar filled with water and the time it takes for the aggregates to dissolve is observed. When the aggregates break up the soil sample becomes a homogeneous layer at the bottom of the jar. If the aggregates are not very stable, they will be broken up in less than 5 minutes. If the aggregates are stable and, therefore, the soil is healthy, they can be kept for several days before falling apart (**Figure 3**).

Soil odour

The smell gives us valuable information about the state of the soil. In order to appreciate the smell, the soil must have a minimum humidity. If the soil is very dry, before smelling it, take a sample, moisten it with water and wait a while for it to homogenise.

• **Sweet scent with distinctive earthy geosmin scent**. Geosmin is a chemical produced by some bacteria and fungi found in the soil. This substance is perceptible when the soil is moistened and is an indicator of a healthy soil. It is the characteristic smell of forest humus.
• **Smell of rotten eggs**. This odour denotes a soil dominated by anaerobic organisms. A healthy soil must be aerobic.
• **Metallic smell**. This odour indicates an unbalanced soil dominated by bacteria.
• **Odourless**. When a soil has no odour, it is that it is a very dry soil or with very little activity of organisms.

The regenerative production model recovers contact with the soil

Healthy soil allows plants to grow at their maximum productivity, without diseases or pests and without the need for external supplements. The most important thing to know how a soil works is **to regain contact with it**. Many farmers work from the top of the tractor, they have lost contact with the soil. This sheet highlights the importance of the soil and is intended to be a guide to which indicators allow us to find out the status of and changes to soil health.

Analysis of a productive system from a regenerative perspective

The elements of the production system on which it is possible to intervene and which are the basis for a Regenerative Productive Model are: 1) the diversity of plants; 2) the return of plant materials to the soil; 3) interventions that block the functioning of soil biological processes; 4) the functioning of the soil and the carbon cycle; and 5) water as a limiting factor for the productivity of the system. Knowledge of these elements and their main components make it possible to evaluate how each system works and what interventions can help improve it.

Bases for a regenerative production model

A sustainable agriculture model that guarantees **food sovereignty** must be based on **feeding the soil and improving the habitat for the soil food web**. There are five elements of the production system in which it is possible to intervene and which must be considered in each specific situation: 1) the diversity of plants; 2) the return of plant materials to the soil; 3) interventions that block the functioning of soil biological processes; 4) the functioning of the soil and the carbon cycle; and 5) water as a limiting factor for the productivity of the system. Knowledge of these elements and their main components (**Figure 1**), together with an analysis of the indicators of the state of health of the soil, let you evaluate how the system is working and which interventions can help to improve most efficiently.

(1) The diversity of plants. The first question we must ask ourselves is whether it is possible to increase the production of the system and its biological activity (inevitably related) by increasing plant diversity, both in spatial and temporal terms. To do this, it is very important to know the growth characteristics of the main elements of our system (trees, pasture plants, extensive vegetables, intensive vegetables and fruit trees), and, if possible, combine them in space (**polycultures, agroforestry**) or time (**crop rotations**) in order to improve the production of the system and the biological activity of the soil (**Figure 2**).

(2) The return of plant materials to the soil. The return of plant materials to the soil is a characteristic of the production system and the type of management. It is one of the aspects that must be changed when trying to modify the production model. What is sought is a return of plant materials (directly, from excrements or compost) that help protect the soil and the formation of a humus layer, and ultimately, nourish the plant.
It is necessary to know the factors that regulate the **balance between mineralisation and humification** of the supplied materials to prioritise the process that is of most interest

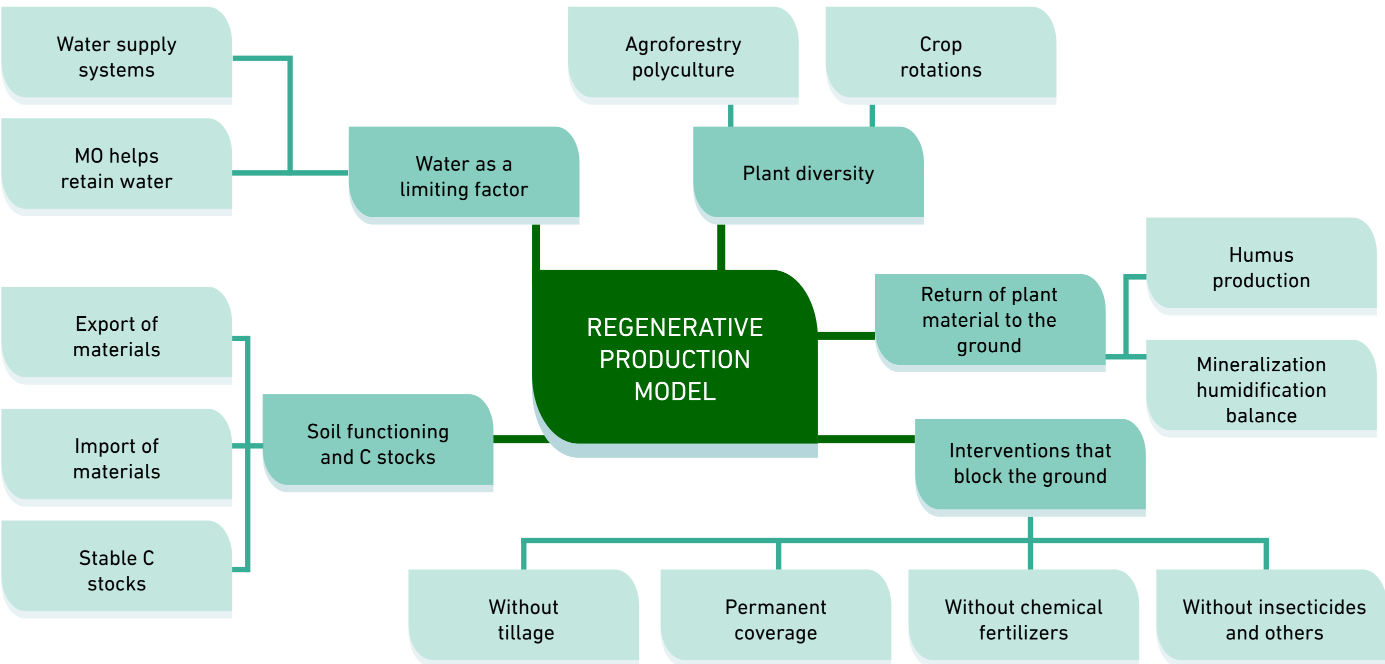


Figure 1. Scheme of the five main elements of the Regenerative Productive Model and the most important components of each one that must be analysed to evaluate how a given system is working.

Figure 2. Image of an organic polyculture field in Planeses, Girona (A) and a field with cereal monoculture (B). Photo: MJ Broncano.

at all times. The objective is that this can be achieved by closing the cycle on the field itself (a clear example would be grazing), without the need to bring external materials or having to make transformations that make us spend time and energy. In some cases, such as intensive vegetable production (orchard), a contribution of transformed external materials (different types of compost) is required. In this case, the investment is acceptable because it is a use that occupies a very small part of the farm. **It is also necessary to provide external materials in situations in which a degraded system** must be restored and the contribution of organic matter is the main element.

(3) Interventions that block the functioning of soil biological processes. Some of the techniques used in conventional agriculture negatively affect the soil food web, to the point of destroying its habitat. Therefore, **the regenerative agriculture model includes** eliminating tillage, minimising bare soil, avoiding soil compaction and the use of chemical fertilisers, insecticides, fungicides and herbicides. For extensive plant production it is necessary to use machinery for sowing and harvesting. The use of heavy machinery can cause compaction of the ground, so it must be done in a way and at a time that the impact is as low as possible. When we are going to work on fields that come from the conventional productive system, it must be taken into account that the impacts of past management can remain on the ground for a more or less long time (which could last more than 5 years), so that it is necessary to act actively to restore the health of the soil.

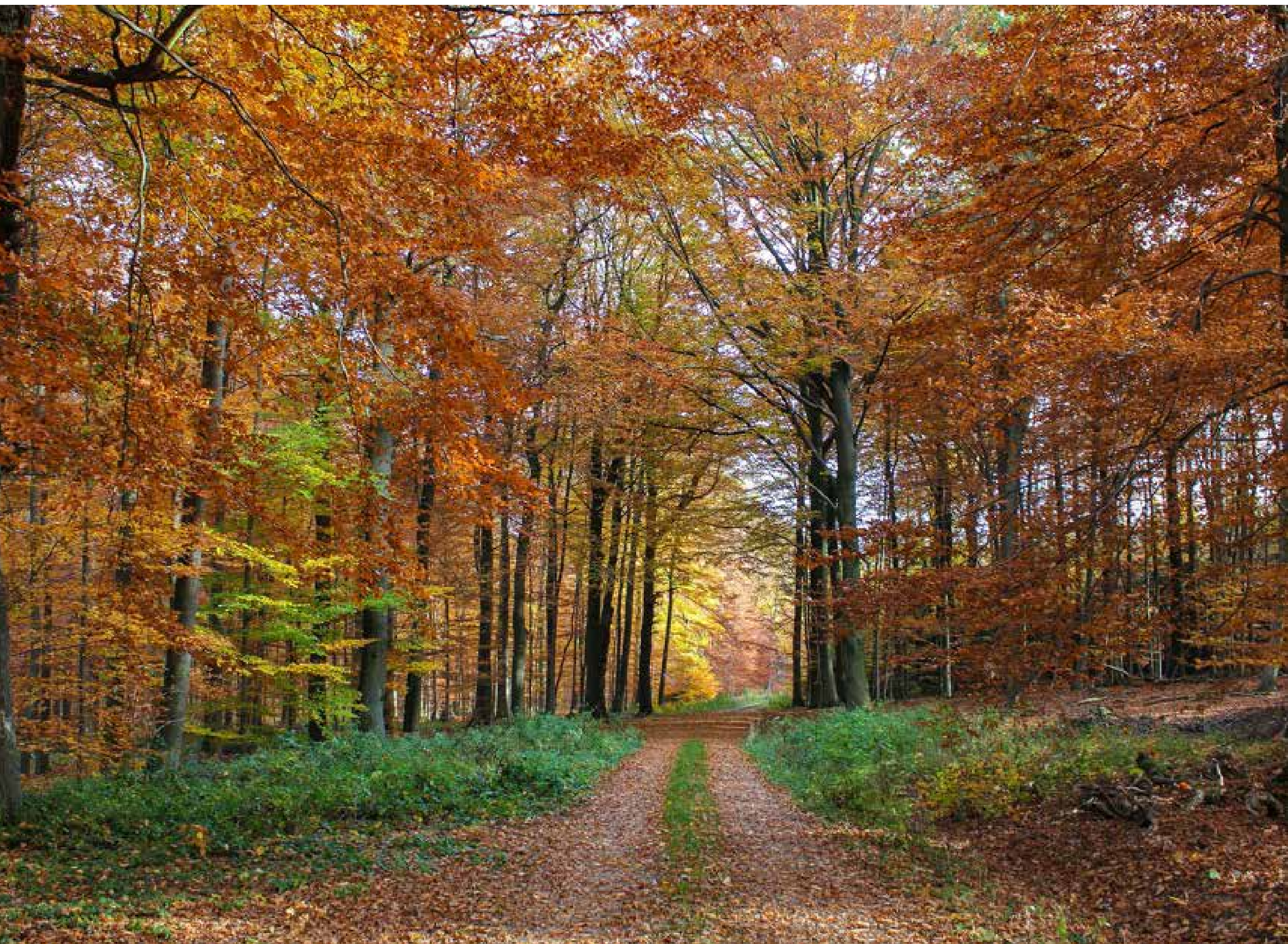
(4) Soil functioning and the carbon cycle. The balance of inputs and outputs of organic materials defines the sustainability of the system. A productive system will always have outputs, but efficient management must ensure that outputs linked to harvesting do not represent a reduction in system stocks (especially soil stocks), and that they are offset by its own productivity. When we go from a management with the conventional production system to a **system based on the natural feeding of the plant,** we are increasing the carbon stock of the soil and eliminating carbon from the atmosphere. Normally, the production of the system itself is used, although on certain occasions it may be necessary to import external carbon into it. When making external carbon inputs, the costs and environmental impact of carbon removal at the source must be assessed.

(5) Water as a limiting factor for the productivity of the system. The increase in the organic matter content of the soil, a result of the regenerative production model, improves soils and helps to maintain a large amount of additional water in the system. Whenever possible, it is good to have systems that improve and increase the water supply. In addition to making an economic analysis of what obtaining this additional water may represent, it **is very important to study the short/medium/long-term availability** of this resource, taking into account climatic conditions (both current and forecasts linked to climate change) of our area.

The regenerative production model: economic costs of changing the model

The production model based on the natural feeding of the plant takes advantage of the resources of the area and the functioning of natural processes. This model **has a much lower operating cost than the conventional model**. But any change **requires an initial investment**. This investment is mainly focused on **introducing organic matter into the soil to feed the food chain and restore the habitat necessary for it to function**. It is a period in which we eliminate external production factors (tillage and agrochemicals), but in which the system still does not have its internal production factors working (because it is building them).

This can cause a temporary reduction in production. This period can be developed either with a low investment but over a longer time, or with a higher investment, making external contributions of organic matter, which will reduce the time necessary for the system to start working efficiently. In any case, this transition requires an investment that can be quantified in money, time and knowledge. These three areas function as communicating vessels and can partly offset each other. Thus, **knowledge of experiences that are already working can save a lot of time and money for a farmer who wants to initiate change**. Therefore, it is very important to disseminate experiences that are already underway, including the Polyfarming system.



Bases of a regenerative production system

Forest management from a regenerative productive perspective

- Objectives of forest management
- Elements of forest maturity to maintain forest biodiversity
- Characteristics of tree species
- Tree growth and crown development
- Forest regeneration
- Forest structure: collective versus individual growth
- Forest products
- Analysis of the forest as a productive system from a regenerative perspective

Objectives of forest management

The forest is the main element of the territory in Mediterranean mountain regions. Forest management is based on improving at least one of the following aspects of the forest: the fuel model, biodiversity, wood quality and forest stability. All these objectives have common characteristics, which are the reduction of tree density and the formation of trees with a larger trunk and crown diameter.

Objectives of forest management

In many Mediterranean mountain areas, the forest is the main element of the territory and the potential source of resources. At the time of application of a cut there are two fundamental questions that the forest manager must answer: 1) how many trees should be cut?; 2) which trees should be cut (or which trees will remain)? The answer to these questions mainly depends on **what the objectives of the intervention are**. These objectives must be specified in the improvement of at least one of the following four aspects of the forest: **the fuel model, biodiversity, wood quality and forest stability.**

(i) **Improvement of the fuel model**. The goal is to **reduce forest vulnerability to fires**. For the analysis of this vulnerability it is necessary to define the type of vegetation or fuel stratum that characterises the structure of a forest plot: a) **crown fuel**, formed by the dominant or co-dominant tree canopies; b) **scale fuel**, which is not part of the crown and includes small trees or shrubs; c) **surface fuel**, which consists of shrubs whose height is less than 1.5 h, grasses and dead remains. The objective is to create structures in which fire spreads through the surface fuel but limits fire spreading to the canopies. This reduces mortality during a fire. This mortality will be even lower for trees with larger diameters. The most important intervention to achieve this objective is the **thinning of the stand**, as well as the **selection of resprouts** within the same individual for resprouting species. This intervention reduces the risk of fire rising to the canopy and favours the formation of larger trees, which are more resistant to fire. Examples of **structures with different degrees of vulnerability to fire** are shown in **Figure 1**.

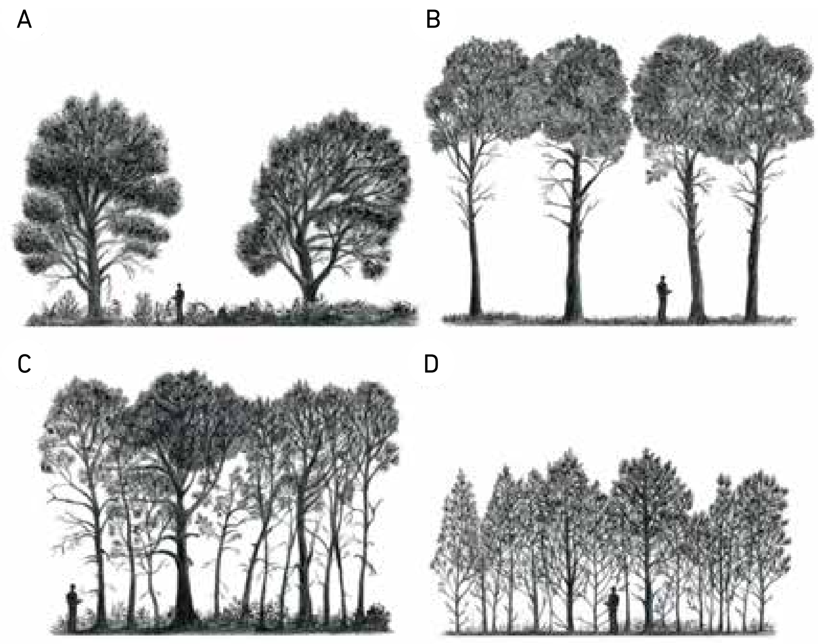


Figure 1. Example of structural types of *Pinus halepensis* forests according to their vulnerability to crown fires: low (A, B) or high (C, D). Credit: Patterns of fuel types and crown fire potential in Pinus halepensis forests in the Western Mediterranean Basin. Alvarez et al. (2012). Author of the illustration: José Luis Ordóñez, CREAF.

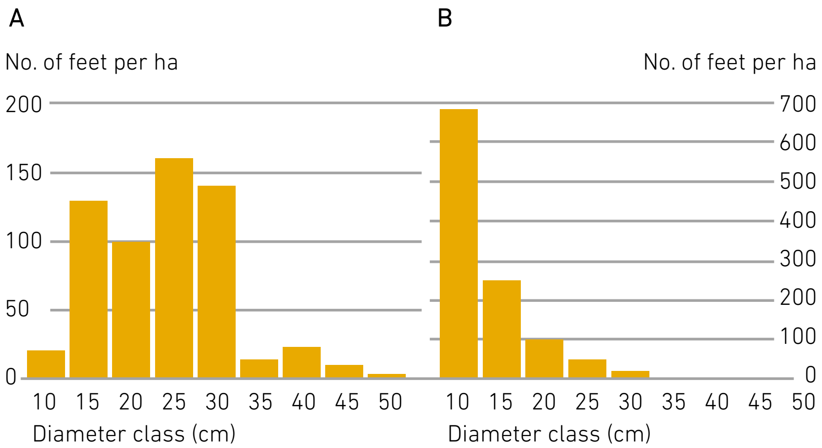


Figure 2. Examples of diameter distributions of two highly contrasted plots: **A**) plot with significant presence of large trees; and **B**) typical plot of Mediterranean forests, with many small trees and very little presence of large trees. For each diameter class the total number of trees per hectare is indicated.

Figure 3. Well-formed pine forest, L'Espà, Berguedà. Photo: Lluís Comas/Carles Batlles.

(ii) Improvement of biodiversity. In the Mediterranean forests there is generally a great lack of large trees, old trees and senescent trees, which are necessary to improve the richness and abundance of fauna associated with their cavities (birds, mammals, etc.). In general, these types of trees, of interest for the conservation of biodiversity, are very scarce in Mediterranean forests and should be prioritised over production trees without representing a risk of loss of quality production. **Figure 2A** present an example of the distribution of diameters of a plot of interest to the fauna: its differential characteristic is the presence of trees whose diameter is greater than 30 cm. **Figure 2B** represents a much more frequent plot, with a large number of young trees and no trees larger than 30 cm.

(iii) Improvement of wood quality (in the long term). This objective tries to achieve large trees with **well-formed trunks** (straight, cylindrical and with few branches), which allow quality wood to be obtained (**Figure 3**). This characteristic of shape **is the opposite of the characteristics sought in the biodiversity conservation** objective that prioritises trees with more irregular shapes and the presence of different types of cavities.

(iv) Improvement of forest stability, resistance to diseases and drought. The presence of well-developed crowns is one of the most important health indicators of a tree. These well-developed crowns are usually obtained by decreasing the density of individuals. In many cases, the response to diseases or disturbances such as drought is related to the density of trees in the forest. Thus, there are many examples that drought resistance increases in cleared holm oak forests with lower resprout densities in relation to the same type of forest without clearing (**Figure 4**).

The common characteristics of these objectives are the **reduction of tree density (or of resprouts in resprouting species**), and the favouring of the formation of trees with a **larger trunk diameter** and a **larger crown diameter** (variables that, on the other hand, are directly related).

Figure 4. Result of three forest management treatments in a holm oak grove during a period of extreme drought in the summer of 2015 in Requesens (La Junquera, Girona). The control forest that was not cut down and therefore had a higher tree density than the one that withstood the drought the worst, with 10% of trees affected or dead. Author: Eduard Pla, based on images from the ICGC.

Elements of forest maturity to maintain forest biodiversity

In the absence of disturbances, the dominant trees in the forest reach a phase of senescence and eventually die. The dead wood that is generated plays a very important role in the carbon cycle and in maintaining forest biodiversity. For this reason, in managed forests a series of maturity elements linked to age should also be very important, such as senescent trees, standing dead trees and dead wood in different degrees of decomposition in the soil, which can produce food or habitat for multiple organisms.

The natural dynamics of forests and the role of dead wood

In the absence of disturbances and without logging, forest conditions are controlled by old, dominant trees. As time passes, some of **these trees reach a phase of senescence and die** naturally, leaving the space free where the new regeneration will develop. This process follows internal dynamics linked to phases of degradation and reconstruction, forming a mosaic where large trees alternate in space and time with gaps with young trees in different stages of development.

When these large trees die, the dead wood is eventually incorporated into the soil after a decomposition process which, depending on the environmental conditions, can be short (as in tropical climates, with abundant water and high temperatures) or very long (as happens in cold climates, where low temperatures delay decomposition). In any case, this **dead wood plays a very important role in the carbon cycle** and in maintaining biodiversity, which includes the organisms that participate in the decomposition of wood and those that depend on it as a habitat or source of food. Although this role is difficult to quantify, there is a consensus that **dead wood is one of the most important elements for maintaining biodiversity** (**Figure 1**). Thus, in an area of high conservation value located in the Pyrenees, it has been found that **a large part of this value is linked to dead wood**: a third of the fungi are wood decomposers, there are 465 species of saprophytic coleopterans that are heritage species in many cases (either endemic species or species protected at European level), and approximately a quarter of mammals and a fifth of nesting birds use cavities in dead trunks (**Figure 2**).

Figure 1. Images of epiphyte typologies: various species of lichens (above), and cormophytes, mosses and saprophytic fungi (below and from left to right). Photos: Lluís Comas/Carles Batlles.

Figure 2. Images of various types of cavities (from left to right): crack, feeding, brood, insects, base and branch on the trunk. Photos: Lluís Comas/Carles Batlles.

The dynamics of natural forests is known mainly from studies of boreal forests in north-central Europe and, especially, North America, while in the Mediterranean region there are few examples of forests that have spent a long time without exploitation or natural disturbances. **In the Mediterranean**, the ancient and intense use of forests, the pressure of agriculture and fires have meant that forests with these elements of maturity are rarely found, since **trees do not normally reach the natural stage of senescence and death**. For this reason, it is absolutely advisable to preserve a series of maturity elements in managed forests that guarantee the different processes and allow forest biodiversity to be maintained.

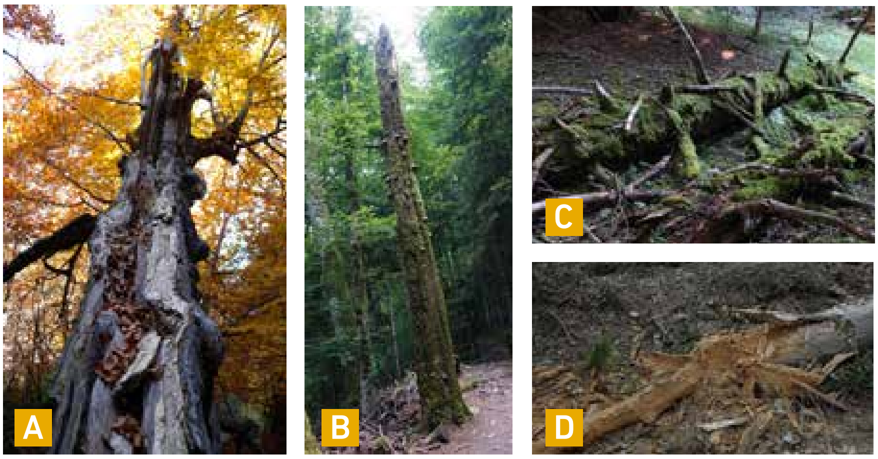


Figure 3. A) Senescent trees, Gresolet (Berguedà). Photo: Lluís Comas/Carles Battles; **B**) Standing dead tree, photo: Javier Retana; **C**) Barely decomposed dead wood, photo: Lluís Comas/Carles Battles; **D**) Very decomposed dead wood, photo: Javier Retana.

Elements of forest maturity

The most characteristic **elements of forest maturity** are linked to the age (and to a lesser extent to the size) of the trees, and represent a source of food or habitat for multiple organisms.

- **Mature, senescent and aged trees**. Large (> 40-50 cm in diameter) and old-aged (from 150 years) trees have a density in the forest that does not exceed 10-15 feet per ha at most (**Figure 3A**). They are characterised by the **asymmetric shape** of the crown and the presence of **holes** that make it less dense, relatively long trunks **free of low branches** (i.e. forest trees as opposed to trees with open spaces), **long and even thick branches** in the upper part, **deeply wrinkled and old bark**, signs of decay due to a rotten core, and structures with **large and prominent roots**, among others. These trees have many cavities that serve as shelter for insects, birds and mammals; they also have associated complexes of fungi and other organisms different from those of younger trees.

- **Large standing dead trees**. When these older trees die, some remain standing for a long time (**Figure 3B**). Thus, in cold climates, standing dead trees can last as many years as they are alive. These standing dead trees can reach **densities of 30 to 70 feet per ha in North American forests**, but in Spanish forests this density is found in very few stands. Again, these trunks have **multiple cavities** where many species of animals live, mainly insects, and are reservoirs for fungi, mosses and lichens.

- **Dead wood in different degrees of decomposition on the ground**. Dead wood in the soil is perhaps the **most characteristic variable in naturally dynamic forests** compared to managed forests. This wood can be found in all stages of decomposition, from wood from trees that have recently died and is still hard and with a low degree of decomposition, to highly decomposed, soft or spongy wood, which practically dissolves when touched (**Figure 3C, D**). In addition to fallen logs and branches and stumps, **the presence of piles of logs and branches from felling is also important**. Many animals and fungi live in this substrate, which is a reserve of legacies (spores, seeds, insect eggs) that will help regeneration after disturbances, and is also an important reservoir of water.

Species that feed on dead wood versus pest species

Maintaining part of the dead wood in managed forests is one of the most important changes that has been obtained from the knowledge of how the natural dynamics of forests work. Traditionally, **management has systematically (and often exhaustively) removed dead wood from the forest**, considering it an unproductive element and a source of pests. However, we now know that forest insect pests (**Figure 4A**) are necessarily linked to living trees. These pest species can be classified into primary and secondary pests according to their ability to colonise vigorous trees or weak trees respectively, but they always feed on living tissues. Once the tree dies, these pest species abandon it and leave their place to **saprophytic insects**, (**Figure 4B**), which feed on the tree from the moment it dies until it is reduced to the state of decomposed organic matter. These insects belong to very large families and have thousands of species, all of them incapable of attacking living tissues. Therefore, **dead trees do not present any problem for the forest**. On the contrary, different studies seem to show that in them we find a significant entourage of parasitoids and predators that exert a certain control over forest pest populations.

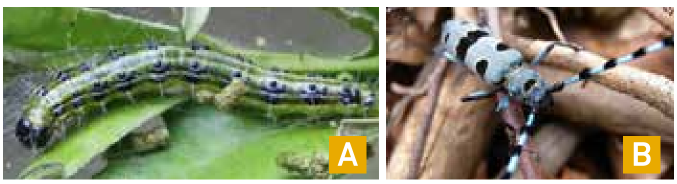


Figure 4. A) Boxwood caterpillar (*Cydalilma perspectalis*), example of a pest. Photo: Emili Bassols, La Garrotxa Volcanic Zone Natural Park. **B**) *Rosalia alpina*, example of saprophytic species. Photo: Lluís Comas/Carles Batlles.

Characteristics of tree species

Trees have different shapes and growth rates depending on the species they belong to. The species determines the growth, the hardness of the wood, the root structure, the longevity, or the type of regeneration of trees. In turn, each species responds differently to environmental conditions and therefore, only lives in certain environments, with certain temperature, humidity, light and soil characteristics. Knowing these characteristics of the species and their response to the environment is essential to be able to properly manage forests.

Species-related characteristics

Different characteristics are specific to each tree species: **longevity, hardness of the wood, depth of the roots or type of reproduction** (**Table 1**). Other variables, mainly structural (such as crown shape or height), also depend on the species, but may be more conditioned by environmental components, whether they are environmental or forest management factors.

We can make a first classification of tree species based on the **type of growth**, fast or slow, that they have. **Fast-growing** trees are trees that live for fewer years, have shallower roots, retain and accumulate less CO_2 in their trunk, and produce softwoods that decompose more quickly. In this group we find **conifers** (pines, firs, spruces, etc.) and **riverside trees** (alders, poplars, birches, willows, etc.). In contrast, **slow-growing** trees develop deeper roots, tend to live longer and provide carbon reservoirs for longer. They produce hard, **heavier and slower-degrading woods**. Representative species of this group are holm oak, beech, chestnut, walnut, etc.

Figure 1. Birch, a heliophile species. Les Planes de Son (Pallars Sobirà). Photo: Lluís Comas/Carles Batlles.

Characteristics linked to environmental factors

Trees have strict requirements in relation to the environmental factors necessary for them to survive: **each species has a maximum and minimum range outside of which it cannot survive.** Climate and soil encompass most factors (water, temperature, nutrient availability, etc.) but factors such as **tolerance to shade or response to disturbances** (related to the type of regeneration of each species) must also be considered.

Thermal conditions determine the distribution limits of forest species. Of the climatic factors, **water** is the most important limiting factor in the growth of trees in the Mediterranean area. Forest species are also distributed in a gradient from greater to less **tolerance to shade**, from heliophile species (generally fast-growing, such as birches,

Figure 2. Beech forest in autumn. Beech is a shade tolerant species. Photo: Pixabay, CC0.

	Species	Type of growth	Hardness of the wood	Longevity	Depth of the root	Type of regeneration	Distribution	Frost resistance	Drought resistance	Tolerance to shade	Lim tolerance	Low soil fertility tolerance
PLANIFOLIOS	HOLM OAK (*Quercus ilex*)	Slow	Hardwood	500-700	Deep roots	Seed and regrowth	From 0 to 1400 m	Low	High	Medium	Indifferent	Medium
	DOWNY OAK (*Quercus humilis*)	Slow	Hardwood	300-500	Deep roots	Seed and regrowth	From 400 to 1500 m	Low	Medium	Medium	High	Medium
	CORK OAK (*Quercus suber*)	Slow	Hardwood	300-500	Deep roots	Seed and regrowth	From 0 to 1000 m	Low	High	Medium	Low	Medium
	CHESTNUT (*Castanea sativa*)	Slow	Hardwood	500-700	Deep roots	Seed and regrowth	From 0 to 1500 m	Low	Low	High	Low	Low
	BEECH (*Fagus sylvatica*)	Slow	Hardwood	300-500	Deep roots	Seed and regrowth	From 1000 to 1700 m	Low	Low	High	Indifferent	Low
	BLACK POPLAR (*Populus nigra*)	Fast	Softwood	<100	Shallower roots	Seed and regrowth	From 0 to 1800 m	High	Low	Low	Indifferent	High
	ALDER TREE (*Alnus glutinosa*)	Fast	Softwood	100-150	Shallower roots	Seed and regrowth	From 0 to 600 m	High	Low	Medium	Indifferent	High
CONIFERS	ALEPPO PINE (*Pinus halepensis*)	Fast	Softwood	100-150	Shallower roots	Seed	From 0 to 1000 m	Low	High	Low	High	High
	SCOTS PINE (*Pinus sylvestris*)	Fast	Softwood	300-500	Shallower roots	Seed	From 500 to 2000 m	High	Low	Low	Indifferent	Medium
	AUSTRIAN PINE (*Pinus nigra*)	Fast	Softwood	150-300	Shallower roots	Seed	From 800 to 1500 m	High	High	High	High	High

Table 1. Characteristics of some of the main tree species that have to do with the species itself or its ability to respond to environmental factors.

pines, poplars, etc.), which tend to be **colonisers or pioneers in open areas** (**Figure 1**) and that depend on high levels of light for their germination and development, to shade-tolerant species that can remain in the understory for decades waiting for a clearing to grow in height and achieve maturity, such as holm oak or beech (**Figure 2**), among others.

Soil is decisive for the growth of trees, as it represents their support while providing the nutrients and water necessary for their survival. The **pH** and presence of certain ions (Ca ++, Na +, CO -, etc.) are factors that determine the presence or not of certain species of trees, distinguishing between **calcic and silicic species** depending on the best soil type for them.

Tree growth and crown development

Trees prioritise growth in height because this determines their position in the competition for light. Once this growth is guaranteed, their diameter increases. The growth of the tree takes place through the crown. The shape of the crown is determined by the shade conditions in which the tree grows (competition). A tree is balanced when its crown occupies at least one third of its height.

Tree growth

The growth of trees takes place both in height and diameter. Each of these growths gives different information about different aspects of the tree.

(a) Height growth

Height growth is very important for the tree because it determines its position in the competition for light and is the quick way for the tree to create new branches and enlarge the size of its crown. For this reason, **a tree, once its breathing needs are satisfied, prioritises height growth**. Being a priority, this growth is independent on the level of shade (or competition) the plant has for a wide range of conditions. **When the level of shade is very high, it finally ends up producing a decrease in height growth** and, in extreme conditions, it leads to the death of the tree. Since the plant invests in height growth first, **it reaches its maximum height at a relatively young age**. This degree of independence of the height growth from the competition means that the height/age relationship is considered a good indicator of the potential of a tree to grow in a given site. In fact, **the maximum height of a species in a site, which depends on the type of soil and its climate** (temperature and water), is what defines the growth potential of that species, which we call site quality.

(b) Diameter growth

Once it has guaranteed height growth, if there is surplus, the tree invests in diameter growth. For this reason, **diameter growth is highly conditioned by the competition conditions the tree experiences**: if competition is high, diameter growth is modest, if competition is low, diameter growth is significant. Thus, diameter is the synthesis of site quality, competition and age, and does not give us any information on age or site quality separately. The diameter of a tree has a much more elongated growth over time than its height.

The crown depends on the tree's growing conditions

The shape of the crown is the external characteristic of the tree that will give us the most information about its vitality, capacity for growth, response to release and maturity of the tree. A healthy tree will always develop a suitable crown. The size of the crown **is related to the competition for light conditions in which the tree grows and is determined by the living branches**. When the lower branches die because of the shade, the size of the crown decreases. The branches are support the leaves, where photosynthesis takes place. **The tree maintains a living branch if its photosynthesis/respiration balance is positive**. If the branch is not well lit and the balance is negative, the branch dries up and eventually falls. When the branch that dries up is large, it costs more to fall and remains dead on the tree for a while.

The size of the crown is related to the health, vigour and diameter growth of the tree (**Figure 1**). **A large, well-lit crown also has better conditions to produce fruits**. We say that a tree is balanced when its crown occupies more than 1/3 of its height, up to half. With a crown smaller than 1/3 of the height, the tree's vigour and growth is negatively affected. If the crown is larger than the middle of the tree, the tree has very thick lower branches and a conical-shaped trunk, which can be an inconvenience for using the wood (**Figure 1**).

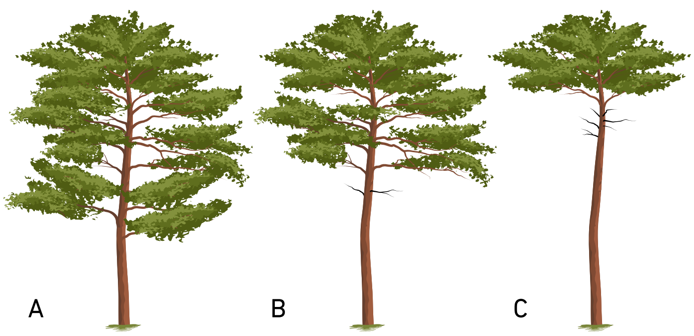


Figure 1. Diagram of the crowns of three trees of the same species growing under different conditions: A) tree that has grown isolated (in the middle of a meadow); B) tree that has grown in a forest with optimal density; C) tree that has grown in a forest with excessive density.

The history of the tree conditions the shape of its crown, i.e. the proportion of living and dead branches. The canopy gives us a lot of information about how the tree has lived, its vitality, what its most likely development will be in the future, and what its response will be if there is a forestry intervention that frees it from the shade. The goal of the forest manager is to achieve the most appropriate crown size at each moment of the tree's life. The state of the canopy at the time of making an intervention will condition the tree's response and therefore, the manager's options.

Effect of age on crown shape

With age there is a decrease in the crown's recovery speed. Thus, if a branch breaks because of the wind, in a young tree the growth of new branches will quickly fill the space. **A mature tree has a slower reaction**, the crown of the tree becomes lighter, with gaps between the branches, globally acquiring an open crown shape, which is the clearest external characteristic to identify a mature tree (**Figure 2**). These changes with age in the shape and density of the crown have **a major effect on the individual's ability to compete,** and the way light and water pass through the crown.

Figure 2. On the left, mature tree (flat and hollow crown) and, on the right, young ones with a more pointed and closed crown and with the branches upwards. Photo: MJ Broncano.

When the tree reaches this stage of maturity, in isolated tree conditions (without competition) it can remain in these conditions for a long time. In fact, in isolated trees there can be decreases in crown height (death of part of the crown) that, over time, the tree can recover. However, **when a mature tree faces competition from a young tree**, with a faster response capacity, it usually does **not have the time necessary to recover** and its space is occupied by the young tree which ends up drowning the mature tree. This is a common situation that we find in many abandoned dehesas (**Figure 3**).

The rapid increase in the crown is mainly linked to the increase in tree height. The answer is limited to whether the crown is already so small that it affects height growth, or if the individual is of an age that means that it has already reached a height close to maximum and cannot grow any more. **When the tree has already completed its height growth** (which occurs at an early stage of its age), we say that the crown, and therefore, the tree, is already formed, and it is very difficult to modify its growing conditions.

Tree response to shade release

When a tree is freed from the shade that was affecting it, it must adapt to the new conditions, and this is done by **increasing the size of the crown**. An important factor in deciding whether to intervene in a forest is knowing how to assess **the capacity and speed of the response by the trees to increase the size of their crowns**. The more balanced the crown is before release, the more vigour the tree has, and the faster the reaction. For the same degree of competition, the answer depends on the shade tolerance characteristics of each species. **Shade-tolerant species**, such as holm oak, can keep canopies alive for longer than shade-intolerant species, such as pines, and therefore maintain the ability to respond to competition release for longer.

Figure 3. Abandoned dehesa, Vall del Bac (Girona). Photo: Lluís Comas/ Carles Batlles.

Forest regeneration

There are two main mechanisms for the regeneration of forest species: reproduction by seedlings and regeneration by resprouts. Seeder species mainly reproduce by seedlings produced from seeds. The success of their reproduction depends on the environment in which they are to germinate and the shade tolerance characteristics of the species. Resprouting species regenerate by sprouts produced from buds located on the trunk, roots or stump. The resprouting characteristics depend on the site quality of the plot and the type of disturbance.

Types of species according to their main regeneration mechanism

The regeneration of forest species **occurs mainly by two mechanisms**: reproduction by seedlings and regeneration by resprouting (**Figure 1**). In the first case, new individuals are generated from propagules produced by existing ones, while in the second case, it is the pre-existing individuals themselves that maintain themselves after logging or a disturbance.

- **Reproduction by seedlings from seeds** is the most widespread reproduction mechanism among plants. It consists of the production of seedlings from seeds that germinate when environmental conditions are favourable. In the Iberian Peninsula, the **main seeder species** are of the coniferous genera *Pinus* or *Abies*, although many resprouting species such as *Quercus* can also produce large numbers of seedlings.

- **Resprouting, i.e. the production of sprouts from buds present in pre-existing organs** such as stumps or roots, is one of the most important mechanisms of plant regeneration against natural and anthropogenic disturbances. Resprouting is considered a mechanism by which a plant returns to a juvenile state after being disturbed. In the Iberian Peninsula the **main resprouting species** are of the genera *Quercus, Fagus, Corylus* and, to a lesser extent, *Populus* and *Betula*.

Figure 1. A) Aleppo pine (*Pinus halepensis*), a seeder species. Photo: iStock, seven75, **B**) Holm oak (*Quercus Ilex*), a resprouting species. Photo: MJ Broncano.

The regeneration of seeder species: the case of pines

Pines are the main group of seeder tree species in the Mediterranean. All of them **reproduce exclusively by seeds**, although there are some species that can produce sprouts, such as *Pinus canariensis*, a rarity among pines. Pines **present a highly variable cone production**, with years of strong production and years of almost zero production, interspersed with years of medium production. Most of the species show similar phenology, with seed dispersal from late winter to spring and even summer.

Figure 2. *Pinus halepensis* young tree in an open area. Photo: MJ Broncano.

The seedlings of all **pines grow rapidly in open areas**, where the saplings outnumber the herbaceous vegetation and reach significant growth during the first years (**Figure 2**). In forest conditions the pattern is different. The seedlings of *P. nigra* are, among those of the peninsular pines, the ones that **best withstand certain shady conditions** (in fact, it could be said that they are the only ones). On the other hand, the seedlings of the rest of the pines need light to grow, so their regeneration is very low in the understory of a forest, even of the species itself.

Some species, such as *P. halepensis* or *P. pinaster*, only disperse part of their seeds stored in the crown and maintain a **bank of seeds inside cones called serotines** that remain closed for a long time. The seeds are released from these serotine cones by the heat and dryness induced by a severe forest fire or an extreme drought. This allows massive seed germination to occur in the autumn after the fire, creating a wave of pine regeneration during the first year after the fire (**Figure 3**). The remaining pines do not have serotine cones, so in summer, which is the period when most forest fires occur, all the cones in the crown are empty and the soil seed bank is also exhausted. Regeneration of these species after large fires is entirely dependent on the **release of seeds** from unburned margins or from surviving tree islands, since seeds and seedlings do not survive the fire. For this reason, in a large part of the burned forests of these species, the presence of pine seedlings is very scarce or null.

Figure 3. Regeneration of *Pinus halepensis*, in the first few years after a fire in a forest of the same species. Photo: Javier Retana.

Figure 4. Resprouting of an oak stool affected by a fire. Photo: Pilar Cortés.

The regeneration of resprouter species: the case of holm oak

Holm oaks and downy oaks constitute the main group of resprouting tree species in the Mediterranean. **Holm oak (*Quercus ilex*) is a very clear case of a resprouting species**, since it sprouts vigorously after disturbances (**Figure 4**). The shoots are produced by the activation of dormant buds located at the level of the stump, the root crown or, to a lesser extent, the roots. The resprouting of holm oak after disturbances (both thinning, drought, herbivory or fire) is, in all cases, **higher than 85%.**

The **quality conditions** of the site (growth potential of a given stand), combined with the intensity of management of the plot, will determine the current state of the holm oak forest and its response to felling. Intense thinning generates structures with many sprouts for both high and low site qualities. As the thinning is of a lower intensity, the closing of the crowns generates a natural selection of sprouts, decreasing their density. This effect is more significant in high site qualities where greater growth allows a greater closure of the canopy. For low intensity thinning (irregular management) this selection effect means that in high site qualities the resulting structure has individuals with few or only one stem per stool. On the other hand, for low site qualities, where lower growth does not allow complete closure of the crowns (or this occurs very slowly), the effect of natural selection of resprouts is less, and we will find structures with many stems per stool.

Under the current management conditions and disturbance regime, **the regeneration of holm oak stands seems to be ensured through the resprouting of individuals**. It might be accepted that this type of regeneration is enough, but the oaks can also **reproduce sexually by acorns**. Normally, the annual production of acorns is rather low, although there are years with very strong production peaks. Acorns are large and heavy, so they have enough reserves to develop new seedlings, although they also have a high risk of being predated. All this makes the presence of holm oak seedlings and saplings quite high in holm oak stands. These young individuals cannot compete with the adult trees that sprout after a disturbance, but they can remain in the understory of the forest for many years as they have a high tolerance to shade. These individuals can live in canopies for a longer time, and therefore, also maintain the ability to respond to the release of competition when an opening occurs in the holm oak canopy.

Forest structure: collective versus individual growth

There are two types of highly contrasted forest structures: even-aged forest and uneven-aged forest. The even-aged forest is a homogeneous forest where the trees are of the same age and have similar competition conditions. The uneven-aged forest is one in which the trees are of different sizes and different competition conditions. Each of these forest structures is characterised by a type of tree growth: collective growth in the case of the even-aged forest, and individualised growth in the case of the uneven-aged forest.

Forest structure: even-aged and uneven-aged forests

Differentiation is the process by which a tree occupies its neighbour's space to be able to develop its crown. In a forest stand, **if differentiation does not take place, the trees grow without being able to increase its crown**, which becomes unbalanced. The differentiation process can occur naturally or as a result of cutting. The spatial relationship between trees of different ages and sizes defines the structure of the forest. This structure will determine the effect of the natural differentiation of the trees. We can distinguish two types of structures that create very different canopy development conditions: even-aged forest and uneven-aged forest (**Figure 1**).

- **The even-aged forest** is the structure resulting from a disturbance that has removed all the trees. It can be the result of a heavy fire or a clearcutting. It also occurs in reforestations, in which all the trees are of the same age and the preparation of the land gives them similar competition conditions. In these situations, young individuals (seeder species) or sprouts (resprouter species) grow without competition from adult trees. The result is a homogeneous forest, both in terms of structure and species composition.

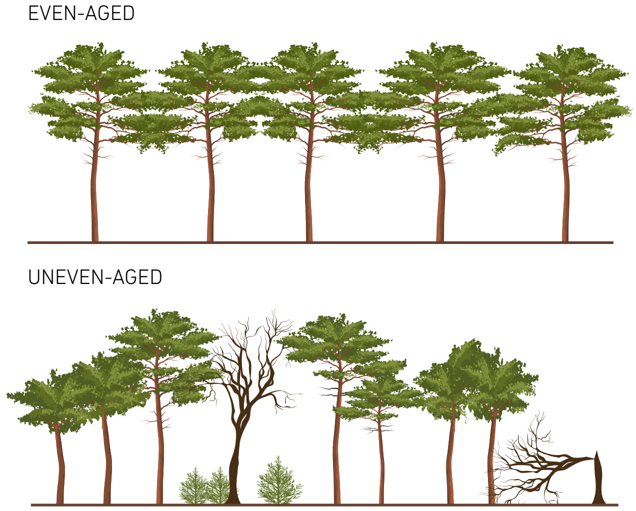


Figure 1. Even-aged and uneven-aged forest structure.

- **The uneven-aged forest** is one in which the trees are of different heights and the growth of each tree depends not only on its height, but also on that of the trees that surround it. Therefore, the rate at which trees move from one size class to the next is different for each class, and it also varies over time, because as trees grows larger, competition decreases.

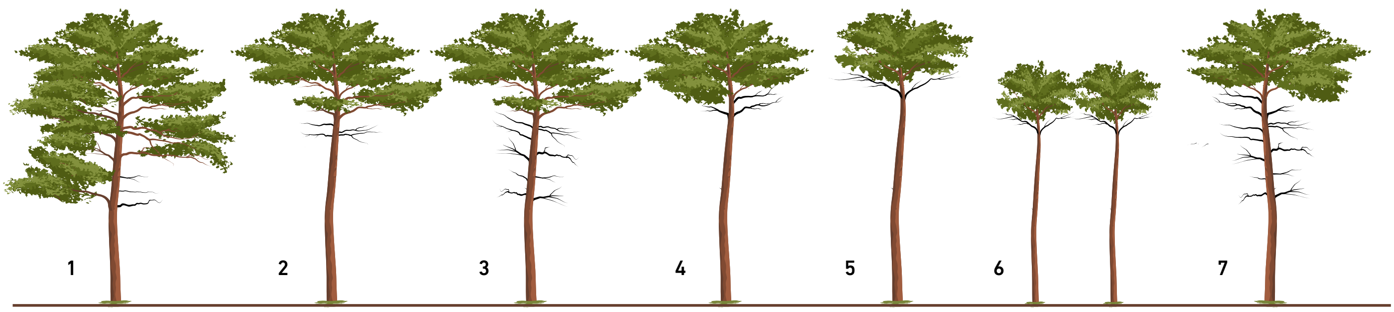


Figure 2. Different situations in an even-aged forest: (**1**) **forest boundary tree** (the crown develops on the side that has space), (**2**) **tree with a balanced crown and a well-formed trunk** resulting from the control of the density at throughout forest growth (adequate density throughout growth), (**3**) **tree with a balanced crown and trunk with large branches** (correct current density but initial too low), (**4**) **tree with a balanced crown to one side** but greater competition for another that makes the crown small, (**5**) **tree with a small crown and well-formed trunk** (adequate initial density but without a decrease, leading to a high final density that causes a decrease in diameter growth), (**6**) **trees with a very small crown that causes a decrease in height growth** (**7**) **tree with a small crown and very large dead branches** that indicate that the growth of the tree occurred under isolated growth conditions and that the forest subsequently closed (this is a typical situation resulting from the abandonment of wooded pastures).

Each of these forest structures is characterised, as indicated above, by a particular type of tree growth: 1) **collective growth in the case of the even-aged forest**, and 2) **individual growth in the case of the uneven-aged forest**.

Collective growth

Collective growth is characterised by the fact that the **conditions are created by trees of similar height** (and usually of similar ages), so that the competition is the same for all individuals growing together. The equality of conditions between all trees makes the natural differentiation between individuals insufficient for a tree to be able to surpass its neighbour and occupy a space that allows it to develop a balanced crown. So, over time, **competition increases** and the crowns become increasingly unbalanced.

This type of growth ends up generating trees with small crowns, cylindrical trunks and, usually, a reduced individual physical stability (depending on the size of the crown). Under these conditions, the stability of a tree is determined by the collective support effect between the trees that touch it (collective stability). If this collective effect is lost (for example, by thinning that removes part of the trees), the trees that remain have low individual stability and run the risk of being knocked over by the wind until they regain **a balanced crown** (**stability individual**) or **the crowns are closed with their neighbours (collective stability).**

This structure generates environmental conditions inside the forest (determined by light conditions) that are homogeneous throughout the stand, but that vary significantly over time (from the moment of regeneration to the maturity of the forest). Within this type of growth, we can find **varied situations according to the space** that the trees have to develop the crown, the degree of natural differentiation that occurs in the mass or differentiation by felling. **Figure 2** shows different situations and how to identify them.

Individual growth

In this case, the growing conditions are created by a mixture of trees with different age and height. The heterogeneity of the environmental conditions inside the forest (mainly light) and the age of the trees makes the differentiation processes occur naturally. Small trees thrive in semi-shady conditions with **high initial competition**. As the tree grows, it has increasingly favourable light conditions, i.e. **competition decreases** with growth which allows the development of balanced crowns.

The forest is controlled by large trees, but their crowns do not touch. How tight they are (density of the mass) depends on the climate (the availability of water) and the **tolerance of the species**, variables that often coincide. In these growing conditions, in which adult trees do not touch the crowns, physical stability depends only on the individual and is given by the development of a balanced crown. **Indoor forest** (**low light**) **environmental conditions** vary over a short distance, creating different tree growth situations. However, on a larger scale there is a mosaic of light conditions that remains more or less constant over time. **Figure 3** shows different situations found in individual growth conditions and how to identify them.

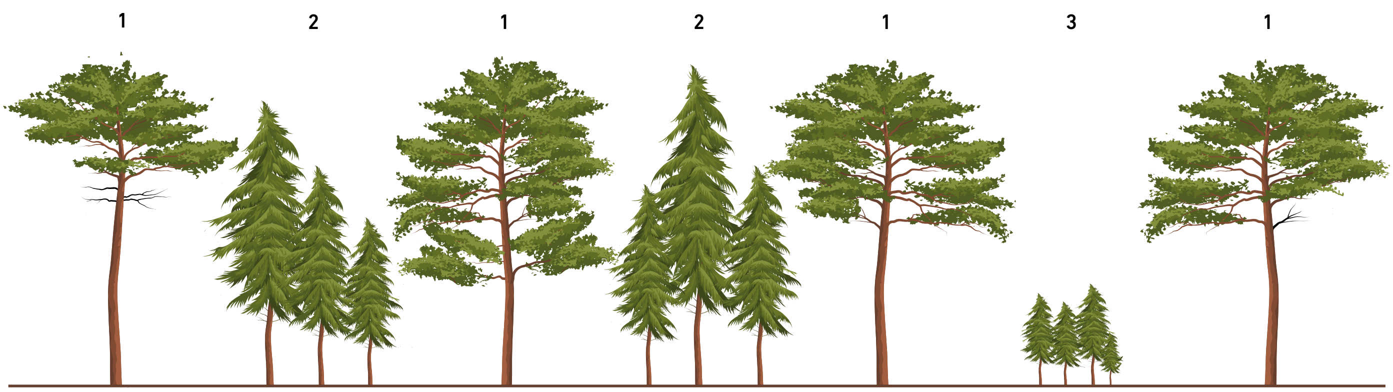


Figure 3. Different situations in an uneven-aged forest: (**1**) **adult trees that dominate the canopy** (there are four): large crown >1/3 with large branches, well-formed main trunk; (**2**) **intermediate trees**: small branches, large competition, the conditions of environmental heterogeneity (light) and different ages make one of the trees ends up dominating the others in its environment; (**3**) **young trees**: conditions of major competition, regeneration that appears when a large tree is cut or dies.

Forest products

The Mediterranean forest produces quality sawn wood, firewood, beams and poles as the main products of forest management. But it can also become an important source of resources for agricultural and livestock exploitation, thus improving the economic performance of other activities. The use of forest products, such as leaves for livestock feed, BRF, biochar, crops on wooden beds or biofertilisers, allows improved profitability of the entire use of farms.

Biomass of the different tree fractions depending on the species and size of the tree

Four fractions of the aerial biomass of a tree can be distinguished, from which different products of forest use are obtained: **trunk, branches >7 cm, branches <7 cm and leaves**, as we will see in the next section. The proportion between components varies greatly between forest species. In **Figure 1** we see the biomass values for four of the species that can be used in the area where Polyfarming is carried out: holm oak, downy oak, Aleppo pine and poplar. Aleppo pine and holm oak dedicate proportionally less biomass to the trunk and more to the branches, especially those smaller than 7 cm, than poplar and, especially, downy oak. From the information of the **Ecological and Forest Inventory of Catalonia**, we have obtained equations for the weight of the trunk, branches >7 cm, branches <7 cm and leaves depending on the size of the tree for the four previous species. With these equations we have determined how the different fractions vary for the four species depending on the size of the tree (**Figure 2**). There are obvious **differences between sizes**, but also important differences **between species in the different fractions**. The trunk values are slightly higher for holm oak but vary similarly between species. Holm oak also has higher values of branches >7 cm for the lower diameters, but later it is reduced and the poplar increases the most. In the case of branches <7 cm and leaves, the values are higher for holm oak and, to a lesser extent, for Aleppo pine than for poplar and downy oak.

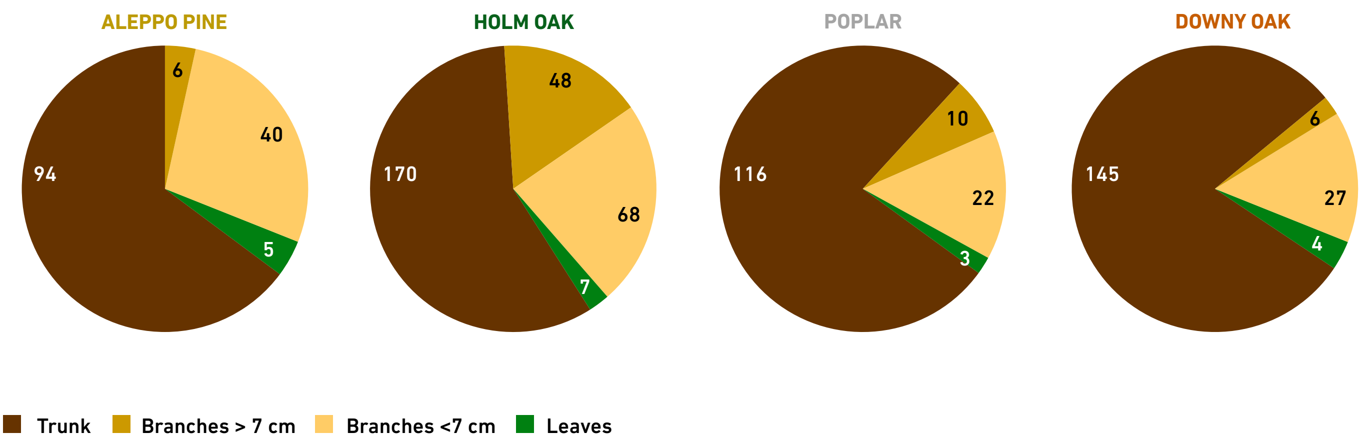


Figure 1. Distribution of aerial biomass in the different components of the tree (trunk, branches> 7 cm, branches <7 cm and leaves) for a standard tree with a normal diameter of 20 cm of four Mediterranean species: Aleppo pine, poplar, holm oak and downy oak. The numbers in each compartment indicate the absolute weight values (in kg of dry matter per tree).

Products generated from the different fractions of the tree

There are many main products that the Mediterranean forest generates with forest thinning: **depending on the species, quality sawn wood, firewood, beams or poles are produced**. These products come mainly from the thickest trunks or branches. But the remaining fractions of the tree can also become an important source of resources for agricultural and livestock use. Some of these resources, those developed in the Polyfarming system, are shown in **Figure 3** and are described below.

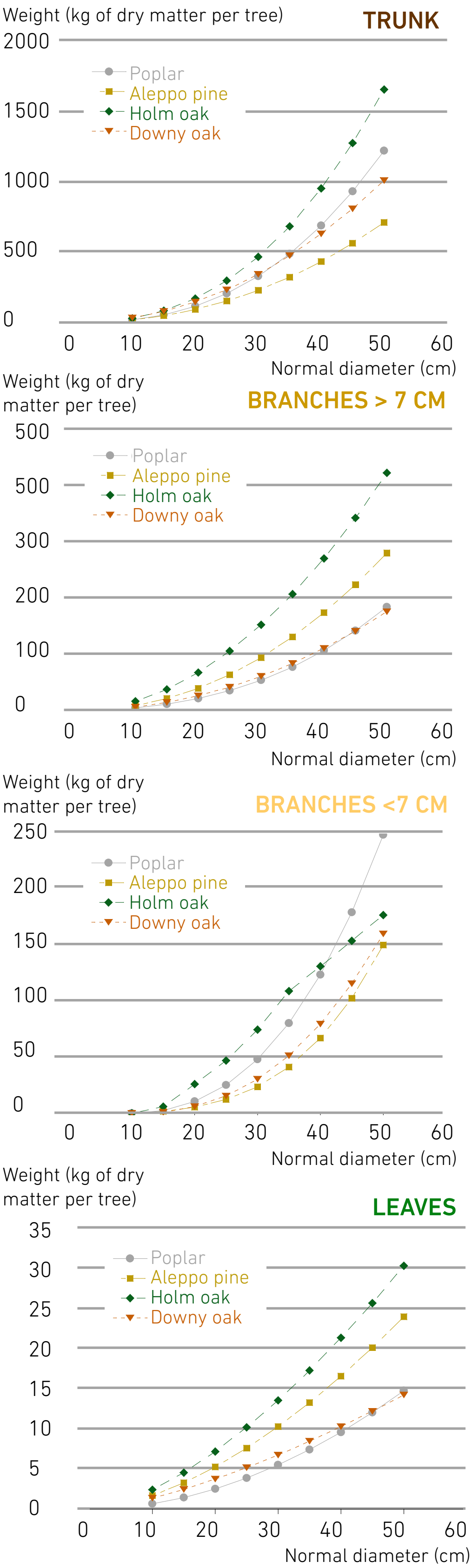


Figure 2. Weight (kg of dry matter per tree) of the different fractions of aerial biomass: trunk; branches > 7 cm; branches <7 cm, and leaves, **depending on the size of the tree** (normal diameter, in cm) for the **four species considered: poplar, Aleppo pine, holm oak and downy oak**.

- **Logs**. They are the main products of forest exploitation and, in many cases, the only ones. Depending on the species and quality of the trees, they are obtained from the **trunks, firewood, wood, beams and sticks**.

- **Branches larger than 7 cm**. Larger branches can also be used to produce firewood. But the logs coming from felling and that are not suitable for other uses can be used to bury them under the soil of the orchard and the fruit trees, so-called **crops on wooden beds**. For this technique, it is preferable to use logs with dimensions greater than 20 cm that allow larger volumes of buried wood to be obtained.

- **Branches smaller than 7 cm**. Branches smaller than 7 cm contain soluble or barely polymerised lignin, which is the basis for the formation of a highly reactive humus. These branches are the base material to produce two products that improve agricultural soils: (i) **BRF**, which is obtained by crushing these freshly cut branches; and (ii) **biochar**, which is produced from the pyrolysis of dry branches. In the first case, a stable humus is obtained that improves the soil's structure and water retention capacity. In the second case, charcoal is produced that improves the physical properties of the soil.

- **Leaves**. The green leaves of trees that have just been cut can be a perfect complement to the **livestock feed**, especially in winter when felling is done. A tree species that is perfectly adapted to this use is the **holm oak**, as well as other hardwoods that **do not lose their leaves in winter**. In contrast, oaks and other deciduous species cannot be used for livestock feed, because they do not have green leaves in winter. In the case of pines, it is not possible to combine cutting in winter with consumption by animals, because they do not eat the needles.

- **Forest floor**. The humus of the forest floor is the basis for obtaining microorganisms. These microorganisms allow the production of **biofertilisers**, which serve to nourish and strengthen orchard plants or fruit trees without blocking the biological processes that occur in healthy soil.

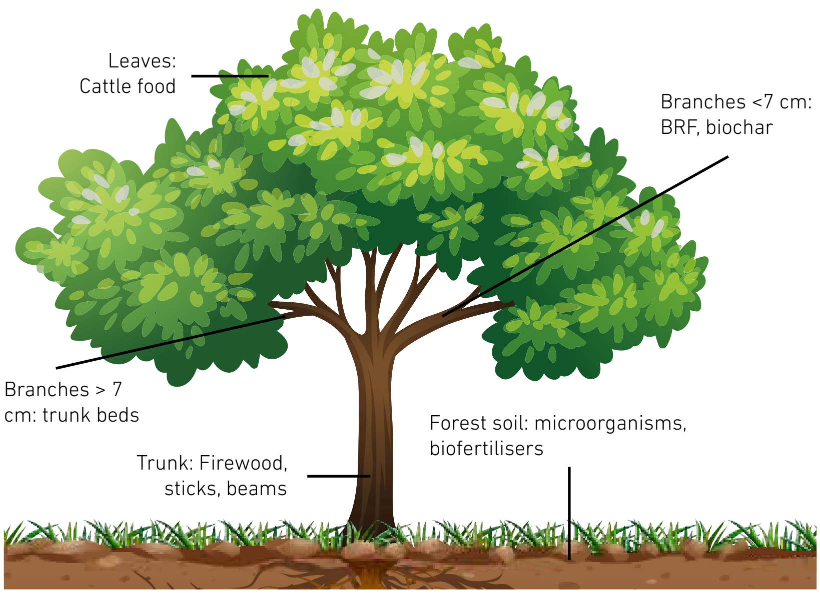


Figure 3. Scheme of the different products obtained from the different fractions of the aerial part of the trees after a forest harvest.

Analysis of the forest as a productive system from a regenerative perspective

The forest is an important productive system, due to the materials it produces and because it can create very important carbon stocks. Unlike agricultural systems, plant nutrition in the forest is the result of natural processes. However, most of our forests are highly transformed and the biological activity of the soil and, with it, productivity is reduced.

Application of the principles of the regenerative model to a forest

The regenerative production model encompasses five basic principles that can be applied to a forest system.

1) Plant diversity.

The greater the biodiversity, the better the forest functioning. This is usually linked to greater environmental heterogeneity, a greater mix of species and elements of forest maturity (**Figure 1**). However, the diversity of many of our forests is greatly reduced because **management has favoured monospecific forests** and has eliminated elements of maturity from the forest (senescent trees and dead wood). However, this management effect is not inevitable, and it is possible to manage productive forests favouring greater diversity and the recovery and maintenance of the maturity elements.

A basic factor to maintain these diversity characteristics, as well as to guarantee good forest growth conditions, are the tree's growth conditions, expressed in the **shape of its crown**, and the growth conditions of the forest, expressed in **its structure** or how trees of different ages and sizes are distributed through the stand. These two fundamental characteristics are inevitably related, and knowledge of their operation will allow us to guide the dynamics of the forest to achieve the best stability and production conditions, in a sustainable way. In very intense harvests, where few or no trees are left (i.e., clearcutting), **thinning can cause temporary situations of loss of micro-climatic conditions and a lack of production**. For a time, the forest is no longer a forest, and we must understand how it works in this state and which elements (shrub stratum, herbaceous stratum, thinning remains, soil humus) guarantee the maintenance of the biological activity of the soil.

2) The return of plant materials to the soil.

Leaves constitute the main form of return in the forest. The accumulation of leaves occurs following micro-topography, which leads to significant spatial variability (**Figure 2**). It is a material with a certain degree of lignification and a low nitrogen content. **Decomposition occurs on the surface,** in the humidity and temperature conditions of the interior microclimate of the forest. The process is carried out mainly by fungi, which decompose leaves forming a stable forest humus. For this process to continue, it is necessary to maintain the supply of leaves and the microclimatic conditions of the interior of the forest. This is guaranteed by a continuous presence of trees. **The objective of forest management in a regenerative context is that forest conditions are continuously maintained**. The growth, return and incorporation of organic materials into the soil should not be interrupted at any time. There is also a return in the form of branches, especially linked to forest harvest. These branches have a much slower decomposition that depends on the degree of crushing they experience. Large-sized wood is the material used after thinning and is not usually part of the return.

Figure 1. Mixed forest in autumn. Photo: iStock, Danier.

Forest exploitation produces a change in the microclimatic conditions and in the edaphic conditions (due to the removal of soil by dragging trunks). This encourages mineralisation of forest humus, affects biological processes and can represent a significant loss of soil carbon stocks.

Figure 2. Leaves on the forest floor. Photo: MJ Broncano.

Figure 3. Heavy machinery for log extraction. Photo: Marc Gràcia.

3) Interventions that block the functioning of soil biological processes.

When the harvesting is very intense, its effects on the forest humus can be important **and leave the soil uncovered**, leading to a degradation of the biological activity of the soil. The use of heavy machinery (**Figure 3**) necessary to extract large logs can also **cause compaction and destruction of the topsoil** if works are carried out in conditions of high humidity. In the exploitation of the forest from **a regenerative point of view**, the interventions are scattered and occasional and do not generate a significant impact. This type of management always keeps the ground covered and does not cause compaction phenomena on the forest floor.

4) The functioning of soil and the carbon cycle.

The forest is the terrestrial system that is capable of maintaining a larger carbon stock in the aerial part (although it should not make us forget the importance of the stocks in the soil). This aerial stock follows some variations in the shape of a sawtooth, linked to the use of the forest, with an average stock over time. This average value is the one that determines the greater or lesser effect of a forest as a carbon sequester. A determining element of this average stock is the presence of large trees.

The use of the forest affects the carbon cycle of the system in a more or less significant way through three different processes: **decreasing the carbon stocks of the aerial part** (extraction of logs, **Figure 4**), **decreasing the carbon stocks of the soil** (increased mineralisation processes), **and temporarily eliminating a more or less important part** (or even all) of the return of leaves that feeds the soil. These processes have a temporary impact, but if they are prolonged over time they can generate a loss of system production. A forest with a good productive capacity can compensate for the extractions (wood) **and losses** (soil) **of carbon** caused by harvesting. It is important to bear in mind in forest management the elements that can affect this productive capacity: diversity, continuous production, microenvironmental conditions inside the forest and factors that block the soil trophic network. Due to the time scale of forest dynamics, these elements of forest management can go unnoticed.

5) Water as a limiting factor for the productivity of the system.

The main elements for the **best use of water** in the forest are maintaining forest humus and the presence of dead wood on the forest floor. **The regenerative forest management system produces and maintains an important forest humus** and creates a structure dominated by large trees, but which maintains all ages. This allows a more efficient use of water and a greater capacity to adapt to environmental changes (diversity of conditions, ages and species).

Structure also has an important effect on the way trees make use of available water. In young forests with very high densities, the forest cover can be so closed that when it rains, the canopy retains a very important amount of water that does not reach the ground. The decrease in the density of trees and the presence of mature and senescent trees, with lighter crowns, **allows a better arrival of water to the ground**. At the same time, reducing the density of trees helps decrease competition among them for water, which is the limiting factor. In the current climate change situation, this modification of forest structure conditions (reduction of the density of stems) is the fastest way to help the forest to adapt to drier climate conditions than it had when it began to grow.

Figure 4. Truck with logs leaving the forest. Photo: Pxfuel, CC0.

Bases of a regenerative production system

Management of the meadow and the animals that graze on it from a regenerative productive perspective

- Functioning of the pasture
- Types of pasture species and combinations thereof
- Needs and behaviour of the animals in the pasture
- Types of domestic farm animals
- Main breeds of domestic farm animals
- The role of dung beetles in pastures with livestock
- Analysis of a pasture as a productive system from a regenerative perspective

Functioning of the pasture

The optimal resting point of the pasture is the optimal time for grazing because it combines the needs of plants and the needs of livestock. At this point the plant has already passed the maximum growth phase, has recovered the reserves of roots, has the most efficient water consumption, and its nutritional value is balanced. If the cattle graze before this point there is a degradation of the pasture, and if it does so after there is a loss of production.

Functioning of the plants of the pasture

Knowing the functioning of the ecophysiology of the resprouting of the plants of the pasture is essential to guarantee good grazing and the associated environmental and economic benefits. Resprouting **functioning can be synthesised in the growth curves after grazing the aerial part and the underground part** (**Figure 1**). Three types of changes occur over time:

(a) Growth pattern (quantitative changes). The grass plant (**1**), after being grazed (**2**), begins the regrowth of the aerial part using the accumulated reserves in the roots. The growth of the aerial part is maintained at the expense of the roots (**3**), consuming the accumulated reserves. This is maintained until the photosynthetic capacity of the new leaves is enough to generate a surplus that can be stored again as a reserve in the roots (**4**). From this moment there is a very **rapid growth of the aerial part and a recovery of the accumulated reserves** in the roots. Growth during this period can be more than 10 times higher than growth during the first days of resprouting. Just the plant reaches maturity (**5**), the reserves of the roots have already recovered, and the growth of the aerial part decreases rapidly until it stops (**6**). This coincides with the appearance of flower buds and the reproduction of the plants.

(b) Variations in the plant's nutritional value (qualitative changes). The pasture at the start of resprouting (**2-3**) is poor in fibre and rich in soluble nitrogenous compounds, which can cause diarrhoea in cows. **Before reaching its maturity point (5), the composition of the pasture is more balanced**, with a better proportion of fibre and with nitrogen in the form of amino acids, more suitable for animal nutrition. From this moment on, the protein content decreases and the plant begins to lignify, producing **a loss of the nutritional value of the plant**. This loss is more pronounced in C4 plants than in C3 plants. From a nutritional point of view, while the plant is in a growth phase (before entering maturity), **there are important differences in nutritional value within the same plant. The upper third of the plant**, where growth occurs, is the one with the lowest cell wall content and a high protein content (which is around 14-18% regardless of the species). Therefore, this upper third of the plant has a higher nutritional value than the rest.

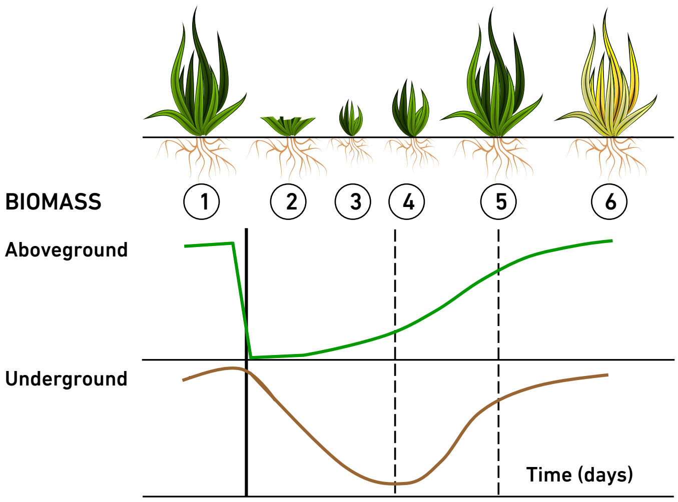


Figure 1. Changes in the organic matter of the aboveground and underground parts of a pasture plant after grazing.

(c) Variations in water consumption. From the start of the maturity of the plant (**5**) growth reduces rapidly until reaching zero. However, the water consumption by the plant is maintained, so that the **water consumption per unit of dry matter produced increases greatly**. If the plant is regrazed (or harvested) before this time, the water consumption per unit of production will be much lower. This explains why pastures grazed at the optimum point can lengthen the growing period when the dry season arrives.

The optimal resting point of the pasture

The optimal resting point is the **optimal time for pasture grazing** combining the needs of the plants and the needs of the livestock (**Figure 2**). From the above information, it is deduced that the optimum resting point occurs before the plant enters maturity (**5**). At this time **a series of important aspects are achieved**: (**i**) the plant has already passed the maximum growth phase; (**ii**) the plant has recovered the reserves of the roots; (**iii**) the consumption of water per kg of organic matter produced is the most efficient; and (**iv**) the nutritional value of the plant is the most balanced. If it cannot be grazed at that time, there are different negative effects:

- **Grazing before the optimal resting point**. If the animals graze before the optimum resting point, production is being lost because the entire exponential growth phase

Figure 2. Pasture at the optimum resting point, with grasses about to glean. Photo: Marc Gràcia.

Figure 3. Pasture after the optimal resting point, where many grasses are already spiked. Photo: Marc Gràcia.

(between 4 and 5) is not used, and the pasture does not offer balanced nutritional characteristics. But what is more important, the plants have not been able to recover the reserves of the roots, so **their resprouting capacity is reduced**. If this situation is repeated continuously, the plant loses the ability to resprout, causing degradation and even loss of the pasture. In summary, grazing before the optimal resting point represents a loss of production and degradation of the pasture, and if it is repeated over time it can be difficult to recover.

- **Grazing after the optimal resting point**. If the animals graze after the optimal resting point, a quantitative loss of production occurs, since the plant remains in the pasture with a very small production. There is also a qualitative loss because there is a **decrease in the plant's nutritional value**. In addition, the consumption of water per unit of dry matter generated is higher, which also represents reduced production in the dry season. In summary, grazing after the optimal resting point **represents a loss of production for the farmer**.

Criteria for determining the optimum point of a pasture

Determining the optimum resting point is critical in pasture management since this is the precise moment when the animals must enter the pasture. The time required to reach the **optimal resting point** can be from **18 to 120 days**, depending on the climate, the species, the season, and the moment's climatic conditions. Depending on the type of plant, this optimal point will last a few days or longer in time. It is important to have **criteria that allow us to identify this optimal point**.

• **Grass height.** The height of the pasture, considering the climate, the species and the season, is used as a criterion. Thus, for example, in humid temperate climates the references are 25-30 cm high for the optimum point. Although each farmer may have references for his/her area, this criterion can lead us to confusion because**,** depending on the specific climatic conditions of each year, **the plant can modify its phenological cycle** by varying the height at which the optimum point is reached. Thus, in dry years the plant advances maturation and seed production and the optimum point is reached with lower heights.

• **Basal leaves withered or in senescence**. This is a general indication, valid for any species. When the first basal leaves wilt or dry out, it is time to put the cattle on the pasture.

• **For grasses**, the optimal point coincides with the appearance of flower primordia at the base of the stem. In practice, this is determined when the first individuals of the pasture begin to glean.

• **For legumes**, the pasture is at its optimum resting point when **30-50% of the plants are in bloom**. We have to be careful because in certain areas the plants can flower permanently and this criterion does not work.

In pastures with several species, which is the general and desirable situation, **each species has a specific vegetative cycle** that seldom coincides with the cycle of the other species present in the pasture. Thus, there is no one ideal optimum point for all species simultaneously. In order to decide the optimal resting time in mixed pastures, there are two alternatives:

• **In a well-established pasture, an average resting point is calculated**, as close as possible to most species, and preventing important species from being below their optimum point.

• We can also **prioritise a certain species**, either because we want to increase its density or because it shows an obvious level of degradation. In this case, all the pasture is managed (optimal resting time) based on this species that is to be increased or protected, without considering the situation of the others.

Types of pasture species and combinations thereof

Pastures are plant resources that serve as food for livestock. Herbaceous grasses can arise spontaneously or can be sown. Most grass species are not very tall and the roots are not usually very deep, generating a diverse and dense herbaceous carpet. These species are highly adapted to grazing or mowing. They fundamentally belong to two large families: grasses and legumes. In the meadows, mixtures of two or more forage species, mainly grasses and legumes, offer more advantages over pure sowings.

Figure 1. Close-up of dactyl grass (*Dactylis glomerata*). Photo: MJ.Broncano

Figure 2. Close-up of the legume alfalfa (*Medicago sativa*). Photo: MJ.Broncano

Pasture species

A pasture, according to the Spanish Pasture Society (SEP), "**is any plant resource that serves as food for livestock,** either directly (in grazing) or as fodder". Herbaceous pastures are made up of grasses, legumes and other herbaceous species that can arise spontaneously or can be sown. These pastures can include other shrub and/or tree species, which can also feed livestock, provided that grasses and other herbaceous forages remain predominant, they are **shrub pastures and tree pastures**, respectively. There are also pastures of agricultural origin, which have been cultivated, and give rise to **forage crops**.

Most pasture species are **plants that usually live for several years or are perennial**. They are generally not very tall and the roots are not very deep, creating a diverse and dense herbaceous carpet. These species are **highly adapted to grazing or mowing** (hay or silage) and, with proper management, can be used for any of these cases. Depending on the geographical, edaphic and climatological conditions where the meadow is located, it will contain some species or others adapted to such conditions.

The species that grow in the pastures belong fundamentally to two large families: **grasses and legumes** (**Table 1**). Also, of some importance, but to a lesser degree, are the **Composite**, **Cruciferous** and **Chenopodiaceae** families.

• The most abundant family in the meadows are **grasses** (**Figure 1**). This is a very broad family that includes species that are very useful for animal feeding, either by grazing or harvesting. They are the main **source of energy for livestock**, with high fibre values, but with a low protein intake. This causes them to have **low digestibility** and frequently show mineral deficiencies. They are plants that need N to grow.

• The second group in importance are **legumes** (**Figure 2**). These are species that produce forages of **high nutritional quality** for animals due to their richness in protein and **high digestibility**. This is due to the ability to fix atmospheric N. They are more selective plants with respect to the environment than grasses and have hard seeds that generate a long-lasting seed bank in the soil. Although their consumption by animals has a beneficial component due to the **antimicrobial effect** of their secondary metabolites, some precautions are also necessary, since their **direct ingestion can cause bloating** in the animal (except lotus and safflower).
• We can also find **other families**: Brassicaceae, Quenopodiaceae, Compositae, etc. They are present in variable abundance

	Species	Life	Size	Establishment period	Implantation speed	Productivity	Resistance to grazing	Palatability	Nutritional quality	Resistance to frost	Resistance to drought
GRASSES	RAY GRASS (*Lolium perenne*)	Perennial	80 cm	Spring-Autumn	Very high	10-12 Ton MS/ First year	High	High	High	Low	Low
	DACTYL GRASS *(Dactylis glomerata)*	Perennial	60-120 cm	Spring	Medium	9 Ton MS/Ha	High	Low	High	Medium	Medium
	BARLEY (*Hordeum vulgare*)	Annual	20-120 cm	Spring-Autumn	High	5-8 Ton MS/Ha	Medium	Medium	Medium	Medium	Medium
	OATS (*Avena sativa*)	Annual	150 cm	Autumn	High	11 Ton MS/Ha	Medium	High	High	Low	Low
LEGUMES	ALFALFA (*Medicago sativa*)	Perennial	10-80 cm	Autumn	Very high	8-12 Ton MS/Ha	Medium	High	Very high	High	High
	COMMON SAINFOIN (*Onobrchys viciifolia*)	Perennial	15-80 cm	Spring-Autumn	High	4-5 Ton MS/Ha	Medium	High	High	High	High
	SUBTERRANEAN CLOVER (*Trifolium subterraneum*)	Annual	20-30 cm	Autumn	Low	2-12 Ton MS/Ha	Very high	High	High	Low	High
	VETCH (*Vicia sativa*)	Annual	60-150 cm	Autumn	High	6-8 Ton MS/Ha	Medium	High	High	Medium	High
OTHER FAMILIES	COLZA (*Brassica napus*)	Annual or Biannual	30-150 cm	Late summer	High	9 Ton MS/Ha	Low	High	Very high	High	High
	MEDITERRANEAN SALTBUSH (*Atriplex halimus*)	Perennial	100-300 cm	Spring-Autumn	Medium	1-5 Ton MS/Ha	High	Low	Low	High	High

Table 1. Characteristics of the main types of pasture species.

and can be annual or perennial. They have a **regulatory role for biodiversity** and provide livestock, in addition to food, with antioxidant or medicinal compounds, among others. They are often used as forage crops.

In the pastures, the **mixtures or associations** between two or more forage species, mainly grasses and legumes, offer **advantages over pure sowing**. One of the most outstanding improvements is at the level of the **nutritional quality** of the meadow: grasses offer carbohydrates while legumes **provide the necessary protein and salts** for livestock. The mixture of species also favours the reduction of the risk of weathering or bloating of cattle mainly due to the direct consumption of legumes. The soil is enriched thanks to the ability of legumes to fix atmospheric nitrogen in the soil, which also benefits the grasses and prevents fertilisation. Also, the fact of having species with different growth, precocity and size characteristics ensures different productions throughout the year and **favours their use by livestock.** The life of the pasture is prolonged as the different species follow one another in production. Finally, the mixture of species also confers a **diversity** of flora and fauna that produces **stability** by minimising climatic or management effects.

Needs and behaviour of the animals in the pasture

Pasture management requires combining the performance characteristics of the vegetation with the needs and behaviour of the animals. Aspects to consider for pasture management are: 1) the way the animals eat, 2) the amount they eat, 3) the nutritional needs they have, and 4) the impact they cause on the plot. These aspects vary considerably if free grazing is carried out on the entire pasture area, or if intensive controlled grazing, in which the pasture is divided into plots and the herd only enters one of them each day, is followed.

Figure 1. Herd of cows following free grazing in Pla de la Calma (Montseny, Barcelona). Photo: MJ Broncano.

To achieve maximum performance in pasture management, the characteristics of the functioning of the plants must be combined with the animals' behaviour and needs**. Aspects to consider for pasture management** are: 1) the way the animals eat, 2) the amount they eat, 3) the nutritional needs they have, and 4) the impact they cause on the plot. To understand how the animal works, we will consider a pasture with food to feed a herd of cows for 10 days. Throughout this sheet we will compare two different situations: (i) **free grazing**, in which the animals have the entire pasture surface from the first day to the last (**Figure 1**); (ii) intensive controlled grazing, in which the pasture is divided into 10 plots and the animals are introduced to a different plot each day (**Figure 2**).

The way the animals eat

Animals eat differently if they have a large area available for several days or if the area is smaller and they graze it for less time.

- **In free grazing**, animals roam the pasture area and choose the plants that interest them most, grazing them selectively. This means that the animals eat the plants that they like the most on the first day. In the following days, **as the best plants are exhausted, they begin to eat the plants that attract them the least**, and so on until the last days when the least beneficial plants are eaten. Free grazing implies that the animals change their diet every day, in a way that has a negative effect on production.

- **In intensive controlled grazing**, the animals only have the necessary amount of feed each day (one tenth of the meadow) (**Figure 3**). In these conditions, the grazing behaviour of the animals changes and they graze in a more aggressive way, in which **they know that they must eat everything in the field**. When it comes to a herd, as the animals are in high densities, the presence of the other animals in a reduced area causes the cows to acquire this **aggressive grazing pattern**. The result of this behaviour in the feeding of the cows is that the animals eat the same quality of grass every day (mixture) and there is no change in feeding, as in the case of free grazing.

The amount the animals eat

The amount the animals eat also varies depending on whether they have a large area for many days or a small area for less time.

- **In free grazing**, it has been observed that the amount of food a cow eats from the moment it enters a new pasture decreases significantly over the days. This behaviour is not due to the decrease in the quantity or quality of the pasture, but is linked to the fact that the pasture is being trampled on and dirtied and to the behaviour of the animals themselves.

Figure 2. Herd of cows in a plot following intensive controlled grazing on the Planeses farm (Girona). Photo: MJ Broncano.

- **In controlled intensive grazing**, this effect of reducing the amount of grass eaten does not occur because it is **new pasture each day**.

The nutritional needs of the animals

The type of grazing distinguishes the different nutritional needs that the animals may have in a herd.

- **In free grazing**, all animals have the same diet, regardless of whether their nutritional needs are different (nutritional needs depend on the age, sex and reproductive status of each individual).

- **In intensive controlled grazing**, the farmer **can divide the herd into two batches**, one with the **highest nutritional needs**, and the other with the individuals with the **least nutritional needs**. The batch with the highest nutritional requirements can enter the plots first and will take advantage of the upper parts of the plants, which have a higher nutritional value. Once this group leaves, the second batch, with lower nutritional needs, enters and eats the intermediate and lower parts of the plants.

The impact the animals cause on the plot

Finally, **the impact of the animals on the plots is different** depending on the type of grazing, since overgrazing of the pasture and compaction of the soil depend on whether they spend more or less time in the plot.

- **In free grazing**, the animals remain in the field for several days, and in favourable growing seasons, the resprouting of the first eaten plants (the best for the cow) begins while the animals are still in the field. The animals mainly select these sprouts, so the **plant's needs are not respected and overgrazing occurs**. In addition, the wandering behaviour of the animals throughout the entire plot during their entire stay (several days in many cases of free grazing), has an important effect on the compaction of the soil.

- **In intensive controlled grazing**, cows are only in each plot for one day and therefore, **do not have time to eat the sprouts of the first plants that were eaten**. Furthermore, the trampling compaction effect disappears because the cows are only in the field for one day, they move less and the field has a very high recovery (i.e. rest days) time.

Figure 3. In intensive controlled grazing, the pasture is divided into plots, and the animals spend a short time in each one. Photo: Ángela Justamante.

Types of domestic farm animals

The main types of domestic farm animals are grouped into two broad categories depending on the digestive system they have and the type of food they consume: ruminant or polygastric animals (cows, sheep and goats) and monogastric animals (pigs, birds and rabbits). This sheet describes some of the characteristics that distinguish these species: type of feeding, size, main use, energy needs, use of the environment and preferred foods and the average CO_2 emissions of each one.

Figure 1. Chickens eating in a meadow at Planeses farm. Photo: AV Video.

Different types of animals can be produced on farms depending on the final products to be obtained. Depending on the animal species that is introduced, we will talk about different kinds of livestock: **cows, sheeps, goats, pigs** and other less common, but no less important, such as **birds** (poultry farming) (**Figure 1**) or **rabbits**.

This set of animals is grouped into two large types depending on the digestive system they have and which will determine the type of food they consume (**Table 1**): **ruminant** or **polygastric** animals (cows, sheep and goats) and **monogastric** animals (pigs, birds and rabbits).

All ruminant animals are herbivores. They have a stomach divided into 4 compartments with a mouth that specialises in grasping the pasture: with a long and rough tongue and incisors that hold the grass and allow it to be cut. Among them we can **distinguish different types depending on the vegetable part they consume**. Thus, among the farm species we find that both cows and sheep are grazing ruminants, feeding mainly on herbaceous pastures, with a wider mouth to capture a greater volume of grass. For their part, goats are browsing ruminants, in addition to grass they feed on leaves, shoots, seeds, fruits and bark, they have a neck with more developed muscles to be able to reach and chew more resistant food. In contrast, monogastric animals only have one stomach (except birds). Many of them can consume a wide variety of foods: pigs, chickens and ducks are omnivores, while rabbits are herbivores. All have **different ways of chewing food** (except birds which do not have teeth but a gizzard) and **different digestion**.

Nutritional needs mainly depend on the sex, age and physiological state the animal is in. Within the same animal species, the energy needs and therefore, the use of resources, vary depending on the productive purpose that it has: **meat, milk or eggs** (**Table 1**). Thus, for an animal in dairy production it will be essential to know which point it is at in its productive cycle: if it is lactating and producing milk or if it is in the drying period.

	Species	Feeding type	Size	Use	Energy needs *	Use of the medium	Favorite foods	Average CO_2 emissions (kg eq/kg protein)
RUMINANTS	COWS (*Bos primigenius taurus*)	Grazing hebivore	Big size (bull 300 a 900kg)	Meat (weight 600kg)	End of gestation 8,7 Breastfeeding beginning : 9,7	Herbaceous, bushy and tree grasses	Tree and bushy species sprouts such as the holm oak, oak, arbutus, kermes oak, mastic tree, and acorn.	295
				Milk (weight 600kg)	End of gestation 7,6 Breastfeeding beginning : 22,6	Herbaceous	Pasture, grasses and plants: stem, seeds, leafs and roots	87
	SHEEPS (*Ovis aries*)	Grazing hebivore	Medium size (male: 45 a 160 kg)	Meat (50kg)	0,62	Herbaceous, bushy and tree grasses	Tree and bushy species sprouts such as the holm oak, arbutus, heather, mastic tree, etc.	201
				Milk (50kg)	Maintenance: 0,41 Breastfeeding beginning 0,83	Herbaceous	Pasture, grasses and plants: stem, seeds, leafs and roots	148
	GOATS (*Capra aegagrus hircus*)	Browsing ruminants	Medium (20 a 140 kg)	Meat (50kg)	Maintenance: 0,6-0,8 Breastfeeding beginning 0,9	Herbaceous, bushy and tree grasses	Rastrojeras - Grass trees: Rokrose, broom and lentisk. Fruits: acorn and carob bean. Crops remainings: stubbles.	201
				Milk (50kg)	Maintenance: 0,69 Breastfeeding beginning 1,20	Herbaceous	Pasture, grasses and plants: stem, seeds, leafs and roots	148
MONOGASTRIC	PIGS (*Sus scrofa domesticus*)	Omnivorous	Medium - big (110 a 360kg)	Meat	Maintenance: 2850 Breastfeeding beginning 3100	Herbaceous, bushy and tree grasses	Cereals, fruits, vegetables, insects, small mammals, vegetable remainings and animals, fresh pasture, worms, and seeds.	55
	CHICKENS (*Gallus gallus domesticus*)	Omnivorous	Small (0,62 a 4 kg)	Meat	2950-3180	Herbaceous	Cereals, fresh grass, approx. worms, insects ... and seeds	35 (Chick)
				Eggs	2850-3450	Herbaceous		31 (Chicken)
	DUCKS (*Anas* sp.)	Omnivorous	Small (0,72 a 1,6 kg)	Meat	2400-3200	Herbaceous	Seeds, cereals, plants, insects, algae, fish	Data not available
	RABBITS *Oryctolagus cuniculus*)	Grazing hebivore	Small (1 a 2,5 kg)	Meat	2140-2380	Herbaceous	Herbs: grasses> legumes and composites> umbelliferous (carrots), tree bark and leaves	Data not available

Table 1. Characteristics of the main types of domestic farm animals. *Ruminants: forage units (UFL)/day. Pigs, chickens, ducks and rabbits: metabolizable energy (ME) (kcal/kg).

Main breeds of domestic farm animals

Livestock breeds originated from the adaptation of animals to their environmental and geographic surroundings and human-directed action to increase the production of farm animals. The set of breeds in our country is compiled in the Official Catalogue of Cattle Breeds of Spain (2019) which distinguishes them between native promotion breeds, native breeds in danger of extinction and integrated breeds from outside the Peninsula. This sheet shows some of the most representative breeds of the different types of livestock.

A breed is defined as a sufficiently uniform population of animals that it can be considered different from other animals of the same species (Regulation 2016/1012, of June 8, 2016 on animal husbandry). There are two main factors that give rise to livestock breeds:

1) **Environmental and geographical action**: depending on where they live, animals have been modifying their bodies in order to adapt to different environmental conditions. This group includes **autochthonous breeds**, with traditional production systems, which require animals that, although less productive, have very valuable functional characteristics, which make them unique in their places of production and allow progress towards a necessary sustainability (Official Catalogue of Cattle Breeds of Spain, 2019).

2) **Human action through directed reproduction:** livestock species are improved for productive purposes. Thus, dairy breeds have been improved to have large udders, with a great potential to produce milk, much more than what the baby cows need for their development**. Breeds destined for meat tend to be larger**, more prolific and precocious: they develop more quickly and reach sexual maturity earlier.

In Spain, the main livestock breeds present in the territory are listed in the **Official Catalogue of Cattle Breeds of Spain (2019)**. It includes "**autochthonous breeds**", which may be either "**in development**" (in expansion) or "**in danger of extinction**" and "**integrated breeds**" from outside the Peninsula, which have been here for more than 20 years and have genealogy and performance controls.

Some of the most outstanding breeds within each type of livestock and productive purpose are described below.

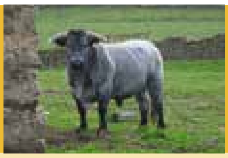
Figure 1. Herd of cows of the Simmental or Fleckvieh breed, which is the breed used in Polyfarming. Photo: Maria Josep Broncano.

Cows breeds

In Spain there are 46 breeds of cows, which include 8 breeding breeds, 32 breeds in danger of extinction and 6 integrated breeds with known yields. The most representative are:

a) Beef cows

MORUCHA



Autochthonous promotion breed locally adapted to the dehesa area that comes from the Iberian Tronco Negro. It has the highest fertility of all the Spanish meat breeds, with a productivity of 0.75 calves/year.

RUBIA GALLEGA

Autochthonous promotion breed more than 500 years old originating from Galicia. It is characterised by being very rustic and easily adaptable to any territory. Docility and meekness that facilitates handling. Productivity of 0.69 calves/year.

BRUNA DE LOS PIRINEOS

Breed in danger of extinction widespread in the Catalan Pyrenees and Pre-Pyrenees. It is raised extensively in high mountain pastures, with transhumance from the valleys. Docile animal.

b) Milk cows

HOLSTEIN FRIESIANS

Integrated breed that is the first in milk and cheese production in Spain. It represents 60% of the total count.

PARDA

Integrated breed that ranks second in dairy production for the manufacture of cheeses. Abundant on the Cantabrian coast: Asturias, Santander and the Basque Country, where it has easily acclimatised.

SIMMENTAL OR FLECKVIEH

Integrated breed that has been in Spain for more than four decades. It is one of the most important and widely distributed in the world with dual purposes, they produce milk and meat. It is the most fertile breed.

Sheep breeds

In Spain there are 44 autochthonous breeds of sheep, of which 10 are for promotion and 34 are considered in danger of extinction. There are 4 integrated races from other locations, plus 2 races that are foreigners in expansion.

a) Meat sheep

CHURRA

Autochthonous promotion breed and one of the most primitive in the Peninsula. Very high count, with great production of both milk and high-quality lambs.

MERINA

Autochthonous promotion breed, described by the Romans. It is the most valued breed in the world for wool production. It is the breed that has given rise to most of the current meat breeds.

RIPOLLESA

Native breed in danger of extinction. It is of Catalan origin. Very rustic, it takes advantage of resources that are difficult to value when there is a lack of forage. Its meat is linked to the traditional gastronomic tradition.

b) Milk sheep

LATXA

Autochthonous promotion breed, abundant in the north-east of the peninsula. Adapted to mountainous areas with high rainfall. Milk destined for the production of Idiazabal and Roncal cheeses. Coarse and long wool.

MANCHEGA

Autochthonous promotion breed, which owes its name to the geographical area where it is most abundant. Adapted to dry and hot climates. High rusticity. Herd instinct. High longevity and shelf life. Production of Manchego cheese.

CARRANZANA

Abundant **autochthonous promotion breed** in the north of the peninsula. Adapted to mountainous areas with high rainfall. Used for the production of Idiazábal cheese.

Main breeds of domestic farm animals

Goat breeds

We found a total of 22 breeds described in the catalogue, of which 3 are for promotion and 19 are classified as “in danger of extinction”. The following stand out:

a) Meat goats

RETINTA

Native breed in danger of extinction. Its name comes from its red colour. Breed whose origin is considered to be very old. It is raised extensively in Extremadura for its meat.

MALLORQUINA

Native breed in danger of extinction. It extends through the Sierra de la Tramuntana and the Llevant mountains of the island of Mallorca. It is raised extensively and is appreciated for its meat and antlers (a fact that has generated hunting reserves).

PIRENAICA

Native breed in danger of extinction. It originated and distributed in the Pyrenees, mainly in the Aragon’s section. It is a breed adapted to cold mountain climates whose main productive use is meat.

b) Milk goats

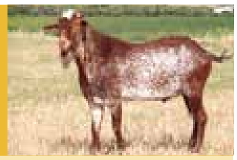
MURCIANO-GRANADINA

The most numerous **autochthonous breed** in Spain whose origin comes from the south-east of the peninsula. It is appreciated for its high milk production and for its fat content. It is essential in the production of Murcian cheeses D.O.P.

MALAGUEÑA

Native breed, originally from Malaga. It combines the extensive milk production with the production of high-quality suckling goats. It has a high rusticity, being very adaptable to different production systems and environments, even in very disadvantaged areas.

FLORIDA



Native breed whose name comes from the red spotted coat on a white background or vice versa. Breed that spans Andalusia and Extremadura. Highly rustic animal valued for producing milk with a high fat content.

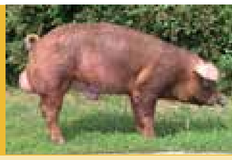
Pig breeds

There are 16 breeds of pigs in the Peninsula, of which 3 are promotion breeds, 9 are in danger of extinction and 4 are integrated breeds. Among them, the following can be highlighted:

IBERIAN PIG

Native breed evolved from *Sus scrofa ferus*. Traditional system of extensive bait exploitation with the use of the natural resources of the pasture (herbs and acorns). Iberian pork products with a great gastronomic quality.

DUROC



Integrated breed from the USA widely distributed in Europe. It is rustic and adapted to hot climates. It stands out by providing quality to the meat due to the fat infiltrated in the products.

CELTIC

Native breed in danger of extinction. Originally from the Celtic Trunk of European origin. Traditionally the breed has been exploited extensively in Galicia. Among its products, Galician bacon and Galician chorizo stand out.

Avian breeds

Among the official breeds there are 20 breeds of chickens recognised in Spain. Of these, 19 are considered to be in danger of extinction. Other breeds, although not in the catalogue, are widely used for both meat and egg production..

a) Meat hens

CORNISH

Breed not included in the Spanish official catalogue. It owes its name to the fact that it comes from the county of Cornwall. These chickens, as well as Cornish crosses, are the most widely used breed in the chicken meat industry. They are heavy and muscular birds with abundant and juicy meat.

BROILER

Breed not included in the Spanish official catalogue. The Broiler variety comes from the cross between a Cornish male and a Barred Rock female around 1930. This variety was developed for meat production as chickens grow very quickly and produce highly-prized meat.

EMPORDANESA

Native breed in danger of extinction. Originally from the Catalan region of Empordà. It is semi-heavy with a double aptitude: meat and eggs. Adapted to the low temperatures of the Mediterranean winter.

b) Hens for eggs

CASTELLANA NEGRA

Native breed in danger of extinction. This light breed is believed to have been brought over by the Arabs. Spread throughout the Iberian Peninsula, it is most abundant in the centre. It is a very rustic and disease-resistant breed. Extensive producer of large eggs.

MENORQUINA

Native breed in danger of extinction. Selected by the English during the occupation of Menorca in the 18th century, it was distributed internationally. It is a hen of medium rusticity with great aptitude for producing eggs.

PLYMOUTH ROCK

Breed not included in the Spanish official catalogue. Originally from the United States, it was imported to Europe around 1880. Semi-heavy breed, considered one of the best dual-purpose breeds, although the barred variety stands out for producing eggs.

Rabbit breeds

The European rabbit (*Oryctolagus cuniculus*) was listed as an endangered species by the IUCN in 2019. From the domestication of this species many races arose for different uses: hair, skin, meat or pets. In Spain, there are two breeds of meat that are in danger of extinction.

COMÚN DOMÉSTICO OR PARDO ESPAÑOL

Native breed in danger of extinction. It is believed to originate from Roman times and is considered to be one of the most primitive races. It stands out for its rusticity and discreet reproduction. It has been displaced by larger and more productive breeds.

FLEMISH GIANT RABBIT

Native breed in danger of extinction. It emerged at the start of the 20th century, it is spread over different breeding centres throughout the Spanish territory. They are slow-maturing animals that produce very lean meat.

NEW ZEALAND

Breed not included in the Spanish official catalogue. Very widespread rabbit throughout the world, it emerged in the United States in 1912 with the function of producing meat. In general, it is a prolific breed, with very fertile females, good growth rates and good carcass performance.

Photos from the Official Cattle Breeds Catalog of Spain, with the permission of MAPA.
New Zealand rabbit photo: Unplash, Minsha Walker

The role of dung beetles in pastures with livestock

A large amount of excrement is produced in cattle pastures. Dung beetles play a key role in recycling manure. Dung beetles bury this organic matter to feed and reproduce, and, at the same time, destroy the eggs and larvae of flies and other parasites while removing the soil. These dung beetles are necessary to close the cycle of incorporation of organic matter from excrement to the soil.

Dynamics of manure in cattle pastures

In cattle pastures, forage production is closely dependent on recycling the organic matter produced and the **amount of nutrients available**. Much of this organic matter comes from animal excrement. To give us an idea, an adult bovine produces 12 dungs a day on average, so each specimen can release 4 to 6 kg of dry matter daily in its droppings. This is a huge amount. Fortunately**, manure disappears** quickly naturally for much of the year due to the **action of dung beetles**, which bury this organic matter to feed and reproduce (**Figure 1**). By burying the manure, the eggs and larvae of flies and other parasites are destroyed and the soil is removed, thus increasing its permeability and aeration. The amount of manure buried by dung beetles depends on the size and abundance of the individuals of each species (Lumaret and Martínez, 2005). **Large species can bury up to 500 grams of manure** per individual in one night.

Figure 1. Dung beetles feeding on a cow dung. Author: ID 126525345 © Charissa Lotter | Dreamstime.com.

However, **when there are no beetles** or their numbers are very low, the dung is not buried and **can remain on the pasture for months**, even years. As explained in detail in the book by Begon et al. (2006), an emblematic example of this phenomenon occurred in Australia. In the past two centuries the cow population had increased from just seven individuals (brought in by the first English settlers in 1788) to about 30 million. All these cows produced around 300 million dungs per day, covering up to 2.5 million ha per year with manure. The native Australian detritivores were unable to degrade these droppings, so the loss of pasture under the manure placed a huge economic burden on Australian agriculture. Ultimately, the decision was made in 1963 to bring dung beetles of African origin, capable of burying bovine manure to Australia to make the country's livestock productive again.

Types of dung beetles

Dung beetles use a wide variety of food resources, with mammalian excrement being the main resource, followed in importance by carrion. Beetles present different behaviour when handling manure for feeding and reproduction (Martínez et al., 2015). This allows them to be classified into **three groups** (**Figure 2**): (i) **burrowing beetles**, which separate portions of manure and bury them under the **dung through tunnels**; (ii) **rolling beetles**, which cut dung balls and then carry them some distance on their hind legs to bury them (they are the typical dung beetles); (iii) **dwelling beetles**, which do not move the food, but remain inside or under the dung. The main characteristics representative of these three groups are shown in **Table 1**.

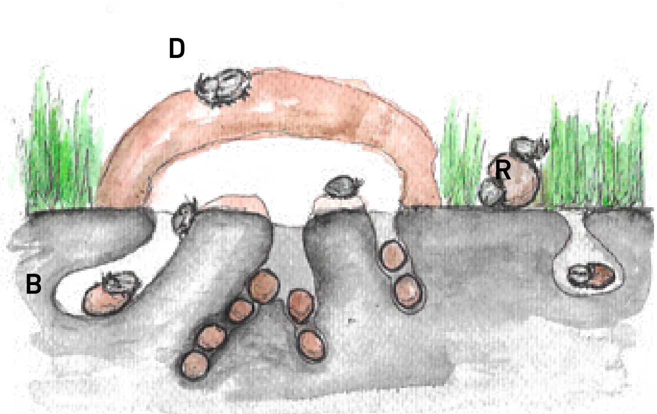


Figure 2. Representation of dung and the way in which the three types of dung beetles take advantage of the manure. B, burrowers; D, dwellers; R, rollers. Watercolor drawing: Victoria Wainer, based on a figure from: Martínez I, et al., (2015) The breeding of dung beetles. Secretary of Education of Veracruz, Mexico.

Types of beetles	Way of making use of manure	Morphological characteristics	Main genera	Image
Burrowers	They bury pieces of manure under the dung where they make the nest	Robust species, with short, wide front legs adapted to dig easily. Great sexual dimorphism	*Geotrupes* *Copris* *Onthophagus*	
Rollers	They transport dung balls away from the dung to make the nest	Less robust but with longer hind legs better adapted for transport	*Scarabeus* *Sisyphus*	
Dwellers	They remain inside or under the dung without nesting	Small and without sexual dimorphism	*Aphodius*	

Table 1. Main characteristics of the three groups of dung beetles.

Life cycle

Manure is a **resource with multiple uses** throughout the life cycle of dung beetles: adults obtain nutrients from the liquid fraction and **larvae feed on the solid part**; but at the same time, manure serves as a meeting place for adults for copulation and egg laying (Martínez et al., 2015). **The female lays an egg in each ball or mass of manure that has been kneaded or buried**. The dung balls harden and dry on the surface, but remain moist and cool inside, so that the larvae can develop and eventually become adults. Young adults come to the surface, feed intensively and, after a time, seek a mate, prepare the nest and start the reproductive cycle again.

The reproductive season of most species of dung beetles is concentrated during the **summer**, although it lasts until the autumn. At that time, young adults or at different stages of development are buried in diapause until the next rainy season in spring, when they emerge and begin to reproduce (Lumaret and Martínez, 2005). Most species of dung beetles only have **one generation of offspring a year** (univoltine species), although some species can have two per year (bivoltine species) and even more than two (multivoltine species).

Environmental and economic benefits of dung beetles

These dung beetles generate significant environmental and economic benefits for ranchers. When there are not enough beetles in the pasture, manure accumulates on the pasture for months, sometimes years, and **pests such as flies and parasites that harm livestock and humans increase**. Pastures are sometimes even abandoned because they are not productive. This represents large economic losses for ranchers who must spend large amounts of money to remove manure from the pastures. On this basis, it can be said that the **economic value of dung insects is very high**. For example, in the United States it has been estimated that, in the absence of these beetles, 2 million dollars would be spent per year (Fincher, 1981, in Lumaret and Martínez, 2005).

The main risk for dung beetles

The good fit between the western European dung beetle fauna and the use of livestock excrement usually minimises these problems. But the above examples show the **danger of what could happen if the richness and diversity of these insects were destroyed** or simply diminished.

At present, the main risk for dung beetles is the **residues of certain drugs that are found in livestock excrement and which can be toxic to dung insects**. These products, among which **ivermectin** stands out, are used on a wide spectrum of endoparasitic and ectoparasitic species of livestock, since they act in a weak concentration and their persistence in the body protects the animal for several weeks (Lumaret and Martínez, 2005). Precisely due to its persistence, they appear in the dungs of treated animals and, due to its great toxicity, **it eliminates the larvae of dung beetles** (Sánchez-Bayo and Wyckhuys, 2019), it bioaccumulates in insects and is transferred to other animals that feed on them (Verdú et al., 2020). In addition, dung from ivermectin-treated animals may be more attractive than those from untreated animals, increasing risk factors for dung insects. **This mortality is a great risk for livestock farms**, since the disappearance, even temporarily, of dung beetles can dramatically lengthen the time for dung to disappear from the soil surface.

Analysis of a pasture as a productive system from a regenerative perspective

Pasture is a productive system that meets the criteria of the regenerative model if livestock management is controlled, i.e. the animals graze at the optimal time. This system maintains its productivity when (1) there is a high diversity of species, (2) the return of materials to the pasture through livestock excrement is maintained, (3) livestock management prevents soil compaction and overgrazing, (4) a well-managed pasture has the capacity to compensate for the outputs produced by livestock uses, and (5) it optimises the use of water and helps the soil have a good capacity for infiltration and water retention.

Figure 1. In spring there are a large number and diversity of plants that provide abundant food for livestock (Santa Pau, Girona). Photo: MJ Broncano.

Application of the regenerative system criteria to a pasture

The regenerative production model follows five basic criteria that can be applied to a pastoral system.

(1) The diversity of plants.
In a pasture it is essential to graze at the optimum point to obtain the maximum production and the maximum amount of food for the soil trophic web. For this food to be more diverse, it is necessary to have **a high diversity of properly managed plants** (**Figure 1**). This high diversity allows there to be a species, at any time of the year, that **produces the maximum possible at that time** to maintain the functioning of the biological activity of the soil. Thus, in places where **winters** are cold, but still allow pasture production, the fact that there are certain species in the mix that can grow under those conditions will make pasture production significant at that time. The same is true of dry summers, there are more drought tolerant species that can grow, even though little water is available. Obviously, all this has a limit, because in certain extremes of cold or drought no species of pasture can grow.

The **greater diversity** of plants at any time improves the nutritional value, both for the soil trophic chain and for livestock. A characteristic case is that of **legumes**: sometimes they are not the plants that have the maximum productivity, but i**ncorporating them into the mix of species is essential** because they fix nitrogen which increases soil fertility. In other cases, there are species such as **rye** that **help reduce the presence of adventitious species**, especially at the start of the installation of the pasture, or have other characteristics that improve the general functioning of the system.

(2) The return of plant materials to the soil.
The return of the aerial part occurs mainly through livestock excrement (**Figure 2**). The excrement decomposes in the pasture mainly due to the effect of **dung beetles** and other insects. Therefore, if the excrement contains chemicals that negatively affect these insects, it will take longer to decompose, the return does not occur properly and the pasture is degraded.

(3) Interventions that block the functioning of the biological processes of the soil.
A well-managed pasture is neither tilled, nor does it require the addition of agrochemicals, so it does not suffer interventions that block the functioning of the soil. When the animals that graze in the meadow are managed properly,

Figure 2. The return of plant materials occurs mainly through animal excrement. Photo: Marc Gràcia.

with high intensities, but very short residence times and long recovery periods, there is no effect of soil compaction. Similarly, if we graze at the **optimum resting point, there is no overgrazing** and the plants recover perfectly because they have sufficient reserves in the roots (**Figure 3**).

(4) Soil functioning and the carbon cycle.
If grazing is done at the optimum point, the roots recover all their reserves and this **is the time when there is more carbon in the soil**. On the other hand, if grazing is carried out before the optimum point, it ends up producing a depletion of the roots, which leads to the degradation of the pasture and the loss of carbon from the soil.

The management of animals on the meadow allows some uses to be obtained (such as meat, milk or eggs) that are exports outside the system. However, a well-managed pasture can compensate for these outputs produced by harvesting without reducing the carbon stock and productivity of the system.

When **surplus grass** is produced, at times when the pasture is at peak growth and it cannot be consumed by animals, the grass is cut and saved for when it is needed. In this case, it is necessary to think about **how to return this output to the meadow**, since it can cause a loss of carbon in the soil and productivity of the system. If possible, these surpluses can be fed to cattle in the same pasture, which recovers a large part of the carbon with their excrement. If it is not possible, for example, because the climate is very cold or very hot and the animals cannot be in the meadow, **the manure has to be taken back to the meadow**. This is a more expensive process, but it avoids outputs that make the system lose productivity and carbon.

At specific times of the year, and when there is no surplus of the pasture, extra external forage must be added. This has an economic cost, but it also has a **double benefit**: it allows us to feed livestock and increase the amount of carbon in the soil more quickly. This situation is especially interesting when we start to install a pasture on a degraded soil.

(5) Water as a limiting factor for the productivity of the system.
In a quality pasture, with soil with a high organic matter content, the **infiltration and water retention capacity** is much higher than in a pasture that grows in a much poorer soil. In addition, when grazing is done at the optimum resting point, the water is used much more efficiently, since the consumption of water per unit of production is much lower.

Whenever it is possible to **use irrigation** in the pasture at an economically acceptable cost, it is profitable to apply it, since it greatly increases production.

Figure 3. Close-up of grass sprouting after being grazed. Photo: MJ Broncano.

Bases of a regenerative production system

Crop management from a regenerative productive perspective

• Aspects that determine crop management
• Combining crops in terms of time and space for greater production and the biological activity of the system
• Types of fruit trees
• Types of garden crops
• Analysis of crops as a productive system from a regenerative perspective

Aspects that determine crop management

How crops function, whether fruit trees, garden or extensive crops, is based on a series of aspects related to their management. These aspects are the following: 1) soil tillage, 2) soil fertility, 3) soil protection, 4) adventitious plant management and 5) insecticide and fungicide use. These aspects vary considerably whether conventional agriculture is carried out or agriculture based on the regenerative production model is implemented.

To understand crop function, the following **aspects of crop management** should be reviewed: 1) soil tillage, 2) soil fertility, 3) soil protection, 4) adventitious plant management and 5) insecticide and fungicide use. This applies to fruit trees as well as extensive or garden crops. Throughout this file, two different situations are compared: (**i**) **conventional agriculture**, in which the various technological alternatives currently available can be used (**Figure 1**) and (**ii**) **regenerative agriculture**, in which its principles are taken into consideration (**Figure 2**).

Figure 1. Conventional orchard with ploughed soil and without adventitious plants. Photo: Pxfuel, CC0-BY 4.0.

Figure 2. No-tillage orchard with the soil covered by crops, adventitious plants, and dead plant matter. Planeses farm (Catalonia). Photo: Ángela Justamante.

Soil tillage

The tillage or not of the soil is one of the main aspects that differentiate conventional agriculture from regenerative agriculture.

• In **conventional agriculture**, a large part of the effort spent on cultivation is invested in preparing the soil for sowing by tilling the soil (**Figure 1**). By ploughing the soil, **the soil loses compaction** and is looser, allowing the roots to break through easily. At the same time, **the soil is aerated**, something necessary for plants to breathe. The plough also eliminates adventitious plants and **facilitates crop germination and growth**.

• In **regenerative agriculture,** the soil is not cleared or tilled, which implies keeping it intact (**Figure 2**). In this way, **its structure is not broken and biodiversity is maintained** because the environment microorganisms and fauna live in is not unbalanced. On the other hand, not disturbing the soil reduces the risk of erosion and **avoids the loss of fertility**. In addition, humid conditions in crops are maintained for longer because the **water does not evaporate as much**. Finally, when there are fruit trees, the fact of not ploughing avoids cuts and wounds in the most superficial roots of the trees.

Soil fertility

Another of the main aspects that differentiate conventional agriculture from regenerative agriculture is how they are used to improve soil fertility.

• In **conventional agriculture**, fertilisation is carried out to feed the plant directly. Plant feeding is based almost exclusively on the **supply of chemical fertilisers** in adequate quantities to achieve maximum crop production. The **excessive use** of these products causes great problems for the environment and living beings, since in high concentrations they can be harmful to organisms and can limit the relationships between the plant and the soil trophic network.

• In **regenerative agriculture**, the plants are not fed, but the soil. **Chemical fertilisers are not used** in this type of agriculture. The soil reaches equilibrium with the life cycle of plants and animals. In the beginning, organic matter, in the form of dry or crushed matter, is incorporated into the soil, which helps to structure it. Organic matter takes time

Figure 3. Worker applying BRF in the soil of a no-tillage garden, with the objective of increasing the organic matter and helping to structure the soil. Planeses farm (Catalonia). Photo: AVVideo.

to decompose, but little by little it will be available to feed the plant, while promoting soil aeration and the functioning of the food web. In this way, as time passes, **soil fertility increases** (**Figure 3**). To help and maintain this process, green manure can be planted in the autumn, cut in the spring and left on the surface of the soil.

Soil protection

Soil protection also clearly varies between the two agricultural models.

• In **conventional agriculture**, the objective of ploughing is to leave the soil bare, without any vegetation. This facilitates the subsequent germination and growth of crops. The problem with exposing the soil is direct exposure to sunlight, which can cause a very **significant loss of water** through evaporation, creating more dependence on irrigation. Another consequence is the **lack of protection** of the soil against rain, which also deteriorates it.

• In **regenerative agriculture**, crop residues remain on the surface of the soil, providing **more protection from the sun's rays**. The organic matter on the surface serves as a cushion for the soil and **prevents it from drying out excessively**. At the same time, this layer also protects it from heavy rains and reduces the risk of soil erosion.

Adventitious plant management

Adventitious plant management is another point that differentiates both models.

• In **conventional agriculture**, **adventitious plants** are a very important problem because they often grow earlier and faster than crops, and end up consuming a significant part of the nutrients that are provided to improve production. Therefore, the success of conventional agriculture largely depends on the **application of increasingly powerful herbicides** that kill these plants. However, it has been shown that the excessive use of herbicides has **harmful effects** on human health and the environment.

• In **regenerative agriculture**, **adventitious plants** are not radically eliminated, but controlled. These plants are considered to **play a role in building soil fertility and in balancing the food web**, as they provide food and shelter for beneficial animals. Therefore, **herbicides are never used** and adventitious plants are allowed to grow until they compete excessively with the crops, at which point they are cut down and left in the field as compost for the system.

Insecticide and fungicide use

The use or not of insecticides and fungicides to control diseases and pests of crops also differentiates both systems.

• In **conventional agriculture**, disease and pest control is based on the use of **phytosanitary products** such as insecticides or fungicides. The use of these chemicals has become widespread due to their ease of application and effectiveness. They are usually fast acting, limiting crop damage. The problem is that pesticides, according to the United Nations (UN), are **harmful to human health and the environment**.

• In **regenerative agriculture**, **pests and diseases** are always present in plants, but chemicals should not be used for this reason. In this agricultural model, **disease control is based on growing healthy plants in living soil**: if the plant is fed correctly, it is more resistant to pests. In addition, pest control **is enhanced by predators and natural parasites** that are favoured by the diversity of plants and especially, by the presence of flowering plants. When it is necessary to use products to directly control a pest, for example, to obtain quality fruits, those that have a low persistence in the system should be used.

Combining crops in terms of time and space for greater production and the biological activity of the system

The increase in plant biodiversity leads to an increase in production and biological activity in production systems. One of the bases to achieve maximum crop production is to combine the elements of the system in space and time. Among the production models that are based on combining crops over time, we highlight the Fukuoka method, the legume rotation method and pasture cropping. Of those that are based on combining crops in space, agroforestry and intensive farming systems without tillage should be highlighted.

Biodiversity is a key aspect of how ecosystems function and are maintained. An increase in plant biodiversity leads to an increase in the production of the system and its biological activity. **Biodiversity is associated with greater complexity in the production system,** which is the basis for mitigating environmental fluctuations, less vulnerability to diseases and pests, preventing soil erosion and stable system performance. **Combining the main elements of the system** (trees, pasture plants, extensive crops, garden crops, fruit trees and even animals) in terms of time and space is one of the bases to achieve maximum crop production.

Combining crops over time

There are different production models that are based on combining crops over time. Among them we highlight the following:

• **Fukuoka method.** In this type of agriculture, a set of techniques described by **Masanobu Fukuoka**, a Japanese biologist, farmer and philosopher, are carried out which tend to reproduce natural conditions as closely as possible. The basis of the Fukuoka method is **crop rotation**, which means waiting for the right moment to carry out the different actions to the crop and the soil. If the natural cycles and physiology of plants are respected, their development is enhanced. In a rice crop, in early autumn Fukuoka sows seeds of white clover, which is a legume that enriches the soil with nitrogen. Then he sows rye and barley seeds among the rice. When the time comes, he harvests the rice, mows it, threshes it, and returns straw to the field. Then the white clover has already grown and allows a reduction of adventitious plants and fixes nitrogen in the soil. At that point, the rye and barley grow between the clover and the straw. Just before harvesting, the rice is replanted and the cycle starts again. In this way, other winter cereals, together with rice, can be grown in the same field for many years, without reducing the fertility of the soil.

• **Legume alternation method**. The method proposed by Luis Carlos Pinheiro, a Brazilian agronomist, is also based on crop **rotation over time**. In his case, he proposes alternating a legume species one year and a non-legume species (cereal or oilseed) in the second year, in order to maintain nitrogen fertilisation every two years. Rotation allows the environment to not always be the same and this **reduces the presence of pests and adventitious plants**. In the first few years it is important to sow the legume in a high density and not to harvest it so it can be used as green manure for the system. Legumes can be combined with some rye, which eliminates adventitious plants and favours soil. In successive years, legumes and non-legumes alternate, and soil fertility and crops progressively improve.

• **Pasture cropping**. This method is an agricultural practice originally developed in New South Wales (Australia). It involves sowing winter cereals directly onto perennial pastures that are active in summer, allowing cattle to graze until sowing time**. The growing periods of cereal crops and pastures are separated** (**Figure 1**): winter crops grow from November to May and warm season grasses grow from March to November. After the cereal harvest, the field is ready for grazing again as soon as the summer grasses respond to the removal of the cover. **The procedure to sow the cereal on the grass in this system requires a series of steps**: (i) before sowing, high intensity grazing is used to reduce the biomass of the grass and suppress the adventitious plants; (**ii**) the sowing method seeks to minimise damage to the pasture while achieving good soil-seed contact; (**iii**) finally, the spacing between cereal rows cannot be excessively wide (since the crop yield is reduced) or excessively close (since it causes too much damage to the pasture). This system has a positive environmental impact because it improves erosion management and the salinity of drylands, an increase in organic carbon and soil cover and the promotion of agrobiodiversity, including native species, although it results in a lower total soil water content.

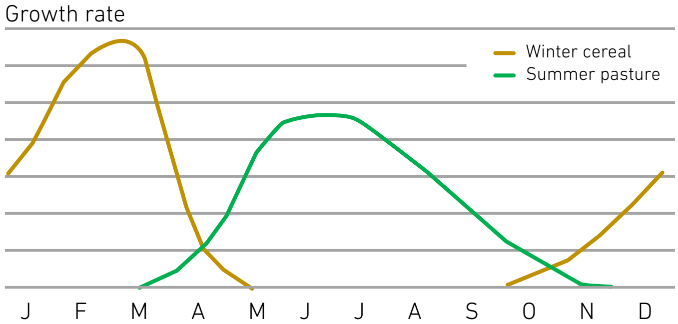


Figure 1. Growth of the winter cereal crop and the summer grass throughout the year in the pasture cropping method.

Figure 2. Agroforestry system where trees are combined with herbaceous crops. Photo: National Agroforestry Center, CC-BY.

Figure 3. Detail of an orchard without tillage with the simultaneous presence of cabbages and wild plants. Photo: MJ Broncano.

Combining crops in space

There are also various models that allow crops to be combined in space, thereby increasing biodiversity and the advantages it has in the production of the system.

• **Agroforestry.** Agroforestry is a farming system that **combines trees and agriculture (crops or livestock) on the same land** (**Figure 2**). These different elements complement each other. This leads to greater resilience, greater biodiversity and more productive use, compared to a monoculture system. The joint result is very positive because the system allows the production of vegetables, grains, fodder and other raw materials from crops, together with wood and fruit from trees. This multiplicity of products allows farmers to access different markets, ensuring a sustainable yield. Among others, **the benefits of combining** trees and crops are: (**i**) the trees serve to fix the soils, and their remains (dead leaves, branches, bark) to fertilise them naturally; (**ii**) the association of agricultural and forest species makes the system more resistant to attacks by pests and diseases; (**iii**) nitrogen-fixing trees and crops can increase the amount of nitrogen available to the entire system; (**iv**) trees can provide protection for crops and shade and shelter for livestock.

• **Intensive crops without tillage.** These systems show a high biological variety because diverse crops and diverse wild plants grow in them simultaneously (**Figure 3**). This plant heterogeneity by itself constitutes a form of **preventive protection**, for the following reasons, among others: first, it generates a **great availability of small habitats** and a multiplicity of food sources, which makes it possible to maintain **permanent populations of predators and parasites of pests**; on the other hand, the variety of species allows **continuous production of organic matter** that helps to improve the structure of the soil and maintain cover for most of the year, which controls erosion.

Why is high plant diversity better in agricultural systems?

The high diversity of plants in regenerative agricultural systems, as opposed to the homogenisation and simplification of intensive agroecosystems, has several excellent advantages:

• **Greater differentiation of habitats.** The high diversity of plants usually entails a greater differentiation of habitats and diverse microclimates. Specifically, the shelter that trees provide when combined with other plants improves the yield of nearby crops and livestock.

• **Soil erosion control.** The almost continuous presence of a high diversity of plants makes it possible to control runoff and soil erosion by means of plant cover.

• **Combination with legumes.** The presence of nitrogen-fixing trees and plants can substantially increase the nitrogen supply to the soil and, therefore, improve the fertility of agroecosystems as a whole.

• **Better use of resources.** Greater plant diversity allows light and nutrients to be used more efficiently than systems with one or few crops. Plants of different heights, leaf shapes and root depths contribute to this better use of resources.

• **Pest and disease control.** Systems with lots of crops are less vulnerable to diseases and pests than monocultures because given that there are lots of plants, flowers are guaranteed for the maximum period possible, and sources of food and shelter are assured for beneficial or predatory species.

• **Resistance to climate change.** Agroecosystems with high species diversity have been shown to have a greater resistance to climate change than single crop species that predominate in conventional agricultural industry.

• **Conservation of the biodiversity of the environment**. Farms with a high crop diversity provide safer and more stable habitats for the natural biodiversity of the areas where they are located.

• **Fewer risks for the farmer.** These multi-crop systems provide a more diverse and stable agricultural economy. Economic risks are reduced when systems produce multiple products.

Types of fruit trees

Cultivating fruit trees allows crop diversification in a regenerative farm together with the production of fruits and noble woods. Fruit trees are classified (1) according to their climatic adaptation and (2) by the characteristics of their fruits. Each climatic area determines which species and varieties of fruit trees can best grow there. Compliance with the necessary resting or dormancy time, induced by low temperatures, is essential for optimal production and quality of the fruit of fruit trees.

Classification of fruit trees

In the fruit growing treatises (Urbina, 2001) there are two systems for classifying fruit trees which are the most common: **1**) according to their climatic adaptation and **2**) by the characteristics of their fruit.

• **According to climate adaptation** (**Table 1**):

- **Fruit trees from the temperate-cold zone**. These trees withstand low winter temperatures (between -10 °C or -15 °C) without being damaged. They need the winter cold to get out of rest and are not suitable for areas with mild winters. The main species are: apple tree (**Figure 1**), pear tree, cherry tree, quince tree and European plum, as well as some species of small fruits such as raspberry and currant bush.
- **Fruit trees from the temperate-warm zone.** They are species more sensitive to low winter temperatures (below -10 °C), but they need winter cold when they rest. They are adapted to hot summers. Some species in colder areas are peach tree and apricot tree, while in warmer areas some examples are: almond, pistachio, hazelnut, walnut, olive and vine.
- **Subtropical fruit trees.** These species are very sensitive to low winter temperatures (below -5 °C). They do not need winter cold during rest and have moderate or high heat needs during the vegetative period. This group includes, ordered from least to greatest need for heat: fig tree, persimmon, orange tree, lemon tree, mandarin, avocado, custard apple and medlar, and the most demanding, the date palm.
- **Tropical fruit trees.** They do not support temperatures below 0 °C, they need warm climates. Some examples are the banana tree, mango and the papaya.

• **According to the productive characteristics and the type of fruit:**

- **Fruit trees with sweet fruit: a) pip**: pear, apple and quince; **b) stone**: peach, apricot, cherry and plum; **c) other species**: fig tree, kiwi, persimmon, banana and pineapple.
- **Fruit trees that produce nuts:** almond, hazelnut, walnut and pistachio.
- **Fruit trees with small fruits**: currant, raspberry, blackberry, blueberry and blackthorn.
- **Citrus:** orange, lemon, mandarin and grapefruit.
- **Vine.**
- **Olive.**
- **Exotic fruit trees** (lychee, papaya) and other fruit trees.

Figure 1. Apple tree cultivation. Photo: Pxhere, CC0.

Crop purpose

Fruit trees and shrubs are grown primarily to **produce fruit**. Fruit production can be used for direct consumption, such as fresh fruits or nuts (when the seeds are consumed), or it can be used for transformation into wine (grape), cider (apple) **or preserves** (**Table 1**). They can also be cultivated for nursery, ornamental purposes or to produce **noble woods**.

Two of the species most used and of greatest economic interest to **produce quality wood are cherry and walnut** (**Table 1**). Noble or quality woods are those that are used to produce veneer or planks that are used for furniture, platforms, musical instruments, etc. Our country (Spain) currently has a deficit in the production of these woods, so the sector is forced to import it. Their plantations are increasingly valued by the owners since they are a profitable alternative that, in addition, can be combined with **agroforestry**. This mixed production technique intersperses agricultural or livestock crops with cherry and walnut plantations. These systems have proven to be a source of biodiversity, decrease the use of pesticides and increase the CO_2 storage capacity of the soil.

Environmental needs of fruit trees

One of the environmental needs that most affects fruit production in fruit trees (corresponding to temperate, cold and warm zone fruit trees) is **rest or dormancy**, which is the temporary suspension of the growth of any structure of the

	SPECIES	Low temperatures tolerance	Winter cold (CH, Cold Hours)	Heat need	Type of fruit	Type of main consumption
COLD-WARM ZONE	APPLE TREE (*Malus domestica*)	VERY HIGH	500-1700	LOW	SWEET FRUIT (pip)	FRESH FRUIT TRANSFORMATION (cider)
	PEAR TREE (*Pyrus communis*)	VERY HIGH	500-1500	LOW	SWEET FRUIT (pip)	FRESH FRUIT
	CHERRY TREE (*Prunus avium*)	VERY HIGH	500-1500	LOW	SWEET FRUIT (stone)	FRESH NOBLE WOOD FRUIT
	RASPBERRRY BUSH (*Rubus idaeus*)	VERY HIGH	750-1700	LOW	SMALL FRUITS	FRESH FRUIT TRANSFORMATION (tined food)
TEMPERATE-WARM ZONE	PEACH TREE (*Prunus persica*)	HIGH	100-1100	MEDIUM	SWEET FRUIT (stone)	FRESH FRUIT TRANSFORMATION (tined food)
	WALNUT TREE (*Juglans regia*)	HIGH	600-800	MEDIUM	NUT FRUIT (stone)	FRESH NOBLE WOOD FRUIT
	OLIVE TREE (*Olea europaea*)	MEDIUM	100-500*	HIGH	OLEAGINOUS FRUIT (stone)	TRANSFORMATION (tined food, oil)
SUBTROPICAL ZONE	FIG TREE (*Ficus carica*)	LOW	90-350	HIGH	GRAIN FRUIT	FRESH FRUIT TRANSFORMATION (nut)
	LEMON TREE (*Citrus X limon*)	LOW	NO	HIGH	TROPICAL FRUIT	FRESH FRUIT
TROPICAL ZONE	BANANA (*Musa paradisiaca*)	VERY LOW	NO	VERY HIGH	TROPICAL FRUIT	FRESH FRUIT
	MANGO (*Mangifera indica*)	VERY LOW	NO	VERY HIGH	TROPICAL FRUIT	FRESH FRUIT

Table 1. Characteristics of some of the main species of fruit trees related to their ability to respond to environmental factors and their fruits.

plant containing a meristem. The rest is induced by the low temperatures of autumn, together with the shortening of the day. Each species and variety is characterised by requiring a different resting period which, if not obtained, causes a delay in **sprouting**. This delay means that the plant has a lower amount of nutrients (due to the lack of foliar surface necessary to carry out photosynthesis), with very important negative effects on fruit production: both lower production and quality (smaller size, colouration and firmness).

There are different models to count the latency periods, these are important because they are **agroclimatic indicators** that help when making decisions about the species and varieties of fruit trees that can be grown in an area. The **Weinberger cold-hour (HF) model** is one of the most widely used: in this model an hour with temperatures below 7.2 °C is counted as a **Cold Hour (CH)** (**Table 1**).

Types of garden crops

The main garden crops are vegetables and aromatic plants. These crops are characterised by being planted on a smaller scale and more intensively. They can be classified (1) according to their environmental requirements and (2) their specific and morphological characteristics. To choose which species to plant, on the one hand, it is essential to know which ones are capable of adapting to the agroclimatic conditions of the area; on the other hand, the characteristics linked to the family to which they belong, their morphology and their relationship with the environment must be known, since species of the same family usually have similar requirements and problems. All this allows us to alternate the species in terms of time and space to obtain greater profitability of the garden.

Figure 1. Regenerative agriculture garden on the Planeses farm (Catalonia) where the Polyfarming system is deployed. Photo: Ángela Justamante.

Garden crops (**Figure 1**) are characterised by being sown in smaller areas, intensively and by having a high value per unit of area planted. The main crops grown in gardens are **vegetables**, but **aromatic or medicinal plants** are also included. In the group of vegetables, which has no botanical basis, the so-called vegetables, legumes and fruits or roots of some plants are included (some examples are tomatoes, carrots, peppers, etc.). **Aromatic plants** usually accompany vegetables because they are very easy to grow and contribute positively to the garden. Among other things, they favour pollination, ward off pests and attract beneficial insects that protect them. The most widely used species are basil, lavender, mint or rosemary, among others.

Classification of horticultural crops according to their environmental requirements

In garden cultivation, it is necessary to know the **agroclimatic conditions** of the area to plant species that can adapt to these conditions during their growing period. The most important climatic characteristics include **temperature, frost-free periods, the season of the year**, which determines the daily variation in temperature, the number of hours of sunshine or the distribution of rainfall. Soil characteristics such as pH, salinity, texture and structure must also be considered. Among this set of factors, two of the most used for vegetable classification are:

• According to their **thermal requirements**:

- **Cold season crops tolerant to frost**: broccoli, broad bean, lettuce or carrot.
- **Cold season crops intolerant to frost**: onion, leek, garlic or asparagus.
- **Warm season crops with average monthly temperatures between 18-30ºC**: tomato, corn, melon or cucumber.
- **Warm season crops with average monthly temperatures above 21ºC**: aubergine or watermelon.

• According to their **tolerance to soil salinity**, they are classified as:

- **Crops sensitive to salinity**: carrot, strawberry or onion.
- **Moderately sensitive crops**: potato, turnip or corn.
- **Crops tolerant to salinity**: beet, courgette or barley.

Crops and local varieties are those that are best adapted to the growing conditions of each area. They are characterised by having a **high genetic diversity because they are more resistant** to attacks by the organisms that feed on them. As for hybrid varieties, they have spread widely because they are more productive than local varieties and the have more homogeneous products, but unlike local varieties, they need a greater amount of external inputs for their growth and protection.

Figure 2. A: Chard culture, from the Quenopodiaceae botanical family. Photo: MJ Broncano. **B:** Cultivation of tomatoes from the Solanaceae botanical family. Photo Pikist, CCO.

Classification of horticultural crops according to their specific and morphological characteristics

A garden usually contains different types of horticultural plants both in space (**polycultures**) and in time (**rotations**). This diversity is associated with greater crop production and profitability, as it implies different uses of resources, both at aerial (light) and soil level (water and nutrients).

To decide which species to plant in the garden and when to do it, it is necessary to know which family the plants belong to because species of the same family usually have remarkably similar needs and problems. It is also important to know the shape and **depth of the roots** to avoid overlap and competition underground. Other aspects to consider are: 1) **the part of the plant that is used** and 2) the type of contribution that the plant makes to the environment it grows in, it can either be a fertiliser or a nutrient extractor.

Horticultural crops can be classified according to their botanical family, life cycle, the depth of their roots or according to the part of the plant that is used. Thus,

• According to **the botanical family to which they belong**:

- **Compounds:** lettuce, endive, artichoke or sunflower.
- **Crucifers:** cabbage, turnip or radish.
- **Cucurbits:** pumpkin, melon, cucumber or watermelon.
- **Legumes:** chickpea, pea, broad bean, bean or lentil.
- **Liliaceae:** garlic, onion, asparagus or leek.
- **Chenopodiaceae:** chard (**Figure 2A**), spinach or beet.
- **Solanaceae:** aubergine, potato, pepper or tomato (**Figure 2B**).
- **Umbellifers**: celery, parsnip, parsley or carrot.

• According to their **life cycle**:
- **Annuals:** potato, aubergine, pumpkin, cucumber, broad bean, spinach or lettuce.
- **Biannuals**: cauliflower, turnip, radish, carrot, celery, chard or leek.
- **Perennials**: artichoke, strawberry, asparagus or garlic.

• According to the **depth of their roots**:
- **Superficial** (45-60 cm): garlic, celery, onion, cauliflower, endive, lettuce, potato, leek or radish.
- **Intermediate** (90-120 cm): aubergine, pea, melon, cucumber, pepper, carrot or broad bean.
- **Deep** (> 120cm): artichoke, pumpkin, parsnip, watermelon, tomato or thistle.

• According to the **part of the plant that is used**:

- **Roots and tubers:** potato, radish, turnip or carrot.
- **Flowers, seeds and fruits**: broad bean, pea, cauliflower, pumpkin, melon or artichoke.
- **Leaves**: cabbage, lettuce or endive.
- **Bulbs and stems**: garlic, onion, asparagus or leek.

Analysis of crops as a productive system from a regenerative perspective

Crops comply with the principles of the regenerative model and maintain their productivity when: (1) there is a high diversity of species due to the rotation of crops in terms of time or space; (2) the return of green or dry plant materials to the soil is maintained; (3) there are no interventions that alter the soil such as ploughing or the use of insecticides, herbicides or chemical fertilisers; (4) there is a balance between carbon extraction and inputs into the soil; and (5) the organic matter in the soil maintains its water retention capacity and this is complemented by adequate irrigation.

Applying the principles of the regenerative model to crops

The regenerative production model is defined by **5 basic principles** that can be applied to crops. The analysis of these principles in the case of crops allows us to assess how the system is working and which interventions could help to improve it most efficiently

1) The diversity and quantity of plants

In regenerative agriculture, maximum crop production is achieved with maximum diversity. This is based on the need to have **plants covering** the ground and growing for **most of the year**. Furthermore, if these plants have different characteristics (greater tolerance to environmental conditions, deeper roots, etc.) it is easier for them to make better use of all the available resources. The maximum diversity of plants is achieved by **combining different crops and even animals in terms of time and space**.

There are different production models that allow crops to be combined over time. All are based on crop rotations throughout the year or between years. In the **Fukuoka method**, rotations are carried out in the same year. Along with rice, which is the base crop, other cereals are grown in winter such as rye and barley in the same field and they are even compatible with the planting of white clover, which is a legume that enriches the soil with nitrogen. In the **pasture cropping system**, winter cereal crops are combined with warm season grasses throughout the year and their periods practically do not overlap. In other cases, such as the **legume alternation method** proposed by **Pinheiro**, the rotations are carried out in different years: one year a legume species is sown and a second year a non-legume species (cereal or oilseed) is sown, in order to maintain nitrogen fertilisation every two years.

Other models **combine crops in space**, thereby increasing biodiversity and its advantages in the production of the system. The clearest case is **agroforestry**, which combines trees and crops on the same land. These different elements complement each other and a greater biodiversity and a greater quantity and variety of products is obtained. But any **orchard without tillage** has a high biological variety, since crops and wild plants grow simultaneously, which gives rise to a significant heterogeneity of species and available resources (**Figure 1**).

Figure 1. Garden without tillage showing the great variety of plants growing in it. Photo: MJ Broncano.

2) The return of plant materials to the soil

The regenerative production system requires the return of plant materials to the soil. **The most important incorporation occurs through the roots**, but the one we can manage is the incorporation of the aerial part on the surface that, in addition to providing nutrients, plays an important role in covering the soil surface.

The **balance between mineralisation and humification is key in this return**. If the process is driven by bacteria, the materials are quickly consumed and represent an immediate nutritional supply. On the other hand, if the decomposition is caused by fungi, the plant matter remains in the soil longer and **creates a stable humus**. Thus, if the return is green remains of crops or adventitious plants at their peak production, the decomposition process is faster. But if the remains are from these plants when they have already been **lignified or even dried**, **decomposition is much slower** and an intermediate decomposition phase can be obtained, which is the **more stable humus**.

In the different types of crops there are certain peculiarities. Thus, in **pasture cropping**, the return of plant material to the ground is combined with the return that occurs with **animal excrement**. In cases of intensive vegetable production, as is usually the case in the orchard, the contribution of external transformed materials (such as BRF or compost) is necessary to compensate for the outputs produced with the harvests.

Figure 2. In the regenerative model, not very heavy agricultural machinery can be used to avoid soil compaction. Photo: CC0.

3) Interventions that block the functioning of soil biological processes

Unlike conventional agriculture, in regenerative agriculture **there are no interventions that block the biological processes of the soil**: the land is not tilled, the soil is not compacted, insecticides or herbicides are not used and chemical fertilisers are not added. The way the regenerative model works allows these interventions to be compensated with the use of the resources of the area and the enhancement of the functioning of natural processes.

However, **regenerative agriculture also uses machinery**. A tractor is used for different activities on the crops; in extensive vegetable production (and also in pasture cropping) direct sowing is used to protect the seed and increase production; and if the harvest is large it is also done with a combine harvester. In all these cases, it must be borne in mind that this machinery can cause soil compaction and therefore an alteration of the soil structure. This risk of compaction is reduced by u**sing machinery that is not too heavy** (**Figure 2**) and avoiding intervening when conditions are not suitable, for example, when the ground is very wet, in order to achieve the least possible impact.

4) Soil functioning and the carbon cycle

Soil function and the carbon cycle depend on the global balance of stocks: when products obtained from the system's crops are extracted, it causes a global loss of carbon stocks. When this **export is small**, **the system can recover naturally**. With the return of green remains and straw from both crops and adventitious plants, and considering the high diversity of plants, in most cases the system allows the production of grain or fruits without the need for external inputs.

Figure 3. BRF covering the irrigation ditches in the Planeses farm. Photo: Marc Gràcia.

However, if **a lot of carbon is removed from the system, mechanisms must be found to return it**. This often happens in gardens, which have a high production and from which a large quantity of products is extracted. In this case, the outputs affect the total stock and the biological activity of the soil and cause a **progressive impoverishment of the system**. Therefore, in the garden it is necessary to add BRF or compost, which are external to the garden and have high amounts of organic matter and nutrients, to restore balance to the system (**Figure 3**).

5) Water as a limiting factor for system productivity

The basis of the regenerative model is to increase the amount of organic matter and, with it, substantially **increases the water holding capacity** of the soil. Despite this, at certain times of the year, such as summer in the Mediterranean, water can become limiting for crops. For this reason, in the regenerative model, **weeds are cut before the summer** to reduce water consumption for crops. In any case, if there is water available for irrigation, it greatly improves the potential of the site for crops, since in any land-based system, the more water, the more production. In the case of the garden, this need for irrigation is especially relevant and, in fact, for many garden crops it is necessary to have irrigation water to achieve acceptable productions.

The Polyfarming system

- The Polyfarming system
- The forest as a source of resources
- Livestock as a management tool
- Crops as recipients of resources
- Operation of the Polyfarming system

The Polyfarming system

• Components of the Polyfarming system

Components of the Polyfarming system

The Polyfarming system proposes a new way of interrelating the different uses on a farm scale, in a way that improves the economic profitability of the farms that apply it. There are many promising agricultural techniques, but the idea is not to simply collect them, but to combine them in order to establish synergies between agricultural, livestock and forestry exploitation. Full-scale Polyfarming is underway in Planeses, a regenerative agriculture farm located in Catalonia.

Figure 1. View of the Planeses farm (Girona, NE Spain) with the different components of the Polyfarming system: (1) forest; (2) fruit trees on pasture where the herd of cows' graze; (3) chickens and rabbits on pasture; (4) non-tillage garden. Photo: AVVideo.

The Polyfarming system: integrated multi-functional agro-silvo-pastoral management

The Polyfarming system aims to demonstrate that a new multi-functional agro-silvo-pastoral management system can be applied to farms in Mediterranean mountains, integrating the different uses of the farm. This system is presented as a profitable management alternative that addresses the problem of abandonment of agricultural and livestock activities in Mediterranean mountain areas and **environmental** (soil degradation, vulnerability to climate change, loss of biodiversity) and **socio-economic problems** (territorial inequalities, loss of productive capacity of the territory) that this abandonment is causing.

The Polyfarming system **has been launched in a pilot farm**, where the proposed agro-silvo-pastoral system is implemented and evaluated on a real scale. The full-scale functioning of Polyfarming is essential to be able to reach the groups of owners who have to guarantee its replicability in the territory. In the Planeses farm (Girona, Catalonia) (**Figure 1**), there are the different elements considered: the forest, the fruit trees on pasture where cows graze, the pasture with small animals (chickens and rabbits) and the untilled orchard.

Components of the Polyfarming system

The Polyfarming system is based on the following scheme (**Figure 2**):

• **The forest is a source of resources**, so that forest management allows quality products, such as wood and firewood to be obtained, and allows other by-products of forest use, such as cuttings, clearings and understory cleaning to be obtained. These by-products are used for the rest of the farm's activities in the form of biochar, BRF, trunk beds or biofertilisers.

• **Livestock is an important tool for managing other activities**: cleaning the understory, managing fruit trees on pasture, improving the fertility of the orchard, etc. At the same time, its integration with other uses significantly reduces the costs and therefore increases farm profitability.

• **Crops (orchards and fruit trees) can be managed more sustainably and profitably in small areas**, using forest resources (biochar, BRF, trunk beds, biofertilisers) and developing pastures to meet the needs of livestock.

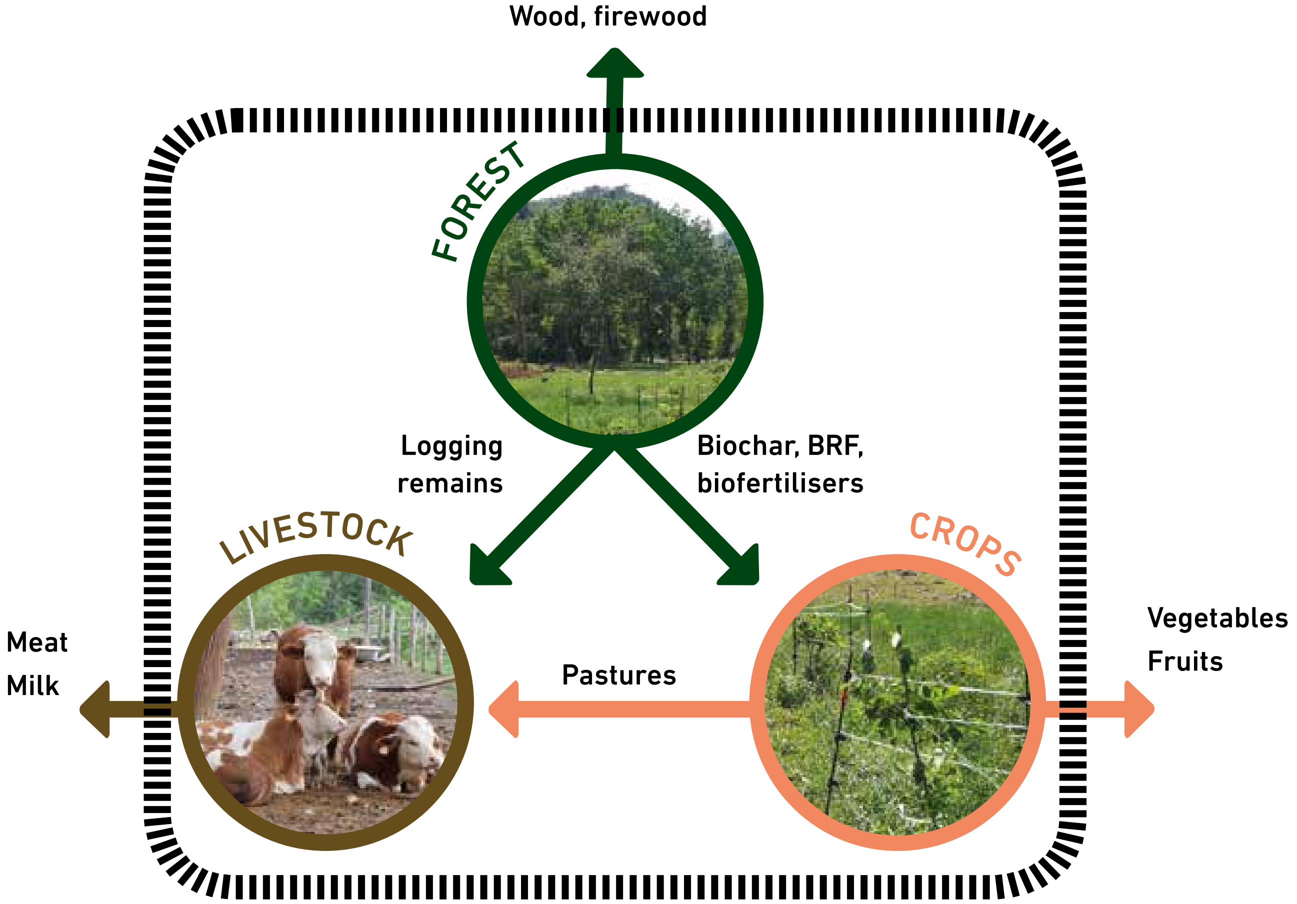


Figura 2. Scheme of the components of the Polyfarming system at farm level. Credit: Lucas Wainer.

Integrated management of the different uses

The **methodological scheme** according to integrated agro-silvo-pastoral planning defines a new way of interrelating the different techniques on a farm scale, so that synergies are established between agricultural, livestock and forestry uses. The Polyfarming system is based on the following components.

- **Integrated forest management** that allows the use of by-products from forest harvesting (cuttings, clearings and understory cleaning) as a base resource for the farm's remaining activities.

- **Management of livestock through controlled grazing**, so that livestock is an important tool for managing of other activities (cleaning the understory, fruit tree management, improving soil fertility).

- **Multiple management of fruit trees** with the production of pastures to complete the needs of livestock.

- **Self-sufficient management of mountain orchards without tillage**, using forest resources: biochar, BRF, cultivation on trunk beds or biofertilisers.

Benefits of the Polyfarming system

The multi-functional management of mountain farms has important benefits at all levels.

• **It improves system productivity**, as it improves soil fertility.
• **It improves adaptation to the effects of climate change**, because it increases resistance to drought.
• **It improves the diversity and landscape of the farm.**
• **It improves the use of the farm's resources**, by putting resources into production that are sometimes abandoned, such as pastures or forests.
• It proposes **accessible technologies** for all farmers.
• **It avoids the farmer's dependence on agrochemical industry products.**
• **It significantly improves the economic profitability** of the exploitation as a consequence of the previous points.
• **It can be combined with recreational activities**, the farmer's own or in coordination with the local tourism sector.

The Polyfarming system

The forest as a source of resources

- Forest harvesting
- BRF (Ramial chipped wood)
- Biochar
- Cultivation on trunk beds
- Bocashi-type organic fermented fertiliser
- Biofertilisers based on reproducing mountain microorganisms

Forest harvesting

The main characteristic that determines forest exploitation is the quality of the forest (shape and size of the trees), linked to the site quality of the stand. The cutting criteria differ according to the site quality of the stand. In low-quality forests, the intervention on the forest is of low intensity, with the aim of achieving a decrease in density. In high-quality forests, intervention on the forest is done by identifying the trees of the future and intervening to improve their growing conditions.

Harvesting of Mediterranean forests

In managed forests, the main disturbance is logging. **Unlike natural disturbance**, where wood always remains in place, generating a return of carbon and protection of the soil, in forest exploitation **there is a significant extraction from the system**. The manager must control the effects of this extraction while promoting trees that allow them to obtain the most suitable product for their needs in the shortest time possible. This is achieved by favouring the differentiation of the trees, in order to have the most suitable canopies at each moment of the tree's life, and by controlling the return of carbon and the environmental conditions for its incorporation into the soil.

Cuttings in high quality and low-quality forests

The main characteristic that intervenes in the planning of forest exploitation is **the quality of the forest** (shape and size of the trees), linked to the site **quality of the stand** (productive potential of the stand). For Mediterranean forests, average height can be used as a good indicator of site quality. Although there is a gradient of situations, we will analyse the cuttings in two site qualities and contrasted situations:

(i) **Low quality**, in which the height of the trees does not exceed 8 m, which is linked to high densities and small diameters.

(ii) **High quality**, with heights exceeding 12 m, which allows proposing a management to obtain trees with a better conformation and larger diameters.

Site **quality conditions**, combined with the **management history of the stand**, determine the current state of the forest and its ability to reach a certain structure over time in response to felling. **Figure 1** shows the combined effect of site quality and the management applied to the structure of a Holm-oak forests.

- **Intense felling** generates a structure with **many sprouts** for both high and low qualities. As the cuttings are of less intensity, crown closing generates a natural selection of sprouts, decreasing their density. This effect is more important in high qualities where greater growth allows greater closure of the crowns.

- **In low intensity felling** (i.e. uneven-age management) this selection effect means that in **high qualities** the resulting structure presents **individuals mostly with only one tree** (from resprouting). On the other hand, for **low site qualities**, where the lower growth does not allow a complete closure of the crowns (or this occurs very slowly), the effect of the natural selection of sprouts is less, and we find structures that maintain a **high number of sprouts per individual**.

The way to apply the cuts will be different depending on the site quality of the stand:

- **In low-quality forests**, the intervention on the stand is done with a spatial criterion, with the aim of achieving a **decrease in density**. Due to the main character of forest improvement of this intervention, the intensity of felling is low, not exceeding 30% of the basal area.

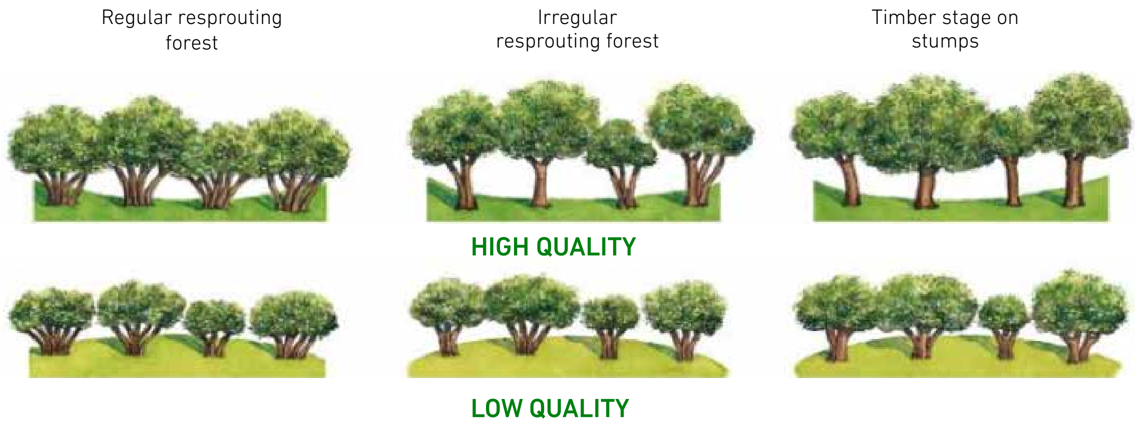


Figure 1. Holm oak structures according to the management model applied (regular resprouting forest, irregular resprouting forest and timber stage on stumps) and the site quality of the stand (high and low). Source: Manuals de gestió d'hàbitats. Els alzinars. Illustrator: Agnés Perelló

Figure 2. Forest worker limbing an oak tree on the Planeses farm. Photo: AV Video.

- **In high-quality forests**, the intervention on the stand is done by identifying the trees of the future and intervening to improve their growing conditions (i.e. cutting their biggest competitors). The goal is to **produce well-shaped and large trees**.

This **sprout selection process** that has just been described will be more or less rapid depending on the **speed response forest of the individuals**, i.e. the time it takes the individual to react and begin to occupy the new available space. This responsiveness depends on the conditions in which the individual has grown and on the characteristics of the species. The reaction of an individual will be faster the younger and more vigorous it is. This vigour of the individual is determined above all by the **size of its crown**, which can be assessed by the % of the height of the tree that the living crown occupies. The vigour is maximum when its height is more than 30% of the live crown. This % will depend on the degree of competition to which the individual has grown (related to past management of the plot), the time during which it is subjected to this competition and the **shade tolerance** characteristics of each species, which decrease with the individual's age. Under very shaded conditions (i.e. strong competition), shade-tolerant species, such as holm oak, have a greater ability to keep canopies alive for longer than non-shade-tolerant species, such as pines, and therefore they maintain the ability to respond to the release of competition for longer.

Carrying out forest harvesting

Once the trees to be cut have been decided, they are **cut and limbed with a chainsaw** (**Figure 2**). **Harvesting** is usually carried out by **dragging the logs with an adapted agricultural tractor from** the tracks. Skidding is carried out upwards at maximum distances of 60-80 m, so the track system must be designed to prevent the skidding being longer. This implies that the **distances between tracks cannot exceed 200 m**. When it is for firewood, the trees can be chopped in the forest, although this process is usually done once they reach the track. They are then cut into 2-2.20 m pieces (measured for trucking) and stacked for transport.

At the end of the harvest, **the remains of branches should be stacked** to facilitate access to the area and reduce the risk of fire.

Cutting criteria

The cutting criteria differ according to site quality of the stand. In each case the criteria are:

• **Low site quality**

- Short low-intensity cuts are made.

- The trees to be cut are chosen mainly by a criterion of homogeneous distribution in space.

- The felling does not require marking on the ground of the trees to be cut, it can be done directly during the harvest.

• **High site quality**

- More intense cuts are made.

- The selection of the trees for cutting is based on the selection of the trees that are left uncut, the 'trees of the future'.

- To favour the trees that we are interested in growing, we first study what they are in the field. Once chosen, the trees that affect their development are cut.

- The characteristics of the trees of the future, **in order of priority**, are: (1) well-developed crowns, (2) smooth bark, (3) large diameter (in relation to the average of the plot), and (4) well-formed trunk. One of these characteristics, type of bark, is illustrated in **Figure 3.**

- If there are **trees of interest to the fauna** (trees with cavities and large standing dead trees), **they will not be cut.**

Figure 3. The bark of the tree as an indicator of the responsiveness of the tree: the image on the left shows a tree with thinner bark, which has higher responsiveness than the one on the right. Photo: MJ Broncano.

BRF (Ramial chipped wood)

BRF is a technique developed in Canada in the 1980s, where it is known as the Bois Raméal Fragmenté (BRF). The technique consists of the chipping of small branches, from which a fungal process is initiated. It is led by basidiomycetes as the basis for the formation of a stable humus that improves the structure and water retention capacity of the soil.

BRF production

The base material to produce BRF are **branches smaller than 7 cm**, which are those that contain soluble or barely polymerised lignin, the necessary base for the formation of a highly reactive humus. **These branches are shredded after cutting** with a shredder (**Figure 1**) before the wood has dried. If the cut is in summer, in a few days the branch is already dry so it must be crushed quickly. In winter, the branches dry more slowly and there is more time to crush them. The chips obtained in this way initiate a fungal decomposition process led by basidiomycetes (white rot), which, from lignin, produces fulvic and humic acids, which are the basis for the formation of aggregates in the soil. Thus, **a stable, long-lasting humus is achieved**, like forest humus, different from the humus produced from other organic residues that do not contain lignin. In this way, compost, for example**, is useful for improving soil life and providing nutrients** to plants.

The limiting factor for its production is therefore the presence of significant volumes of freshly cut branches smaller than 7 cm. In mountain areas, where the forest is an important resource, **the availability of branches from forest felling usually represents an abundant resource** for BRF production. The size and species of the branches have an important effect on the amount and type of humus produced.

• **The size of the tree** largely determines the weight of branches <7 cm. The amount of material obtained after limbing the tree increases rapidly with its diameter. To obtain an enough quantity of material efficiently it is better to **use trees with a diameter greater than 20 cm** at breast height.

• **The species** used to make the chip also plays an important role in the type of humus produced. All the works carried out recommend limiting the use of conifers to less than 10% of the total material used. **The best results are achieved with deciduous trees**, due to the structure of their lignin. In contrast, evergreen hardwoods perform worse due to the transformation of their lignin by "brown rots" that produce polyphenols and aliphatic compounds.

BRF application

The time of application of these chips can be very different, which conditions the characteristics of the product at the time of application and the ease of handling it.

Figure 1. Chipping the branches in the field with a shredder to produce BRF. Photo: Montse González, AV Video.

Figure 2. Pile of BRF that is left to decompose directly in the field for several months before application. Photo: J. Luis Ordónez.

- In the **standard system**, the chips are spread into their final place quickly after the branches are chipped to prevent the material from drying out. Stacking is avoided because anaerobic conditions occur in large piles that encourage the material to start fermenting.

- In the **Polyfarming system,** on the other hand, we leave the chips in small piles within the forest for **between 4 and 12 months** (**Figure 2**). By making the stacks in winter and being small in size, this partly avoids fermentation with a significant increase in temperatures. When the material is collected to be transported to its place of application after a few months, we find **partially decomposed material**, with an appearance and smell similar to forest humus, and easier to handle and transport than the original chips.

The application of BRF can also be carried out in different ways:

- **Directly in the field**. The BRF is applied directly to crops, either garden or fruit trees.

- **In the animal bed.** Chips previously decomposed for a few months in the forest can be used for animal litter. In the Polyfarming system they are used mainly in the **litter of the chicks** where, mixed with other materials such as biochar, they offer a healthy environment for the animals while they enrich them with their excrement. This bed is gradually stirred to facilitate the absorption of animal manure and obtain a high-quality substrate that is used for the garden.

Benefits of BRF for farms

BRF can represent significant benefits for farms that use it. In the short term there may be an immediate interest because:

- **It increases soil productivity and reduces management costs.** BRF encourages weed control, which improves the performance of agroforestry farms in disadvantaged areas.

- **It allows the use of forest subproducts. It allows the use of forest biomass** (remnants of margin cleaning, pruning, etc.) that currently has no commercial use..

Benefits of BRF for the environment

BRF can also represent significant long-term environmental improvements:

- **Reduction of water use.** It allows a significant reduction of the use of water, **up to 50%** in some cases, due to the ability of humus to retain it.

- **Increase in carbon sequestration.** It manages to introduce part of the carbon sequestered by the forest in the agricultural production system. This causes a very important increase in the carbon stock sequestered in the soil, which is one of the fundamental elements in mitigating climate change.

- **Improvement of biodiversity**. It is a system that increases the biodiversity of the soil, as it improves the structure of the soil and balances the pH.

Biochar

Biochar is the name given to charcoal that is produced from the pyrolysis of biomass of plant origin. Biochar improves the physical properties of the soil, since it has a high organic content, is very resistant to degradation and has high micro- and meso-porosity, which gives it a high capacity to retain water, nutrients and microorganisms.

Biochar production

Although biochar can be obtained through the pyrolysis of any type of organic material, in the Polyfarming system the raw material to make it includes **by-products of forest management**, mainly **dry branches** from the cuttings of the previous season.

Biochar can be produced by following different methods. In our case, we propose the use of **self-built transportable boilers**, which are metallic and are cheap to use (**Figure 1**).

The biochar production process **begins with a small fire** inside the reactor, initially it is a combustion characterised by the presence of oxygen. As plant biomass is added, the oxygen in the lower part of the boiler is consumed, **going from combustion to pyrolysis**, which is the reaction that results in coal. When the entire boiler has been filled, the upper part of the pile can reach a high temperature and begin to turn white from the ashes of the combustion itself. At that time the fire **is extinguished with water** and covered, so that oxygen does not enter, and this causes the pyrolysis of the entire pile to take place.

The next day the pile can be uncovered, where the biochar will be found (from pyrolysis) with the ash remains (from combustion). **This pile must be spread on the ground so that it finishes cooling down** and thus avoid further combustion that would transform all the product into ashes.

Application of biochar

Biochar can be applied directly to the soil together with other types of improvers such as fertilisers or compost. Sometimes it must be moistened to avoid losses in the air and it being aspirated by the person applying it.

Figure 1. Transportable boiler to produce biochar directly in the forest. Photo: AV Video.

Figure 2. Biochar sample obtained by the pyrolysis of plant biomass. Photo: AV Video

Figure 3. Activation of biochar in chick litter. Photo: Ángela Justamante.

However, for a more efficient use **it is advisable to previously activate the biochar** before incorporating it into the soil, i.e. loading it with nutrients and microorganisms, which is what the plants will use. In our case this activation is carried out using animals. One part is activated by **incorporating it into the composting process of chick litters** (**Figure 3**). Another part is activated by incorporating it into the chickens' food, whose excrements will end up distributing it over the fields.

Biochar benefits for farms

Biochar can represent important benefits for farms, such as:

• **Improvement of the soil structure.** Biochar helps regulate the pH of very acidic soils, improves their physical and chemical properties and can buffer sudden temperature changes.

• **Increased retention of water and nutrients.** Biochar has a high-water retention capacity, which improves irrigation of the roots and allows the capture and retention of nutrients as it reduces losses due to leaching.

• **Stimulation of microbial activity.** In soils where biochar has been applied, microbial activity is stimulated.

• **Improvement of fertilisers and manures.** The use of biochar as an additive in fertilisers and organic manures can bring improvements in their efficiency.

• **Increase in crop productivity.** Biochar significantly increases the agronomic productivity of degraded soils and improves the physiological response of crops to periods of water stress.

Benefits of biochar for the environment

Biochar also has important environmental benefits that help combat climate change:

• **CO_2 sequestration.** Biochar contributes to the sequestration of carbon from the atmosphere, as it stores more than three times its weight in CO_2, so that for each kg of biochar more than 3 kg of CO_2 are sequestered.

• **Non-degradable organic carbon sink.** Pyrogenic materials such as biochar have high biochemical stability, so the carbon they contain can remain in the soil for a long time.

• **Reduction of greenhouse gas emissions.** By not burning, the emission of CO_2 is avoided, in addition to reducing the formation of other greenhouse gases such as methane (CH_4) and nitrous oxide (N_2O).

Cultivation on trunk beds

Cultivation on trunk beds is a technique in which trunks and branches from the fellings are buried under the soil of the orchard and the fruit trees. These remains act as a sponge that offers a reserve of water and microorganisms to keep the soil alive, promote plant growth and increase the carbon content in the soil. At the same time, the carbon introduced will remain removed from the atmospheric stock for 5 to 10 years.

Material to make trunk beds

Trunks, branches, leaves or any other type of biomass can be used to make the mounds. Normally logs are used from fellings in the forest that are not suitable for other uses (**Figure 1**). Regarding the diameter of the logs, it is preferable to use **dimensions greater than 20 cm** that allow larger volumes of buried wood to be obtained.

In relation to the plant material to make wooden beds, species with different characteristics of hardness can be used. **Hardwoods** decompose slowly, and logs can remain for more than **10 years** retaining water and releasing nutrients. On the other hand, **softwood species** have a faster decomposition that can take place after **5 years**. If there are different types of wood, a good option is to mix hard woods at the bottom of the beds with softwoods and branches at the top.

To carry out this technique **some species of trees work better than others**:

• **The species that work best are**: alders, apples, poplars, birches, maples, oaks, holm oaks, willows, etc.

• **Species that work well are**: cherry, juniper or yew (with aged wood if possible), pine, fir or spruce (with logs cut years ago to avoid high levels of tannin), eucalyptus, etc.

• **Species to avoid are**: cedar, walnut and other tree species considered allelopathic, carob and similar species whose wood takes a long time to decompose, etc.

Figure 1. Stack of logs used as the basis of the trunk bed technique. Photo: Marc Gràcia.

Log burial process

Depending on the type of crop on which they are going to be applied, the logs are buried very differently:

a) When placed in **fruit tree crops**, the trunks are inserted into deep holes, **50 cm wide and 50 cm deep** (**Figure 2A**). Branches and smaller debris are placed on top of the trunks. A layer of soil is placed on them and finally the fruit trees are placed (**Figure 2B**).

b) For use in **garden crops**, the logs are stacked directly on the ground or in shallow trenches about **40 cm wide and 25 deep**. The logs are laid on the bottom as a first layer; a thinner biomass layer of branches and small trunks is arranged on top (**Figure 3A**). Gaps between logs can be filled with litter and other debris. Once the plant material has been placed, it is covered with about 20 cm of the earth extracted from the trench (**Figure 3B**). Planting is takes place on the mounds, taking advantage of the north/south effect created by the logs (**Figure 3B**). Ideally the bed is prepared several weeks before planting, but planting can take place immediately.

Figure 2. Placing the trunk beds in the fruit crops: A) hole with the logs placed at the base; B) planting the fruit tree on top of the log bed. Photo: Marc Gràcia.

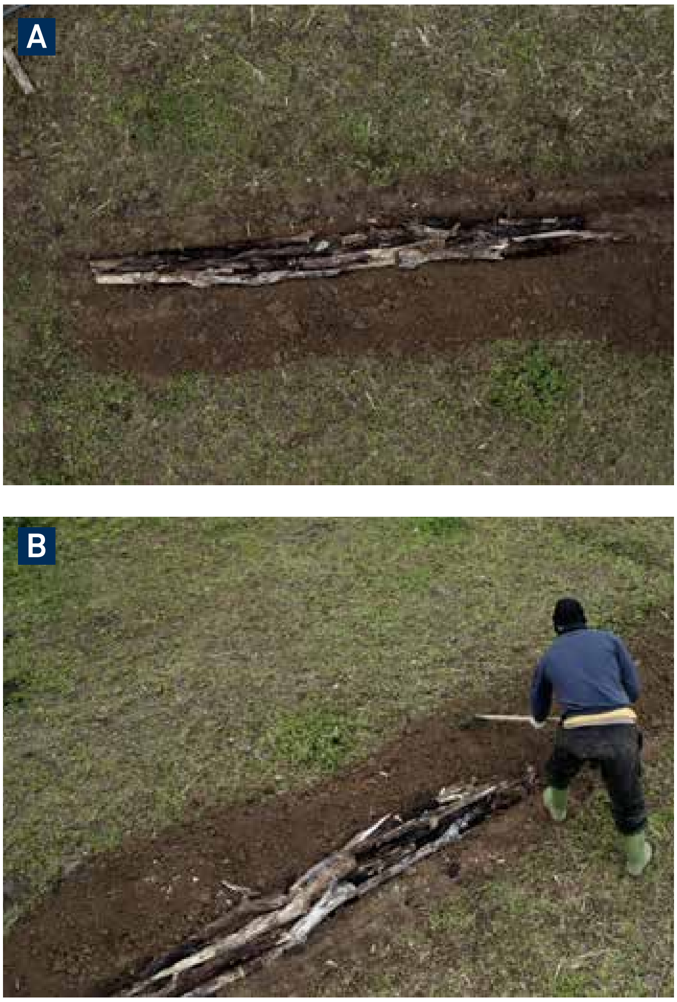


Figure 3. Placing trunk beds in garden crops: A) arrangement of the layer of logs; B) the logs are covered with earth extracted from the trench itself. Photos: AVVideo.

Benefits of cultivation on trunk beds for farms and the environment

Cultivation on trunk beds makes it possible to take advantage of forest remains to improve soil conditions, agricultural production and the environment. The main benefits are:

• The gradual decomposition of wood is a **constant source of long-term nutrients for plants.** A large bed can provide a constant supply of nutrients for 10-20 years.

• Compost wood can generate heat, which can **increase the growing season of plants.**

• The aeration of the soil is increased because the branches and trunks gradually break up, which **improves soil drainage.**

• Trunks and branches act like a sponge: **rainwater is stored** and then released during drier periods.

• These trunk beds participate in the sequestration of carbon in the soil by introducing a slowly decomposing carbon that **helps mitigate climate change.**

• It means forest remains that are unsuitable for other uses can be used, which helps to **improve the profitability of agricultural farms.**

Bocashi-type organic fermented fertiliser

Bocashi-type fermented organic compost is the result of an aerobic semi-decomposition of organic waste, it is carried out by microorganisms that produce a partially stable material with slow decomposition. This product can fertilise plants and, at the same time, improve the soil. The word Bocashi comes from Japanese and means to cook the compost materials taking advantage of the heat that is generated with its aerobic fermentation.

Ingredients and preparation of Bocashi-type fermented organic compost

The main ingredients used to make Bocashi-type fermented organic compost are:

• **Vegetable carbon**: improves the physical characteristics of the soil, which facilitates the best distribution of the roots, aeration and absorption of humidity.

• **Manure**: the main source of nitrogen in the production of fermented organic fertilisers.

• **Rice husk:** improves the physical characteristics of the soil by facilitating aeration, moisture absorption and nutrient filtering.

• **Rice bran**: encourages the fermentation of organic fertilisers and is very rich in nutrients such as phosphorus, potassium, calcium and magnesium.

• **Cane molasses**: the main energy source for the fermentation of organic fertilisers and encourages the multiplicity of microbiological activity.

• **Forest humus**: the main source of microbiological inoculation for the production of fermented organic fertilisers.

• **Common soil:** has the function of giving greater physical homogeneity to the compost and distributing its humidity.

• **Dust from rocks and ashes**: they provide minerals.

• **Water**: ensures the homogenisation of the humidity of all the ingredients that the compost comprises.

The ingredients are mixed by placing **different layers of the different dry components** and, at the end, the entire mass is turned over until a balanced mixture is obtained (**Figure 1**). Then water is added to achieve the desired humidity. Once the mixture of all the ingredients of the compost is finished, the dough is left on the ground with a height of one and a half meters **for three days to start fermenting**. During these first three days the mixture is turned 2 times a day to prevent the temperature from rising excessively. After

Figure 1. Mix of the different ingredients to prepare Bocashi-type organic compost. Photo: Marc Gràcia.

Figure 2. Final appearance of Bocashi-type organic fertiliser. Photo: Marc Gràcia.

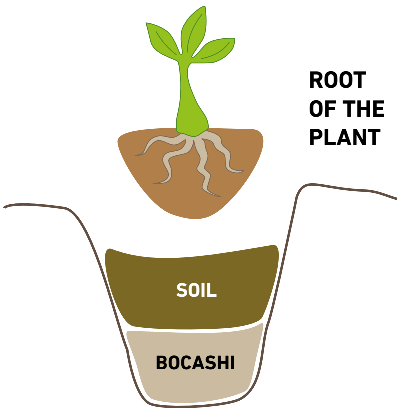


Figure 3 . Application of Bocashi-type organic fertiliser.

the first three days, the mixture spreads to form a covering about 30 cm thick. In the first few days it is turned once a day using a rototiller. Over the days, the turning time is spaced out. **After 15 days, the fermented organic compost has already matured and its temperature is equal to room temperature.** At this time its colour is light grey, with a sandy powdery appearance (**Figure 2**).

Application of Bocashi-type fermented organic compost

There are different ways of applying Bocashi organic fertiliser. For its use in the orchard we propose placing the fertiliser **directly at the base of the hole where the plant will be placed** during transplantation. The compost is applied directly and covered with a little soil so that it does not directly contact the root of the plants (**Figure 3**).

The amount of fertiliser applied to crops is conditioned by different factors, such as the fertility of the farmland, the climate and the nutritional needs of the plants to be cultivated. **Fertiliser doses vary depending on the crop** (**Table 1**). Regardless of the quantity, once the organic compost has been applied, it must be covered with soil so that it is not easily lost and thus obtain better results.

Table 1. Bocashi-type fertiliser doses recommended for some crops.

Crop	Suggested dose
Tomato	125 g in the base
Onion	25 g in the base
Betroot	100 g in the base
Lettuce	50 g in the base
Cucumber	50 g in the base

Storage of Bocashi-type compost

Concerning its storage, normally farmers prepare organic fertilisers according to the immediate needs of their crops. For this reason, **it is not very common to keep them for more than two months** before applying it in the field. If it is stored for a longer time, it is advisable to store it under a cover to protect it from sun and rain.

Benefits of Bocashi-type fermented organic compost for farms and the environment

• **It can be made in most environments and climates** where agricultural activities are carried out.

• **The materials with which it is made are well known** by farmers and easily available locally.

• **It does not require a very high financial investment** in infrastructure.

• Plant growth is stimulated by a series of **natural phytohormones and phytoregulators** that are activated through these fermented fertilisers.

• Through the inoculation and reproduction of native micro-organisms present in the soil, **the materials are gradually transformed into excellent quality nutrients** available to plants.

Biofertilisers based on reproducing mountain microorganisms

Biofertilisers are high-energy fertilisers prepared from microorganisms of different origins dissolved in water enriched with milk, molasses and minerals, and fermented under anaerobic conditions. They are used to nourish and strengthen plants without blocking the biological processes that occur in healthy soil. The forest is the source of mountain microorganisms with which biofertilisers are made.

Obtaining mountain microorganisms

Mountain microorganisms, which are the basis for obtaining the biofertilisers described in this sheet, **are a set of organisms** that are obtained directly from forest humus and that, therefore, are adapted to the application area. They are obtained in a non-selective way, since all the organisms that are in a soil humus sample are reproduced. This sample includes **yeast, fungi, protozoa, and bacteria**.

Mountain microorganisms are obtained by mixing humus from the forest floor with rice bran (in equal parts), adding **molasses as an energy source** and, if necessary, water to reach adequate humidity. The two important aspects that must be considered for the process to work correctly are: 1) that the mixture should be made uniformly, as if the dough were being made for a cake; 2) that the mixture should have the correct **degree of humidity**, which can be verified by the first test: when you take a sample of the mixture with your fist and squeeze it, it should form a solid ball, but when this ball is thrown into the air and it falls on the same hand that has thrown it, the ball must be crumbled into small pieces. Once homogeneous and adequate humidity has been achieved, the mixture is placed in hermetic containers. As the container fills, it must be compacted (you can step on it) so that it contains as little moisture as possible (**Figure 1**). When the container is full, it is hermetically closed and **left for about a month**. The result is a compact mass with a silo smell that is stored in the same container.

Figure 1. Compaction of the mixture (humus from the forest floor, rice bran and molasses) to obtain mountain microorganisms. Photo: AV Video.

Biofertilisers from mountain microorganisms

INGREDIENTS

The main ingredients used are:

- **Mountain microorganisms** (yeasts, fungi, protozoa and bacteria): allow the fermentation of the biofertiliser to take place; they are placed in a mesh bag like a large tea bag.
- **Whey**: has the function of reactivating the preparation and providing proteins, vitamins and fats.
- **Molasses**: it provides the necessary energy to activate the microbiological metabolism during the fermentation process.
- **Rock dust**: activates and enriches fermentation as its main function is to fertilise the soil and plants.
- **Ashes**: provide minerals and elements to activate and enrich fermentation.
- **Water**: facilitates the liquid medium where the chemical reactions of anaerobic fermentation are multiplied.

PREPARATION

For the preparation of a standard biofertiliser, the amounts of the different ingredients indicated in **Table 1** are used.

The biofertilisers are produced in plastic drums with a capacity of about 200 l, with a metal ring or screw-on lid so that they are hermetically

Table 1. Ingredients (and amounts) for the preparation of a standard biofertiliser.

Rock dust	Quantity
Microorganisms	40 kg
Whey	2-4 l (or 20 l serum)
Molasses	4 l
Rock flour	4 kg
Ashes	4 kg
Water	180 l

sealed and good fermentation takes place. **A hose must be attached to a valve with the end inside a bottle filled with water**, to evacuate the gases that are formed during the fermentation process, preventing the entry of air (**Figure 2**).

The preparation of the biofertiliser consists of the following stages:

1. All the ingredients are put in the 200-l capacity drum at the same time (except for the mountain microorganisms) and are stirred until a homogeneous mixture is obtained. **The mountain microorganisms are placed into a mesh bag** (like a giant tea bag) that is introduced into the mixing water.

2. **The drum is hermetically covered** so that the anaerobic fermentation of the biofertiliser begins, making sure that the gas evacuation hose is not clogged and that the end remains inside a bottle with water to prevent the entry of gases.

3. The container that contains the mixture **is left to rest at room temperature in the shade**, protected from sun and rain.

4. It is necessary to wait a **minimum of 20 to 30 days for anaerobic fermentation** (the drum has already been going for a few days without gas escaping). Then the drum is opened and its quality is checked by its **smell (pleasant acid)** and colour (amber brown), before use. It should not have a rotten odour or be blue-violet in colour. Its smell should be of fermentation and its colour should be brown.

Figure 2. Container to prepare biofertilisers, hermetically sealed with a hose attached to a bottle filled with water to evacuate the gases. Photo: Ángela Justamante.

Storage of biofertilisers

Once the process is finished, the biofertiliser is ready to be applied. Before its application, **the biofertiliser can be packaged in preferably dark containers**, so that the light does not affect it. The product can also be left in the same containers in which it was prepared. The time that biofertilisers can be stored can range from **six months to one year**.

Figure 3. Application of biofertilisers of mountain microorganisms in the orchard. Photo: Ángela Justamante.

Application of biofertilisers

The application of the biofertiliser is done **via foliar using a sprayer**. It is applied diluted, in doses that can vary between 2 and 10% (2 to 10 l of biofertiliser in 100 l of water), preferably at the first and last hours of the day, at a rate of a couple of times a week and also after rain.

Benefits of biofertilisers for farms and the environment

- Use of easy-to-find **local resources** (molasses, milk, whey, etc.).
- **Very low investment** in infrastructure.
- **Technology that is easy** for producers to develop.
- **Results** that are observed in the **short term.**
- **Increase in the resistance of plants** against attack from insects and diseases.

The Polyfarming system

Livestock as a management tool

- Rearing chicks and young rabbits before their transfer to pasture
- Raising chickens on pasture
- Raising rabbits on pasture
- Managing cows in pasture through intensive controlled grazing

Rearing chicks and young rabbits before their transfer to pasture

The chicks, when they arrive at the farm, are installed in structures with controlled temperature, good ventilation and a bed of sawdust on which they can rest. Drinking water and food are freely available. They do not move to the field for four weeks. Adult rabbits are raised in individual cages. When the female is receptive, she moves to the male's cage where copulation takes place. After their birth, the young (3 to 12 per litter) live with the mother until they are weaned and taken to pasture, which occurs approximately when they are one month old.

Chick installation and rearing

- Structures for installing chicks on the farm

The chicks are installed in closed and isolated structures, consisting of a brood room, which is a large box where the temperature is high, and a front yard (**Figure 1**). Before the chicks arrive, the structure must be fully cleaned and disinfected, and the drinkers and feeders clean and full. **The size of the structure depends on the number of chicks to be raised**; it is essential that they have enough space to develop. In the **Polyfarming** project the structure is prepared for **200 chicks**.

Figure 1. Chicks recently installed in the rearing structure, Planeses farm (Girona). Photo: Marc Gràcia.

The **best temperature** for rearing newly-hatched chicks is **37º C**. This temperature is gradually reduced until reaching 30º C at the end of the first week of life. The temperature increase is achieved with **special infrared lamps** of which there are several models on the market. The humidity of the breeding area should not exceed 60%, which is achieved by **maintaining good ventilation**. Structures must always be closed and protected from possible predators.

Figure 2. Spreading biochar on the chicks' bed, Planeses farm (Girona). Photo: Ángela Justamante.

- Feeding and caring for the chicks until they are transferred to the pasture

The chicks **usually arrive at the farm one day old**, all having received the basic vaccines. They are not taken to pasture for four weeks. Initially there are 200 in each structure, and after a week they are separated into two boxes and 100 are put in each one.

From day one, the chicks must have drinking water and food freely available (**Figure 1**). The chicks' **diet consists** of granulated compound feed for rearing initiation. **They should not be given grains or grass until they are one month old**. Apple cider vinegar is added to the water, which provides vitamins and minerals to maintain their internal balance and improve their immune system. Subsequently, fermented garlic is also added, which has an effective antiparasitic power.

The chicks must have **a litter or bed on which they can rest**. Beds can be made of various materials. In Polyfarming, a 20-25 cm high wood sawdust bed is used **in which microorganisms and biochar are incorporated so that it is composted** (**Figure 2**). The humidity of the beds must be controlled so that it is always between 20% and 25%. After 10 days, and to avoid compaction, the bed is **stirred with a rototiller**, first every 4 days and then every two. This is a way to avoid having to change the bed continuously. **The alternative is to put a little sawdust on the cement surface and change it regularly**. In the Polyfarming system the compost obtained from the chick litter is later used in the garden.

Figure 3. Individual cage for rearing farm rabbits in the Planeses farm. Photo: Marc Gràcia.

Figure 4. Young rabbits in the nest. Photo: Núria Anglada.

Reproduction and rearing of young rabbits

- Cages for adult rabbit maintenance

Adult rabbits, both male and female, need a clean, well-ventilated living space that is protected from rain, wind, and excessive temperatures. The rabbits are placed in individual **wooden or metal cages made of galvanised wire** approximately 100x50 cm in size and 40 cm high (**Figure 3**). The fact that rabbits are raised in individual cages allows greater control of their reproduction and better sanitary control, which includes cleaning and disinfecting the cage and a lower risk of contagion. It is important that the cages are easy to clean and that they prevent the rabbits from escaping or being attacked by possible predators.

- Reproduction of rabbits

For copulation, the female moves to the male's cage. If the female is capable of interbreeding and the male is active, mating takes place almost immediately. The courtship is very short: the male caresses the female, stimulates and mounts her, and in a few seconds ejaculation occurs. After copulation, it is better to return the female to her cage as soon as possible.

If the mating has been successful and there is a pregnancy, **gestation lasts 31 days**. Twenty-five days after mating, it is necessary to provide the female with dry straw or wool to prepare her nest. **Litters are usually between 3 and 12 young** (**Figure 4**). There are different ideas about when to reunite the females that have just given birth: just after doing so, 10-12 days later, or when the weaning of the kits ends a month later.

- Care of the kits until their transfer to the pasture

The female shares space with the kits until they are weaned. **The lactation period could last a maximum of 56 days**, although it is during the first three weeks when the kits feed only on milk, then they replace it in their diet with feed. During the pregnancy and lactation period, the female increases the amount of daily food she needs. In these phases it is important that there is food and water always available in the cages. The young are usually separated from their mother at about a month of age. At that time, before being taken to the field, the young rabbits are given the enterotoxin vaccine.

Raising chickens on pasture

The raising of chickens on pasture is characterised by the fact that the animals have fresh grass every day. This is achieved with the daily movement of the animals through a system of fences and mobile shelters. With this type of management, chickens become an important element of the plant-animal system, and a main tool to regenerate the soil and the landscape thanks to their excrement.

Feeding the chickens

Chickens are not exclusively herbivores, but **they do eat a lot of grass**. The key to managing these small animals in the meadow is to keep the grass fresh and vegetative. Chickens do not usually feed on very mature plants, as they are less digestible than young plants, nor do they eat the taller plants, in fact, what they do is trample them.

In the meadow, chickens also obtain high amounts of live protein in the form of **worms and insects, as well as seeds** that they also find there. Together, all these resources can represent 30-40% of their diet.

The rest of the resources to complete a balanced diet are provided by the farmers in the **feeders**: an important part is in the form of feed, but cereal grains can also be added. If the cereal is also fermented it is more digestible for the animals. It is also convenient to provide small stones to facilitate the functioning of the gizzard and digestion.

Characteristics of the shelters

The priority for pasture raising chickens is to provide fresh grass every day. For this reason, it is important to **design shelters that move easily**. This system allows chickens to eat fresh grass on a new patch of pasture each day.

The shelters that we use in the Polyfarming system are suitable because of their low cost and flexibility. They are **iron structures of adequate size (3 x 4 m)** without soil and with wheels to transport them by hand every day (**Figure 1**). These shelters have a raised

Figure 1. Mobile shelters for pasture-raised chickens. Photo: Marc Gràcia.

Figure 2. Division of the meadow into sectors in which the mobile shelters move. Photo: AVVideo.

Figure 3. Movement of chickens through a system of fences and mobile shelters in the pasture. Photo: J. Luís Ordóñez.

structure on which a canvas or mesh roof is placed to protects the chickens from the sun, and partly from the rain, and to reduce the risk of predators. Chickens are generally placed under the roof of the shelter to sleep at night.

Division of the meadow into sectors and movement of animals

Chickens are put in the meadow 3-4 weeks after hatching. The chickens are managed in a **pasture divided into corridors** (**Figure 2**). These corridors allow the animals to be moved daily through a system of fences and mobile shelters. **You don't need heavy machinery to move these fences, they can be moved by one or two people** (**Figure 3**).

The daily movement of the animals allows them to always have access to a clean pasture that offers the animal the maximum resources that possible at different times of the year.

Protecting chickens against predators and diseases

Predators can cause large losses on farms, so it is very important that shelters offer the animals the **maximum protection against them**. In general, chickens are susceptible to predation by birds and by some mammals such as foxes. This can be solved in part by placing an electric shepherd around the enclosure to keep predators away, or by having trained dogs in the field.

As regards diseases, well-managed **pasture systems rarely require the use of drugs**, as the system itself, together with proper cleaning, prevents diseases before they occur.

Benefits of raising chickens on pasture for farms and the environment

- It produces **chickens with high nutritional value.**
- It helps to **control crop pests** because chickens consume lots of insects that can be harmful.
- It helps prevent disease and **almost eliminates the use of medications.**
- **It helps to create and maintain high-quality pasture** by means of their droppings.
- **It increases the farm's profitability** because the equipment and maintenance of the system requires a small investment.

Raising rabbits on pasture

Rabbits in pasture are managed exclusively in the meadow. The animals move daily, so that they always have new grass that gives them their maximum nutritional value. They move through a system of fences and mobile shelters that protect the animals against inclement weather and predators. In addition, with this system the animals become the key tool to maintaining top-quality pasture.

The system of raising rabbits on pasture

Grass raising rabbits is a relatively recent activity and, although it is still little known in Spain, it is having significant success in countries such as the United States. The lack of knowledge causes it to be confused with organic production, but there are very important conceptual and technical differences between these two ways of producing. Organic production focuses on the animal and its well-being and only requires a minimum surface area for the animal to be able to live during the last third of its life. On the other hand**, the production of rabbits on pasture takes into account both the animal and the pasture, so it involves a double objective**: (i) that the animal always has a new pasture with all the elements that it can take advantage of, and (ii) that the animal is the main tool to maintain the highest quality of this pasture.

Figure 1. Rabbits are herbivores and basically feed on meadow grass. Photo: Marc Gràcia.

This rabbit production system requires technical conditions that are very different from those of the organic rabbit, both in terms of facilities, where **it is necessary to work with mobile cages and fences to allow the continuous movement of the animals**, as well as the type of feeding, because rabbits on pasture mostly only feed between 80 and 100% depending on the time of year, on pasture.

Figure 2. Mobile shelters for pasture-raised rabbits. Photo: Marc Gràcia.

Feeding and medicating rabbits

Rabbits are fattened exclusively in the meadow, since their diet is **100% herbivorous** (**Figure 1**). **The grass is complemented with leafy branches of species** such as hackberry and ash (in summer), holm oak (in winter), and aromatic plants (rosemary and oregano) to boost their immune system.

With this type of diet, **it is virtually unnecessary to use antibiotics** and vaccines are only used for viral diseases.

Figure 3. Shelters serve as protection for rabbits from inclement weather and predators. Photo: Marc Gràcia.

Characteristics of the shelters and movement of animals

The weaning of the kits and their placement in the meadow occurs when they are 30-40 days old. From then on, the rabbits are managed in a **meadow divided into corridors**. The animals move through a system of fences and mobile shelters every day. Mobile fences keep rabbits in a limited space to get the right impact on the grass and ensure enough recovery time. **These fences can be moved without heavy machinery** and can be moved by one or two people.

Shelters must **protect animals against inclement weather and predators.** Both the shelters and the waterers and feeders should be easy to move. The structure is very similar to that of chicken shelters (see the sheet: "The Polyfarming system. Raising chickens on pasture"): an iron structure with wheels to transport them, with a canvas or mesh roof that protects the animals. The main difference is that rabbit shelters have a wood located about 25 cm from the ground that occupies the entire cage (**Figure 2**). This creates a space where rabbits can hide to avoid the summer heat or climb up to protect themselves when the soil moisture is excessive.

The basic element of this system is the movement of the animals along the meadow, so that th**e animals are kept in a delimited patch of meadow,** with a high density, but only for one or two days (depending on the time of year). The animals are then moved to a new plot, and so on, until they return to the initial plot. The time it takes to return to the same plot can vary between **60 and 80 days**. In this way, each patch of the meadow is subjected to a great impact when the animals are present, but then has a long recovery time.

Protecting rabbits against inclement weather and predators

When working in open spaces, animals are subjected to external climatic conditions that can occur throughout the year. Therefore, **one of the critical points of this system is** to provide the means to protect the animals from climatic elements and predators. This is the objective of the design of the different elements used, especially the mobile shelters (**Figure 3**). The daily movement of the animals also helps to avoid predators, since the risk of predation increases when the animals are kept in a fixed space, and keeps the spaces clean, **breaking the cycle of parasites and limiting problems of moisture on rabbits' legs** (which are linked to moisture and dirt).

In addition to mobile shelters, we use electric fences to protect rabbits from predators, both on the ground and in the air. The fences are placed around the perimeter of the field where the grass plots are located. With this system, predators cannot access from outside. Trained dogs are also used, which can move around the plot where the rabbits are, but without entering it.

Benefits of pasture raising rabbits

The production of rabbits on pasture has clear benefits both for environmental aspects and for the nutritional value of the meat produced.

• On an environmental level, **by using this system, rabbits become the main tool to regenerate fertile soil and a quality meadow.** This is a very efficient way of capturing carbon in the soil and creating and conserving habitats with a high natural value.
• From the point of view of nutritional value, the **meat obtained has a higher density and a higher content of vitamins** (A, D and K) and quality fats (Omega 3). Furthermore, feeding rabbits in the meadow makes it possible to reduce (practically eliminate) the use of antibiotics.
• **This production system is scalable;** there are projects with small productions (100 rabbits a month) and larger projects, with more than 1,000 rabbits a month. In any case, with this system, small-scale production (100 to 500 rabbits per month) is competitive with respect to larger projects. In addition, **the investment required to start it up is small compared to conventional projects:** many of the facilities can be self-built and small areas of pasture are required (from 2 ha).

Managing cows in pasture through intensive controlled grazing

Intensive controlled grazing is based on the fact that the herd of cows moves every day from the plot where they are to another that is the optimum grazing point. In this way, the cattle spend a short time in each plot and there is no risk that they will feed on the sprouts of the first plants they ate. In addition, the compaction effect of the soil by trampling is much lower. This type of management is designed by dividing the pasture into permanent plots of a similar size, which can be reached by a system of roads.

Figure 1. Cows grazing in one of the plots delimited for the application of theintensive controlled grazing system. Photo: MJ Broncano, CREAF.

In the Polyfarming system the herd of cows is managed by **intensive controlled grazing**. This technique is characterised by using very high stocking densities in small spaces with a very short stay and a very long recovery period. The objective is to guide the cattle to eat the best pasture, **without degrading the soil or the plants** (**Figure 1**).

Dividing the meadow into plots and moving the herd

Intensive controlled grazing establishes a grazing plan in order to control the state and evolution of the vegetation and thus determine the ideal time for cows to graze. To do this, a system is designed where **the grass is divided into permanent plots** of a similar size by means of fences and wires (**Figure 2**).

This grazing plan guarantees that the animals move from the plot they are in to another that is **the optimum grazing point,** always considering when the animals last entered. The **time return** daily to the same plot varies: in spring it usually takes the animals around 25 days to return to it, while in summer it takes longer, between 60 and 70 days. For the system to work properly at least as many plots are required as there are days for the longest return period.

The optimal time for cows to graze on a given plot is just before the plants reach maturity. If the animals graze before the optimum time, the grass is consumed before the plant has recovered its reserves and, therefore, the plants can end up deteriorating. However, if the animals graze later, they will not take benefit from all the nutrients that the pasture can offer them.

The cows are transferred from one plot to another via the roads designed for this (**Figure 3**). Movements can take place daily or twice a day and the animals can occupy a complete plot or just part of it, depending on the state of the vegetation.

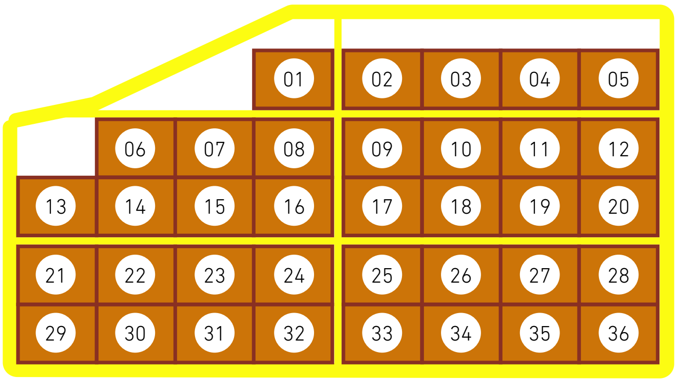


Figure 2. Design of the system of plots into which the pasture is divided to apply the intensive controlled grazing system. The numbers indicate plots, the yellow lines are the paths for the herd to move between plots.

Figure 3. The cows move from one plot to another via the roads designed for this. Photo: AV Video.

Cow management infrastructure

A series of infrastructures are needed to manage a herd of cows by means of intensive controlled grazing. The most important is fencing all the plots using electric wire. **The plots and paths are permanent**, but the system of wires and posts that limit them can be modified, in case interventions such as mowing the grass or the specific reduction of the size of the plot are necessary.

The system of hoses that lead the water to the troughs, which must be in all the plots, is another fundamental structure to be able to carry out this management system properly. Finally, if the cows are dairy, another basic infrastructure is **the milking barn**, which must be in a central area of the pasture surface to reduce daily movement.

Feeding the cows

Cows are herbivorous animals, so **they get all their food from plants**. For a good part of the year, much of their food is obtained directly from the pasture. However, in some months the grass does not grow and additional forage must be provided to complete their feeding (**Figure 4**).

This forage **can come from the farm itself**, from grass cut in months when there is a surplus. If the farm's own fodder is not available, **it must be purchased**, and it must be considered an investment to improve the farm, it is an import of carbon that must return to the soil via cow excrement.

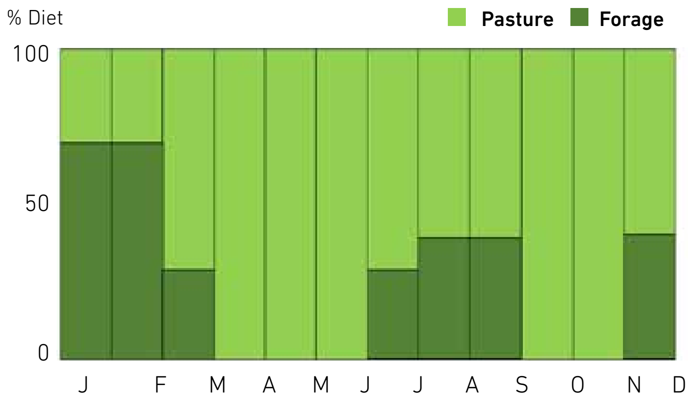


Figure 4. Proportion of the cows' diet that comes from pasture or forage purchased in different months of the year. The data are from the Planeses farm, from the year 2019.

Benefits of cow management through intensive controlled grazing

Managing cows on pasture through intensive controlled grazing has clear benefits both for the environment and for the farms that carry it out.

- It is **achieved when the pasture produces the maximum for each season** and the animals consume it at the best time.
- **Cattle droppings help improve soil fertility by increasing organic matter and nutrients.**
- The little time that the animals spend in the plot **prevents them from having a compacting effect on the soil.**
- It helps to create and maintain high quality pastures with **a very important carbon sequestration effect** in the soil.
- It produces **meat and milk with a higher nutritional value.**

The Polyfarming system

Crops as recipients of resources

- Managing fruit trees on pasture
- Managing an orchard without tillage. I. Design, roads, terraces, irrigation system and planting
- Managing an orchard without tillage. II. Control of adventitious plants, use of forest products, biofertilisers, manure and grazing

Managing fruit trees on pasture

Managing fruit trees in combination with pastures and livestock is one of the most widespread agroforestry systems. Fruit trees are planted in spring and require a good irrigation system and individual protection for each tree, as well as a series of after-care measures to protect against pests or pruning. The installation of the pastures requires adequate terrain, control of the adventitious plants, sowing at the right time and irrigation when possible. This combination of fruit trees and pastures with livestock has clear mutual benefits.

Agroforestry: managing fruit trees on a pasture with livestock

One of the types of agroforestry systems present across Europe is the use of high-value **trees**. These can be fruit trees or trees grown for **high-quality wood in combination with herbaceous crops or pastures**. In these systems, the value of the production of the trees (in the form of fruit or wood) is added to that obtained from the crops and the use of the pastures for livestock feeding (**Figure 1**).

Figure 1. Agroforestry. Dehesa Boyal in Bollullos Par del Condado (Huelva, Spain). Photo: Wikimedia Commons, CC-BY.

The use of livestock as a management tool for the **system** conditions **the species, density and design of the fruit tree plantation in the pasture.**

- **When the animal used is large**, as is the case with cows, it must be considered that the effect of grazing on trees is considerably high. For this reason, the fruit trees chosen should be those that form a tall habit, such as walnut, apple or chestnut trees. In these cases, the planting density is usually low, since the fruit trees are located following the lines that delimit the plots. In this way, the fruit trees are easier to protect during the first few years and they create better shade to protect the livestock from excessive heat. The planting is done in the dividing lines at the rate of one tree every 10-12 m (**Figure 2**). This implies a plantation of about 100-120 trees per hectare.

- When **medium or small animals** such as chickens, ducks, rabbits or even pigs are used, **the grazing height is not so high**. For this reason, shorter species such as pomegranates, plums or apricots can be planted. In these cases, they are usually planted at **higher densities along parallel lines 5 to 20 m apart** (**Figure 2**). Within the line the separation between trees will vary, 3-6 m from each other, depending on the species.

Installing and caring for fruit trees

Fruit trees should be planted at the start of spring. Once the places where the trees will be planted have been delimited, the holes are excavated, which are normally done with an excavator. These holes are about 50x50 cm wide and 50-60 cm deep. At the bottom of the hole, several logs are placed following **the trunk beds technique** (more information on the technique can be found in the sheet "Cultivation on trunk beds"). **These logs offer a reserve of water and microorganisms** to maintain a living soil, they encourage the growth of plants and increase the carbon content in the soil. Branches and smaller debris are placed on top of the trunks. A layer of soil is placed over them and finally the young fruit trees are placed, which are later covered with soil until the hole is filled.

The fruit tree plantation must have **an extended irrigation system** that drip-feeds each tree. Especially in the first few years and later in the drier seasons, water supply is essential to ensure the survival and growth of the fruit trees. Another type of infrastructure that is also essential is an **individual protection for each tree**, in order to avoid the herbivory of the cattle that will be placed in the pasture (**Figure 3**).

Fruit trees have a long life, and for part of their life they are not productive. Thus, for example, in a well-maintained commercial walnut plantation with grafted specimens, at 5-7 years old they may already produce a few kg of walnuts per tree, but it will be necessary to wait 30 years until they reach their maximum production. During all this time **fruit trees require different care** without which subsequent

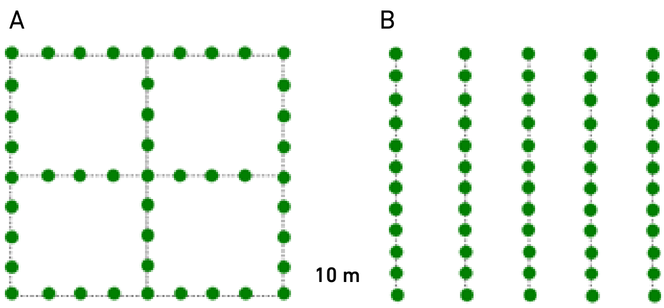


Figure 2. Planting designs of fruit trees on pastures: (a) low density in the dividing lines of the meadow plots, and (b) higher density along parallel lines throughout the meadow.

production suffers greatly. The first key aspect is to carry out periodic reviews to **identify possible pests or diseases** and, if they appear, establish the methods to act against them. The second fundamental aspect is **pruning**. The best time to prune fruit trees is in late winter when the first shoots have not yet appeared, or just after the fruit is picked. It takes quite a bit of experience to prune trees well, especially in tree shape formation pruning, which is done during the first few years, or fruiting pruning to prepare the tree for the following year's harvest, which is done every year.

Figure 3. Young walnut with individual protection against the herbivory of cattle on the Planeses farm. Photo: Marc Gràcia.

Installing and caring for pasture

A quality pasture can take several years to form, and requires a series of steps to develop adequately:

- **Adequacy of the area and soil preparation.** The area must be adapted by removing all stones, logs and other debris that hinder the establishment of the pasture. The soil must be moderately humid to facilitate adequacy works.

- **Control of the vegetation present**. Before planting, the vegetation present in the area must be removed. This can be eliminated mechanically, using hammer brush cutters, or using livestock to graze the vegetation to be removed.

- **Sowing the pasture**. Whenever possible, sowing should be done with a **direct seeding** seeder machine. If this is not possible, broadcast sowing is done, but trying to do it at the time of year when the seeds will have maximum protection. The ideal time to distribute the seeds in the field is in autumn because the seeds will be able to maintain humidity for longer. In addition, in winter the plant does not grow in the aerial part, but it does in the underground part. The biggest problem at this time is that the seeds can be preyed upon by flocks of birds. **The combination of species to be sown depends on the climate in the area and the farm's needs**. In this seed mixture the following is recommended: (**i**) plant species that grow fast, (**ii**) include some legume, and (**iii**) introduce species such as rye (with a very dense root system) that allow better control of adventitious plants.

- **Irrigation of recently established plants**. Seedlings in their early stages are very susceptible to a lack of water. For this reason, if it does not rain enough in the first few days, if water is available and it is possible to install an irrigation system without high costs, it is best to irrigate the surface of the future pasture until the new seedlings are properly established.

- **Reseed if necessary**. On occasion, especially when the seeds have not been well protected, sowing results in a pasture with a very low coverage (less than 4-6 plants per m^2). In these cases, the pasture should be reseeded, focusing on areas where the pasture has more patches without vegetation, and reviewing the factors that prevented adequate initial germination.

- **Control of resprouting species.** When the new grass plants are installed, the cattle go into the pasture. But if many sprouts of shrubs or trees have appeared, just after the livestock leaves the plot these sprouts that the livestock do not consume should be cleared with a manual brush cutter.

From then on, livestock management should consolidate and improve the pasture. If at first there is not enough food for cattle, the feeding should be completed in the plots, because this food ends up improving the fertility of the plot. **The basis of good pasture is correct management of the cattle that graze on it.**

Benefits of integrated management of fruit trees on pasture

Managing fruit trees on pasture has clear benefits both for the environment and for the agricultural farms that carry it out.

• In different agroforestry studies, **a positive synergistic relationship has been seen between fruit trees and pastures** in relation to soil water content and nutrient retention.
• The presence of trees in the meadow **increases the total carbon stored on the farm,** both in the soil and in the vegetation.
• Biodiversity in integrated fruit tree and pasture systems also **increases.**
• **Trees provide shade for livestock** when they grow.
• **Livestock droppings help improve soil fertility** for fruit trees.
• The integrated management of fruit trees and livestock in the pasture increases income and **improves the profitability of farms.**

Managing an orchard without tillage. I. Design, roads, terraces, irrigation system, planting

In a garden without tillage, all structures can be permanent, they can be maintained from one year to the next. The lines consist of a series of elements: the permanent path to move around, the groove through which the main hose passes (which is usually filled with BRF or compost), and the two rows of crop plants. Planting is a slow process, because the soil is not loose and often requires tools, such as a double-handled pitchfork, to facilitate opening the holes to plant in.

Managing a non-tillage garden

The main characteristic that defines the orchard management proposed is the fact that the soil is not tilled. This basically implies leaving the soil intact, so that **its structure is not broken and its biological activity is much better maintained**. An important advantage of this system is that the orchard's structures can be maintained from one year to the next, but other aspects such as planting the crops or removing adventitious plants require more effort. In this sheet and in the next one ('Management of a garden without tillage II: control of adventitious plants, use of forest products, biofertilisers, fertilisers, grazing), the different aspects of managing a garden with these characteristics are described.

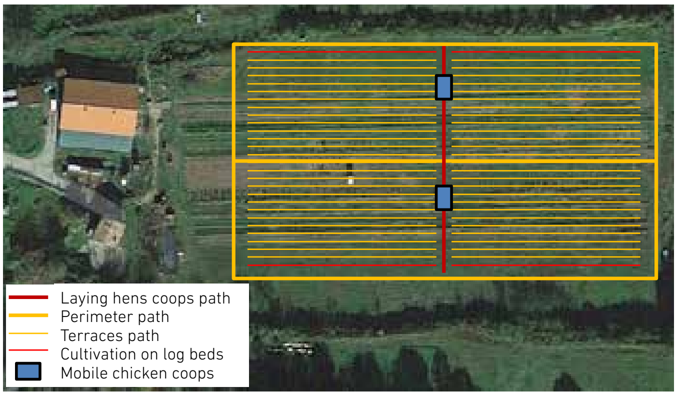


Figure 1. Distribution of the different elements of the Planeses garden.

Orchard design according to the Planeses model

When designing a **non-tillage orchard**, the **Planeses farm** garden will be used as a model (**Figure 1**). The aspects described below must be adapted in each case to the characteristics of the orchard to be designed.

In this type of orchard **all the structures can be permanent** because they are not carved. The design can be maintained from one year to another, including large and small paths, irrigation structures or stakes for supporting plants that need them.

The main elements of the Planeses garden are:

• The garden has a **large perimeter system** and central roads to be able to move around easily and facilitate movement with loads of the various materials that must be transported in the garden: BRF, plants and the different crops obtained from the garden.

• The garden has a **central transversal path where two mobile laying hens coops are located**. In this way**,** the coops can move every day up to the height of the crop lines, to the area where it has been decided that it is more appropriate for the chickens to graze. **Meshes are placed from the hen house to enclose several crop lines**. At night the hens are locked in the hen house again.

• The Planeses orchard has been designed with 1 m wide lines arranged in an east-west direction. The lines are limited by **small permanent paths 0.5 m wide**. In this way, the entire line can easily be accessed from the path. With adapted trolleys with the wheels width separated by 1.2 m, it is possible to circulate through the garden, passing over the lines when there are no tall plants**. The orchard consists of 100 lines 75 m long**.

• The **lines with cultivation on log beds** have been located at the limits of the orchard to limit them from interfering with annual planting as much as possible.

System of crop lines

To avoid compaction and maintain the soil structure**, it is important to tread on the growing areas**, which are the crop lines, as little as possible. For this reason, it is necessary to design the lines with a system of small permanent paths that allows, on the one hand, all the growing areas to be reached without having to step on them and, on the other, facilitated movement with the loads of the various materials that have to be transported. Each line consists of a series of elements (**Figure 2**): **the permanent path** through which the orchard workers can move, the furrow (in our case 7 cm x 7 cm) through which the main hose passes that delivers the water to the plants, the substrate (which can be BRF or compost) that covers the hose from the insulation, and the **two rows of crop plants**.

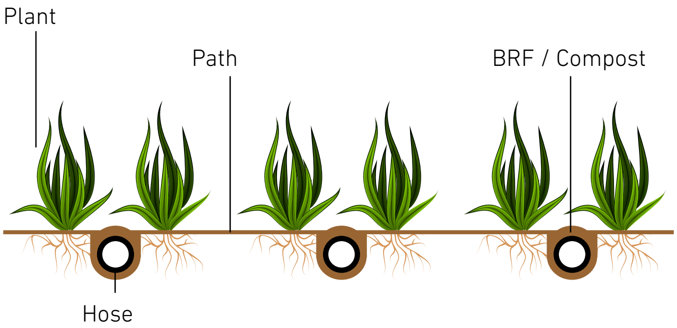


Figure 2. Scheme of the elements that make up a crop line in the garden.

Irrigation system

For an orchard to work properly, an irrigation system that allows water to be supplied efficiently is very important. In the Polyfarming system, the irrigation system is also intended to be used to make an efficient contribution of microorganisms and biofertilisers through the water. For this reason, **it is not possible to use a standard drip system**, which gets clogged immediately, and a system with water outlets that are not clogged with the particles present from the products used should be used.

The system used in Planeses **irrigates by gravity**, without water pressure, and the outlet holes must be large enough so that they are not blocked by the products used or by the lime in the water (**Figure 3**). The irrigation starts from the central path, with a 63 mm pipe from which the **smallest 40-mm hoses emerge for each line**. These secondary hoses have 4-mm perforations every 50 cm. In each case, we must calculate the maximum distance that a hose will accept for water to flow out of all the holes. For the Planeses garden, this distance is 70 m. It must also be calculated how many 70-m irrigation hoses can be fed with the main hose, in the case of Planeses there are 4-5, that is, with the required flow rates, up to 5 lines can be irrigated at the same time.

The irrigation hoses of the crop lines take out jets of water, the objective is for it to remain in the centre of the line. To do this, a ditch is made into which the water falls and is well distributed. The amount of water that comes out of each hole varies, but the trench allows it to be compensated. For this reason, **it is best to fill the trench with BRF or compost**, since this way the water does not escape and the hose is also protected from the sun and does not suffer expansions associated with heating by insulation. The irrigation time varies depending on the system used, in the case of Planeses it is between 20-30 min per line.

Figure 3. Distribution of the irrigation hoses in the crop lines of the Planeses garden. Photo: Ángela Justamante.

Planting

When planting is about to start, the first thing to do is dig up the hoses from the beds and check that water comes out of all the holes, which can be unclogged with a wire. Then the hose is put back in the trench and covered with BRF or compost.

Planting is a **slow process** because a planter cannot be used, **as the soil is not loose**, it is not ploughed. Therefore, the holes where to place the plants must be made individually. There are various tools to facilitate this process. An alternative is to use a double-handled pitchfork, which allows a crack in the ground by nailing it and moving it back and forth. The plant is placed at crack height. With this method, **the water reaches the plant more easily** and an aeration line is opened, which allows greater biological activity of the soil.

It is very important to plant following straight lines and correct distances, as this facilitates the adventitious plants cutting process, as cultivated plants are more easily located. On the other hand, in this type of orchard the soil is more structured and has more organic matter, so the moisture bubble that extends from the tube by capillarity has a shorter reach. This implies that **the plants must be placed closer to the trench** than with the traditional system.

Managing an orchard without tillage. II. control of adventitious plants, use of forest products, biofertilisers, manure and grazing

When managing an orchard without tillage, it is essential to control adventitious plants, from which the aerial part must be cut and left as organic matter in the soil. Other contributions of organic matter can be obtained from forest resources in the form of BRF, biochar or log beds, and using vegetable manures, both green and dry. Biofertilisers are also used to provide essential nutrients at different times in the crop cycle. The garden's function is completed with the presence of animals, such as laying hens.

The **transformation to an orchard without** tillage improves the content of organic matter and the **structure of the soil**, cutting fertilisation and water consumption costs. This conversion **requires a significant contribution of organic matter**, which can be obtained from forest resources in the form of **BRF**, **biochar** or **log beds**, and using **vegetable manures**, both green and dry, to improve soil fertility. Biofertilisers are also used to promote crop growth, and **good management of adventitious plants is essential**.

Controlling adventitious plants

Controlling adventitious plants is one of the most expensive jobs in managing a garden without tillage but, unlike a conventional garden, it is a job that has a **double benefit**: on the one hand, it encourages the arrival of light to crops and, on the other hand, it is a way of returning organic matter to the soil. In an untilled orchard one of the important characteristics is the presence of continuous soil cover (in space and time) (**Figure 1**). Therefore, plants are never uprooted. Adventitious plants **are managed by cutting the aerial part and using different covering systems** that reduce their growth, such as pre-composted BRF covers, straw and other plant materials. One of the objectives is to change the composition of these adventitious plants, in this way they will end up dominating the legumes, which will provide an important input of nitrogen to the orchard.

Depending on where the adventitious plants appear, they will be managed differently. Plants that **come out on main roads can be left**, only if they are too tall for the crops are, they then cut to incorporate them as green manure or as straw. **The adventitious plants that are in the paths of the crop lines are cut with a brush cutter**. Plants that come out in the ditch or between crops should be removed with small tools such as scissors so as not to disturb the crops.

There are **two criteria to decide when the best time to cut adventitious plants** is: (**1**) just before they begin to harm crops, especially due to competition for light, since, in principle, if there is irrigation there are no water problems; and (**2**) when, from a practical point of view, they are easy to eliminate, given that at a certain moment they start to grow a lot and it costs more to remove them.

Figure 1. In the non-tillage garden, crops and adventitious plants coexist. Photo: Ángela Justamante.

Use of forest products to improve crop production

A series of products can be obtained from the remains of forest harvesting, which are used to improve the production of crops in the garden.

• **BRF.** BRF is the **chipping of small branches from trees**, which are left in the forest or in the field for a few months in which they undergo a fungal decomposition process led by basidiomycetes. Thus, a precomposed BRF is achieved that is a stable, long-lasting humus. The BRF can contribute to the orchard in two ways: (**i**) in the Polyfarming system, it is applied in the **trenches of the crop lines**, covering the hoses from insulation; (**ii**) it can also be applied superficially without any work on the soil, providing a layer about 5 cm thick over the entire surface of the orchard. As it is a significant amount of BRF, this contribution is made by areas, so that every 4-5 years the entire orchard is covered with BRF and the process is restarted.

• **Biochar**. Biochar, **a charcoal** produced from the pyrolysis of vegetable biomass, **improves the structure of the soil**. It is not applied directly in the garden, but it is previously activated, i.e. it is loaded with nutrients and microorganisms that are actually used by plants. This activation is achieved by incorporating the biochar into the chick litter. Like BRF, the compost that is obtained is applied in the trenches of the crop lines, covering the hoses. This is how it is done in the farm where the Polyfarming system is applied, Planeses (Girona, Catalonia). Biochar can also be applied directly to the soil in the garden.

• **Cultivation on log beds.** Cultivation on log beds supposes a very important incorporation of carbon into the soil, at the same time as allowing to **retain water** and **create areas with a lot of biological activity**. This technique is mainly used for planting multi-annual and permanent species. The design of the orchard must take into account that these areas cannot be passed with the transport systems used in the crop lines, so they are normally **placed at the ends of the orchard**.

Biofertilisers

Biofertilisers are fertilisers of different origins that **serve to nourish and strengthen plants,** without blocking the biological processes that occur in a healthy soil. All crops go through different stages of growth, flowering and fruiting. At each moment of the cycle, plants have nutrient needs that should be favoured. Thus, in the **vegetative period**, when plants develop roots and stems, they require mainly **carbohydrates and nitrogen**. This is especially important in the weeks after planting, because the roots of the plant are still limited in growth and do not benefit from the natural fertility of the soil. At the time of flowering they need phosphorus compounds. In the period of **growth and maturation of fruits**, plants accumulate carbohydrates, and need potassium to develop their colour. For plants to obtain all these nutrients, it is necessary to supply **different types of biofertilisers**.

Vegetable manures

Chemical fertilisers are not used in regenerative agriculture. However, the orchard has a high production and, therefore, high outputs from the system that have to be compensated. **This requires gradually incorporating inputs** from the garden itself or from the farm's other uses. Different types of products can help fertilise the garden:

• First, dry or **crushed organic matter**, such as BRF, or **composted**, such as chick litter, is incorporated into the soil. This organic matter **helps to structure the soil**, since it will **gradually be available** to feed the crops, while it **favours** the aeration of the soil and the functioning of the trophic network.

• Another option is to **plant green manure** in the fall, which is cut in spring and left on the surface of the soil. If the sowings are legumes, such as white clover or alfalfa, an additional supply of nitrogen is also achieved.

• **The remains of crops and adventitious plants** that are cut are left green or dry on the ground and represent a contribution of organic matter without having to transport it from outside the orchard.

• Finally, the **excrements of the animals** that graze in the garden, such as chickens and ducks, can also contribute nutrients to the system.

Grazing with laying hens

To create a complete ecological system that encourages the garden to function animals should be present. Using animals in the garden contributes to controlling **adventitious plants**, **fertilisation with excrement** and the **elimination of insects, snails and slugs.** However, the risk of using animals in the garden is that they can eat the crops, especially just after planting. Therefore, animals should be chosen that have significant positive effects and whose negative effects can be easily controlled. Chickens and ducks can meet these requirements if the garden design allows them to be moved to where they are needed.

In Planeses the garden has a central north-south path. **Two mobile laying hens** coops are located on this path. During the night and part of the day, the hens are in the hen house, which is the space where food is given to them and where they lay their eggs. Every day the hen house moves up to the height of the crop lines where it has been decided that it is most appropriate for the hens to graze. Meshes are placed from the hen house that enclose two or three crop lines. Every day the hen house is opened so that the **hens can go out to these crop lines for 2-3 hours** (**Figure 2**). If they stay much longer, they may disturb the soil excessively and attack some crops such as cabbage, which they do not normally touch but which they could damage if they are there longer than indicated.

Figure 2. Laying hens grazing on the crop lines of the Planeses garden. Photo: MJ Broncano.

The Polyfarming system

Operation of the Polyfarming system

- Characterisation of the different elements of the Polyfarming system
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Characterisation of the different elements of the Polyfarming system

The Polyfarming system integrates the different uses at farm level: forestry, livestock and crops. Each of these uses can be broken down into several elements. Specifically, the Polyfarming system includes the following: forest, dehesa, pasture, extensive crops, fruit tree crops, garden crops, cows, calves for fattening, chickens, rabbits and hens. These different elements are described in this sheet based on a series of outstanding characteristics: the level of labour and mechanisation they require, and the time of year when they are most active.

Main elements of the Polyfarming system

The Polyfarming system **integrates the different uses at the farm level**: forestry, agriculture and livestock. Each one includes a series of elements that are combined or share products to ensure the integrated functioning of Polyfarming. Specifically, the elements that this system comprises are: forest, dehesa, pasture, extensive crops, woody or fruit crops, garden crops, cows, calves, chickens, rabbits and hens. They are described below in detail, **depending on the level of labour and mechanisation** they require and the time of year when they are most active. However, start-up requirements are not included and can be very high as they depend on the starting point.

- **Forest.** The level of **labour** required for the activities in the forest is **very important**, since forest management is based on the cutting, delimbing and dragging of trees outside the system. **Chainsaws** are used for the first two activities and a **tractor** is used to pull logs. The main activities in the forest are carried out in autumn and winter.

- **Dehesa.** The level of **labour** required to maintain dehesa is low: it includes the movement of animals when they are in it and, every four or five years, the replanting of areas where the pasture is not so good. Once established, the mechanisation **requirements are practically non-existent**. The activities that are carried out in dehesa are concentrated at times when the animals are present, mainly in winter, and occasionally in **summer**.

- **Pasture**. This element is key and interacts with the various animals. In general, the **level of labour** required once established is **low**, since it is maintained by grazing the animals (**Figure 1**). There is only clearing or reseeding works, but when the grass is well established, they should be scarce. The mechanisation required for these activities depends on the total area: if the area is large, a direct seeding seeder is required for reseeding, but if the area is small, sowing is performed manually. Similarly, at times of the year when there is a surplus, it should be mowed with a tool that is adapted to the conditions of the terrain and surface. This element works all year round, except in very cold times in winter or very dry in summer.

- **Extensive crops**. The level of **labour** required is **low-medium**, since it is concentrated at the time of sowing and harvest, for which the direct seeder and the combine harvester are used, respectively. **Fertility is maintained** by **incorporating the plant remains** of the species that grow in the field into the soil and the presence of legumes as nitrogen fixers. The activity period depends on the crops.

- **Fruit trees.** The **level of labour** required by fruit trees is **low-medium**: annual pruning, the application of biofertiliser treatments and a fruit harvest. **The level of mechanisation is low**, since the herbaceous layer under the fruit trees is normally eliminated with animals. If they are not available, then it must be done with a brush cutter.

- **Garden.** The **level of labour** required for garden crops is **very high**, including preparing the irrigation system, planting, adventitious plant control, the application of BRF, compost, fertilisers and biofertilisers and, above all, harvesting. In a regenerative system, without tillage or chemical fertilisers, **there is no mechanisation**, and fertilising the soil is maintained using products such as BRF, compost or wooden beds. The activity in the garden is concentrated in spring, summer and autumn.

- **Cows.** They have a **medium level of labour**, which includes the movement of the animals, their feeding with forage in the months when it is necessary, and, at least, one daily milking. Mechanisation **includes a stable for milking.** They are active all year round (**Figure 2**), like the rest of the animals.

- **Calves for fattening.** In general, they have a low labour force, since they only have to be moved between different plots of pasture, dehesa or forest. **They do not require any type of mechanisation**. They are active all year round.

- **Chickens.** In the Polyfarming system they require a **medium level of labour**, which includes moving the cages into the pasture and feeding the animals. To feed them, a tractor with a trailer is needed to transport the feed to the place where the cages are. They remain active throughout the year.

- **Rabbits.** In the Polyfarming system, the labour required by rabbits is **moving the cages into the meadow**. It does not require any mechanisation. This element remains active throughout the year.

- **Hens.** In the Polyfarming system, the only labour required by hens is their **feed**. Mechanisation is not required. They are kept **throughout the year**, although at certain times egg production decreases.

Table 1 summarises the main characteristics of the elements of the Polyfarming system. It can be seen that the **level of labour required** to maintain the elements varies from very high, as occurs in garden crops or in the forest, to low as in the dehesa, pasture or the different animals that are raised on it. In most systems, there is little or no mechanisation; only the forest and extensive crops require more machinery. Finally, the time of year when they are mainly active varies considerably. However, the overall functioning allows the Polyfarming system to have active elements throughout the year.

Figure 1. Pasture managed by animals in Planeses. This type of grassland requires very little labour. Photo: MJ Broncano.

Figure 2. Cows grazing following intensive programmed grazing in Planeses. Photo: Marc Gràcia.

Element	Level of labour required	Mechanisation	Time of year
Forest	**Very high:** cutting, delimbing, dragging	Tractor for hauling logs, chainsaw	Autumn, winter
Dehesa	**Low:** movement of animals, reseeding (every 4-5 years)	No	Winter, summer
Pasture	**Low:** movement of animals, clearing of unconsumed vegetation, reseeding, mowing when there is a surplus	For reseeding, direct seeder when the area is large. At times of the year when there is a surplus, it should be cut with a tool that adapts to the conditions of the terrain and surface.	All year round, except very cold periods in winter or very dry periods in summer
Extensive crops	**Low-medium:** sowing, harvesting	Direct seeding seeder, combine harvester	It depends on the crops
Fruit trees	**Low-Medium:** pruning, treatments, harvest	Elimination of the herbaceous layer with animals; if this is not possible, use a brush cutter	Spring, summer
Garden	**Very high:** irrigation, planting, control of adventitious plants, application of BRF, fertilisers and biofertilisers	No	Spring, summer, autumn
Cows	**Medium:** feeding, movement, milking	Milking stable	All year
Calves	**Low:** movement	No	All year
Chickens	**Medium:** movement, feeding	Tractor with trailer to transport food	All year
Rabbits	**Low:** movement	No	All year
Hens	**Low:** movement	No	All year

Table 1. Characteristics of the elements of the Polyfarming system: level of labour required, mechanisation and time of year when it is mainly active.

Combination of different elements: benefits of synergies between uses in Polyfarming

The Polyfarming system promotes combinations between forest resources, livestock and crops, based on at least two elements of different uses of the farm interacting in the same place. This sheet describes the different combinations that have been carried out in Polyfarming: grazing in the forest, fruit trees on pasture, cows on pasture, chickens on pasture, rabbits on pasture and chickens in the garden. Its benefits and disadvantages are also shown.

Combining at least two elements in the same place within the farm is always more complex, both in structure and on an economic or functioning level, than working with the elements separately. However, the Polyfarming system actively promotes these practices, since they give rise to **important synergies** and only have some disadvantages, which can be resolved. In Agroforestry, the combination requires trees to be included with agricultural crops and/or livestock simultaneously or sequentially (Mosquera-Losada et al 2009). However, in Polyfarming we include any combination that includes two individual elements, whether there are trees or not.

Figure 1. In Planeses (Girona), where the Polyfarming system is implemented. Cows obtain a large part of their feed from pasture. Photo: MJ Broncano.

Combinations of different Polyfarming elements

- **Grazing in the forest.** According to Casals et al. (2009), forest grazing has historically been practiced in Mediterranean and montane forests and has usually been linked to a mountainous topography, in which the forest serves to maximise existing resources. In the Polyfarming system, cattle grazing in the forest takes place at times of the year when there is little food, **usually in winter or summer**. The resources provided by the forest are of lower quality than those provided by forage grasses. In Polyfarming, the cows, which are used to obtain milk, are not taken to the forest, whereas the calves that are raised to produce meat are taken to the forest at times of the year when grass is not abundant.
- **Fruit trees on pasture.** Fruit tree management in combination with pastures is one of the most **widespread agroforestry systems**. The trees can be fruit trees or high-quality wood and are distributed on the boundaries of pasture plots or in rows along the field. These trees are combined with grasses that can be cut down and used as forage or grazed directly by animals. If there are cattle, the fruit trees have to be protected during the first years, and they create better shade so that the cattle can protect themselves from the heat in summer.
- **Cows on pasture.** Pasture cow grazing developed in Polyfarming is characterised by using **high stocking densities in small spaces** with a very short stay and a very long recovery period. Each day, the herd of cows moves from the field in which it is located to another that is at the optimum grazing point, which is just before the plants reach maturity. Cows are herbivorous animals and, for a good part of the year, much of their food is obtained directly from the pasture (**Figure 1**).
- **Chickens on pasture.** The combination of chickens and pasture is found in a pasture divided into corridors, through which the **animals are moved daily** by means of a system of fences and mobile shelters. In this way, the chickens enjoy new pasture every day and, at the same time, the chickens' own movement activity allows the **pasture to be maintained at no additional cost.** Chickens consume a lot of grass and seeds, and they also get high amounts of live protein in the form of earthworms and meadow insects.
- **Rabbits on pasture.** The combination of rabbits and pasture is similar to the previous combination. In this case, rabbits feed almost exclusively on grass, since their **diet is 100% herbivorous**. As in the previous case, the rabbits move daily to patches distributed in the pasture by means of a system of fences and mobile shelters that do not require heavy machinery. The pasture is greatly impacted when the animals are present, but, after they have moved on, the plots have a long time to recover.
- **Hens in the garden.** The use of animals in an orchard can favour its functioning, since it creates a more complete ecological system. Using animals in the garden **contributes to adventitious plant control, fertilisation with excrement and the elimination of pests**, but runs the risk of them eating or damaging the crops. In Planeses, the hens are in the hen house at night and part of the day. The hen house is moved to the area where it has been decided that the hens will graze and meshes are placed to enclose some terraces where the hens stay for several hours.

Advantages and disadvantages of the different combinations

In general, the benefits of combining the different elements are very high, although some disadvantages must also be considered (**Table 1**).

Combination	Benefits	Disadvantages
Grazing in the forest	• Beef cattle and horses **adapt well to mountainous topography** and lower quality food sources provided by the forest at times of year when no other food is available. • **Calves** (or beef cows if applicable) consume felling waste and help **maintain the understory**, reducing vulnerability to fire. • The presence of animals in the forest facilitates the decomposition and **incorporation of logging remains in the soil**, improving its fertility. • Feeding of calves or cows in the forest **reduces the cost** of buying feed at times when no other resources are available.	• **Dairy cows cannot be brought into the forest** because their feed requirements cannot be met by forest resources. • It is not practical to keep cows in the forest if they need to be milked in the stable every day.
Fruit trees on pasture	• The presence of trees in the meadow **increases the total carbon stored** on the farm, both in the soil and in the plants. • **Biodiversity** in integrated fruit tree and pasture systems also increases due to the presence of more soil organisms under the trees. • Trees, when they grow, provide **shade for livestock** that feed on the pasture. • Livestock excrement helps to **improve soil fertility** in the area of fruit trees. • The integrated management of fruit trees and pastures **generates more income** and improves the profitability of farms.	• Fruit trees and pasture use **common resources** such as nutrients and water, so competition can be established between them. • If there are animals feeding on the pasture, **protection is required for the fruit trees**. • In general, it is necessary to wait several years to reach maximum fruit tree production. During this time, the fruit trees need various types of care without providing a significant benefit.
Cows on pasture	• The cows' own movement activity allows the **pasture to be maintained** without additional costs. • In this way, the **pasture produces the maximum** for each season and the animals consume it at the best time. • Livestock excrement helps **improve soil fertility** by increasing organic matter and nutrients. • Animals don't spend long on the plot to avoid having a compaction effect on the soil. • This system produces meat and milk with a **higher nutritional value** than the conventional system.	• The system requires a **large area** to place the plots so that it can function for much of the year. • In a system divided into plots **it can be limiting** and complicated to bring water to each plot.
Chicken on pasture	• Chickens get **30-40% of their diet from the pasture**, both grass and insects or seeds. • This system favours the **control of crop pests**, since chickens consume many insects that can be harmful. • Their presence in the pasture helps to **prevent chicken diseases** and practically eliminates the use of drugs. • Chickens help to regenerate the soil and obtain quality pastures thanks to their droppings. • Animals have a permanently **healthy environment** with fresh grass every day. • The system makes it possible to produce chickens with a **high nutritional value.** • With the chicken-pasture system, the profitability of the farm increases, because the equipment and functioning of the system only requires a **small investment**.	• When chickens get older, their droppings make the pasture dirtier, so it will take longer for them to return to the same plot. • Chickens do not normally consume all the grass and, once they have moved on, it is often best to **clear the pasture to even out the grass**. • Under these conditions, chickens are more **susceptible to predation** by birds of prey and mammals such as foxes.
Rabbits on pasture	• Rabbits get almost **100% of their diet from the pasture**. • They have a permanently healthy environment with **fresh grass every day**. • Raising rabbits in the meadow **reduces, almost eliminates, the use of antibiotics** and only vaccines are used for viral diseases. • The rabbit meat obtained has a **high nutritional value**, with a higher content of vitamins (A, D and K) and quality fats (Omega 3). • The investment required to put this system into operation is small compared to conventional projects.	• Rabbits in these conditions are **exposed to predators,** so they must be well protected, even from the dogs that watch in the field. • Rabbits are also very **exposed to inclement weather**, so shelters must be designed to be able to protect them sufficiently.
Hens in the garden	• The presence of hens helps to **eliminate insects and pests** that are harmful to crops. • Hens also help **reduce the presence of adventitious plants**. • The excrement of the hens contributes to **fertilising the garden**.	• If they remain in the garden for a long time, the hens can **disturb the soil excessively** and attack some crops. • After planting, it is not a good idea to put hens in the garden because they **step on and damage the plants**.

Table 1. Main benefits and disadvantages of the different combinations of elements of the Polyfarming system.

Complementarity of products and labour between uses in Polyfarming

The Polyfarming system proposes an integrated system of forestry, livestock and agricultural uses (including fruit trees and orchards) that interact and complement each other. At farm level, this is achieved through: a) a complementarity of products that (i) cuts costs, since what is left over from one use is applied to another, and (ii) obtains more products in the same area; and b) a complementarity of jobs and labour, since (i) if a job in the same place serves two activities at the same time, the costs go down, and (ii) if the labour can be shared temporarily performance is much more optimised.

The integrated system that Polyfarming proposes requires a precise knowledge of each exploitation: what elements it produces, what labour it requires and when it is needed. At farm level, the spatial and temporal planning of the different uses makes it possible to complement **products and labour** (**Figure 1**), with the aim of reducing the necessary external resources and production costs and increase the efficiency of the system.

Figure 1. Polyfarming worker at the Planeses farm (Catalonia), where the Polyfarming system is implemented. Photo: Ángela Justamante.

Complementarity of products

Combinations connecting various uses at farm level almost always led to significant synergies. Among them, the **complementary of products** that are obtained stands out, which offers two great advantages:

a) It allows cost savings, since the external resources for the functioning of a certain use are obtained without a cost from the resources generated by other uses, which leads to a reduction in the farm's costs.

b) It allows to more products to be obtained in the same area: fruit and meat, forage and milk, vegetables and eggs, etc. Obtaining different products in the same area requires some extra work, such as protecting the fruit trees from the livestock, but there are also additional benefits, such as fertilizing the soil with animal droppings.

Table 1 shows the **complementarity of products between different uses.** These products of one use applied to another use r**educe the farm's overall costs.** Examples of this are the forest trunks that are used to make log beds in the crops, the BRF and biochar to make the compost of the garden, forest leaves and pasture for feeding the animals, or grain and forage of the extensive crops for feeding chickens and cows. There are also more intangible 'products', such as the shade of fruit trees for livestock, livestock excrement as fertilisers for the pasture soil or the removal of the understory of the forest to reduce the risk of fire.

		Receives			
		Forest	Livestock	Fruit trees and pasture	Garden and extensive crops
Contributes	Forest		It provides material (stakes) for mounting the fences. It allows feeding of calves in months of scarce resources.	It provides material for electric fences and the protection of fruit trees. It provides logs for wooden beds.	It provides logs for crops on wooden beds. It produces BRF and biochar to form compost that is applied to the garden.
	Livestock	It manages the understory to facilitate access and reduce the risk of fire.		It allows the pasture to be maintained without external inputs. It maintains soil fertility with its excrement	It activates BRF and biochar that are used as compost in the garden. It helps to eliminate pests and weeds in the garden (hens).
	Fruit trees and pasture	--	They offer pasture for livestock. They provide shade at warmer times of the year.		--
	Garden and extensive crops	--	They contribute to the feeding of the hens. They produce grain and fodder for chickens and cows.	--	

Table 1. Complementarity of products between the different uses.

In Polyfarming, there can also be **complementarities even with the same use**. Some examples would be: (i) the presence of legumes in the pasture increases nitrogen fertilisation of fruit trees; (ii) the successive presence of cows and calves in the pasture makes it possible to obtain **milk and meat in the same area**; (iii) the first presence of rabbits (herbivores) and then chickens (omnivores) in the same pasture helps to manage it better, **obtaining two different products**; (iv) in cereal crops on permanent pastures (pasture cropping) the **grain of the cereals and the forage of the pastures are obtained with the same use.**

Complementarity of jobs and labour

In the Polyfarming system, work and **labour complement each other in time and space**. This entails clear benefits at farm level: a) if a job performed for one activity also serves another at the same time, overall costs are reduced; b) if labour can be temporarily shared between uses, **resources are optimised**. For this reason, it is essential to analyse what labour is needed and when it should work in the different activities of the farm.

Table 2 summarises the calendar of the need for labour in the different activities of the different uses throughout the year. **The activities of the forest and the orchard can be seasonally compatible** since, due to legal limitations, **the activities in the forest can only be carried out in the months without a risk of fire** (from November to March), while in the orchard, the labour force is important from April to November. However, both uses require a large amount of labour concentrated over time: in the forest a minimum of two people working is required, while in an orchard like that of Planeses (around 1.5 ha), it takes between 2 and 3 workers throughout the day. **The activities of livestock and fruit trees are compatible daily**, since they are located in the same area and do not occupy the whole day. In the case of fruit trees, significant labour is required at key times, such as pruning or harvesting. In the case of cattle, labour is essential throughout the year (**Table 2**) and every day. Total daily dedication depends on the types of animals on each farm, rather than the number of animals of each type: thus, the daily work required to move a herd of 10 cows is not very different from that required to move one of 60.

ACTIVITY	J	F	M	A	M	J	J	A	S	O	N	D
Forest exploitation	■	■	■								■	■
BRF production	■	■	■								■	■
Biochar production	■	■	■								■	■
Production of biofertilisers												
Calf management in the dehesa	■	■	■					■	■			
Cow movement and feeding	■	■	■	■	■	■	■	■	■	■	■	■
Milking cows and collecting milk	■	■	■	■	■	■	■	■	■	■	■	■
Calf movement in the pasture				■	■	■	■			■	■	■
Rabbit movement	■	■	■	■	■	■	■	■	■	■	■	■
Collection of rabbits for sale	■	■	■	■	■	■	■	■	■	■	■	■
Chicken movement and feeding	■	■	■	■	■	■	■	■	■	■	■	■
Collection of chickens for sale	■	■	■	■	■	■	■	■	■	■	■	■
Hen movement and feeding	■	■	■	■	■	■	■	■	■	■	■	■
Egg collection	■	■	■	■	■	■	■	■	■	■	■	■
Fruit tree pruning										■	■	
Fruit tree treatments and monitoring		■	■	■	■	■	■					
Harvesting the fruit of fruit trees								■	■			
Sowing extensive crops								■	■			
Grain harvest in extensive crops				■	■							
Forage harvest in extensive crops				■								
Irrigation preparation for the garden				■	■	■	■	■	■			
Garden planting				■	■	■	■	■	■	■	■	
Removal of adventitious plants from the garden				■	■	■	■	■	■	■	■	
Biofertiliser and manure application						■	■	■	■	■	■	■
Harvesting the products from the garden						■	■	■	■	■	■	■

Table 2. Calendar of the need for labour in the different activities throughout the year at the Planeses farm.

Flows and integration between uses in the Polyfarming system

The functioning of the Polyfarming system as a whole is based on integrating the different elements of the forest, livestock and crops. The flows that are established within and between them, including the production and return of materials within each one and the movement of products between elements, compensate the outputs of the system. The products of the Polyfarming system include the final products for consumption (or outputs), such as firewood, fruits or meat; intermediate products to apply to other elements, such as biochar, grass or forage; and external inputs to the system that cannot be produced in it, such as feed, seedlings or seeds.

Flows in the different elements of the Polyfarming system

The basis of the Polyfarming system is the functioning of the different elements as a whole. For this, the flows established in each of them must be understood, which include: (i) the **production of vegetables** (trees, pastures and crops) from solar energy, (ii) the **return of materials** within each element (both dead plant matter and animal excrement), (iii) **system outputs** (products obtained from different uses), (iv) **movement of products between elements**, as a result of putting the Polyfarming system into operation, and (v) the **external inputs to the system** which, with the Polyfarming system, are greatly reduced.

• **Forest**. In the forest there are no inputs from other elements. The main input is the production of trees, which is performed by CO_2 in the atmosphere and nutrients and water in the soil. The cycle is mainly closed internally with the return of the leaves to the ground. **Wood extraction** represents an export of biomass, which, if carried out without destroying the conditions of the system, recovers naturally. In the Polyfarming system, there are also **BRF and biochar outlets** (**Figure 1**), **large logs** for the trunk beds and **humus** from the forest floor to obtain biofertilisers, but in the model proposed they are small outputs in general.
• **Dehesa.** It is an element where the only input derived is from the **biomass production of trees** and pastures that may exist. The return of materials mainly occurs through the leaves and other plant parts that die and decompose. The outputs of the system are very scarce, since the calves that graze consume leaves, but deposit their excrement in the same area.
• **Pasture.** The main production of pasture accumulates in the soil. When the meadow is established, there are almost no other inputs from outside the system, **the only input is the forage** that can be given to the animals at certain times, as long as it is not from the farm. The cycle is closed by the return of the biomass consumed by the animals through excrement. If management is carried out respecting the functioning principles of the meadow (management of the herbivorous plant relationship) and all its elements (including the presence of decomposing beetles), **the system recovers naturally** from the outputs linked to the harvesting (meat, milk, etc.).

Figure 1. Pile of BRF, a product obtained from the forest. and applied to the garden. Photo: MJ Broncano.

• **Extensive crops.** In principle, the only input is the seeds for sowing, since crop fertility is maintained by the incorporation into the soil of plant remains of the species that grow in the field and the presence of legumes as nitrogen fixers. This is carried out with the use of species associations and rotations, such as those carried out with the **Fukuoka method and that of cereal crops on permanent pastures** (pasture cropping), which are described in the sheet "Combining crops in terms of time and space for greater production and the biological activity of the system". The main output is the grain of the cereals, which is used to feed the chickens, and the forage, which is normally used to feed the cows in the months when there is not enough grass in the meadow.
• **Fruit trees.** The basic input of fruit trees is **plant production from CO_2**, water and nutrients from the soil, and their main output is the fruits they produce. Their combination with grasses, where there are legumes, increases the amount of nutrients available to fruit trees without additional inputs, and this is also achieved by placing wooden beds from the forest in the planting hole at the time of installation. Different biofertilisers with invigorating and insecticidal effects are usually applied to achieve quality fruits.
• **Garden.** The garden is an intensive element that is maintained by the contribution **of external carbon and nutrients,** since the outputs of vegetables are important. In a regenerative system, without tillage or agrochemicals, the intensive garden can be maintained with the addition of a significant amount of compost (obtained from BRF and biochar from the forest that are activated in the bed of the animals) that is then applied to crops (in many cases it is grown on compost). The main input is seedlings.

• **Cows and calves**. The diet of cows and calves is basically obtained from the meadow, where they also leave their excrement to maintain fertility. At certain times, the calves are taken to the dehesa or to the forest, where they mainly consume leaves and where they deposit excrement to maintain the fertility of the system. The only notable input is the **external forage** that is needed in a few months for the cows, provided that the farm is not capable of producing it itself. The main outputs are milk from cows and meat from calves.

• **Rabbits**. The diet of rabbits is completely herbivorous, so **they feed exclusively on the meadow** and do not require additional food inputs. The excrement that they release remains in the meadow itself, so that it does not impoverish its fertility, since the outputs in the form of meat are small compared to the internal cycle that is maintained.

• **Chickens**. Chickens obtain 30-40% of their diet from the meadow, so there are important inputs into the system in the form of **feed and grain.** Part of this grain can come from intensive crops, if they produce it in enough quantity. As in the case of rabbits, chicken droppings are released in the meadow itself, so that its fertility is maintained, which is not affected by the output in the form of meat.

• **Hens.** Hens spend part of the time in the garden, where they consume insects and grass. However, **their main food is grain**, which represents the main input in this case. Their output is the eggs produced.

Integration between uses: circulation of products in the Polyfarming system

To understand how the Polyfarming system works as a whole, integrating the different uses, it is necessary to identify the products that are introduced (**inputs**), and those that leave the system (**outputs**) or that **move between the different elements** (**Figure 2**). The products are the result of the use of a certain element, either as a final product for consumption or as an intermediate product to be applied to another element, or external inputs to the system that cannot be produced in it. In a model farm with the elements described in the "Characterisation of the different elements of the Polyfarming system" sheet, these products could be summarised as follows:

• The **final products** (**outputs**) of the system include: firewood, wood, fruits, vegetables, meat, milk and eggs.

• **Intermediate products** that move between different elements include: grass, forage, grain, leaves, biochar, BRF and wood beds.

• Finally, there are a series **of products from outside the system (inputs)**: seeds, seedlings, feed, forage and grain, the last two in case the internal production of the system is not sufficient as a whole.

The origin or destination of these products from the different elements identified in the Polyfarming system is represented in **Figure 2**, where the three main uses at the farm level are separated: forestry, agriculture and livestock.

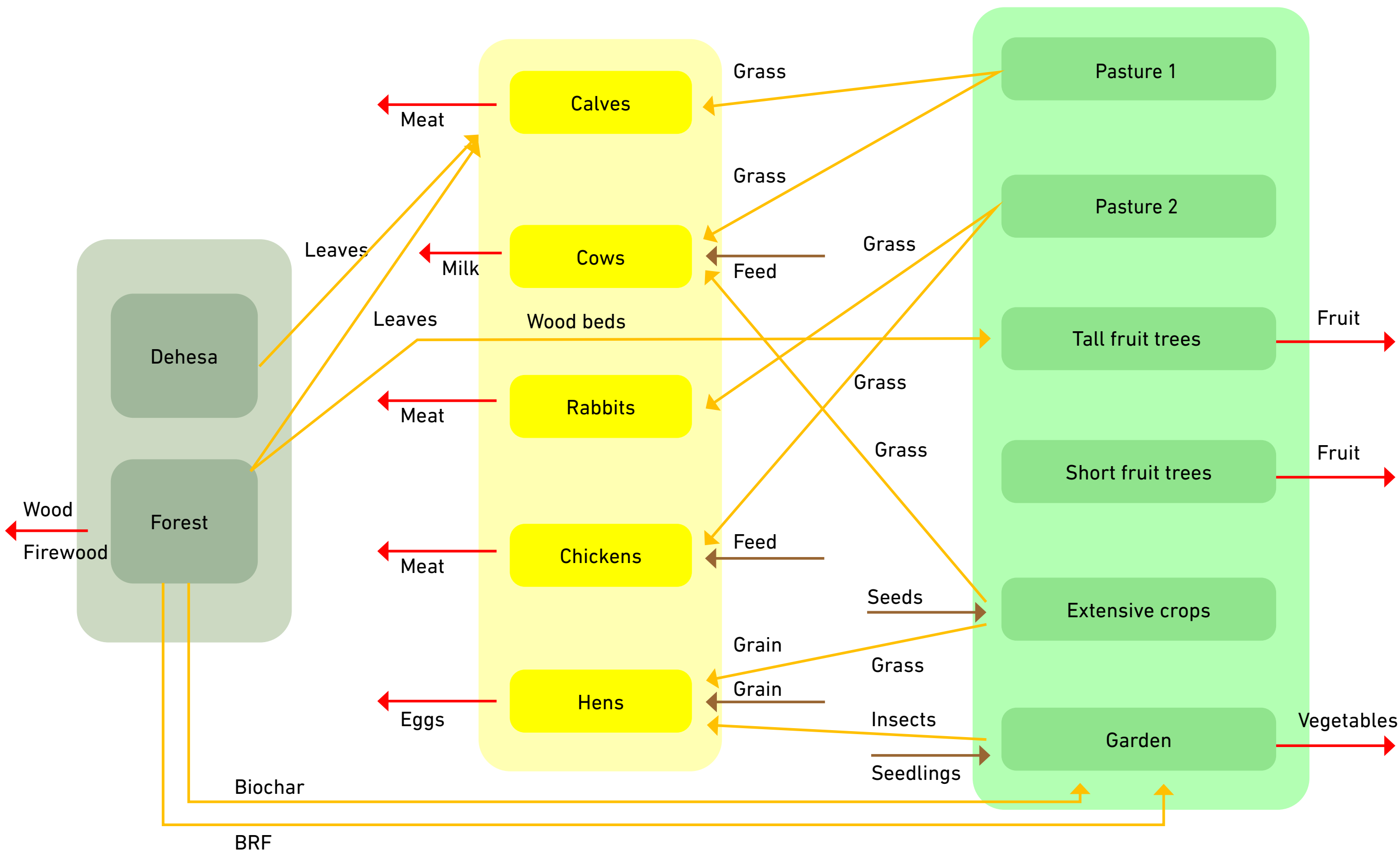

Figure 2. Circulation of products between the different elements of the Polyfarming system. Final products or outputs, red arrow; intermediate products between elements, orange arrow; products coming from outside or inputs, brown arrow. Uses: forestry (dark green), agricultural (light green) and livestock (yellow).

Lessons learned after the implementation of the Polyfarming system I. Forest, pastures and crops

From our own experience and from interactions with other researchers and producers, the Polyfarming team has acquired extensive knowledge over the years about each of the elements that intervene in the system and their joint functioning. This sheet summarises the main lessons learned about the forest, pastures and crops, including installation and functioning aspects and the combinations between elements.

Figure 1. Wood extraction works in the forest. Photo: AVVideo.

Lessons learned about the different elements of Polyfarming

This file summarises the most outstanding aspects and lessons learned after having applied different techniques of the Polyfarming system in the forest, pasture and crops, both woody and herbaceous. Thus, from the monitoring and studies carried out at the Planeses farm and taking advantage of the exchanges of valuable information with other researchers and producers, both ranchers, farmers and foresters, we have been able to extract the following lessons.

Forest

• The main characteristic that determines forest use is the **quality of the forest**. In low-quality forests, the intervention on the stand is of low intensity, with the aim of achieving a decrease in density. In high-quality forests, intervention on the stand is done by identifying the trees of the future and intervening to improve their growing conditions.
• Forest exploitation requires a **minimum of two full-time workers** during the winter months.
• The **network of tracks** is essential to determine if the exploitation is viable or not. If the network of tracks is not enough, clearing the logs may not be feasible.
• **Wood extraction** (**Figure 1**) represents an export of biomass, which if performed without destroying the conditions of the system is recovered naturally.
• In the Polyfarming system, there are also **BRF and biochar outlets** (obtained from the small branches), large logs for the wooden beds and humus from the forest floor to obtain biofertilisers.
• The resources provided by the forest for livestock are of lower quality than those provided by forage grasses, so it **plays a secondary role in feeding the animals**.

Dehesa

• **The density of trees** that must be left in an area destined for pasture must be low because otherwise it is difficult to establish the pasture in high shade conditions.
• The main problem with establishing a pasture in the dehesa is the **damage caused by wild boars**, which usually lift the soil where the pasture is beginning to settle.
• Even if there is no pasture, calves can do a good job of keeping the understory of the dehesa at low levels, if they visit it regularly.

Pasture

• **The initial installation** of pasture requires an adaptation of the terrain, weed control, seeding at the right time and

Figure 2. Garden without tillage in the farm Planeses. Photo: Ángela Justamante.

irrigation, when possible. Quality grass can take several years to form.
• When the pasture has been established, it is **livestock management that should consolidate and improve the pasture**. If the management is carried out respecting the functioning principles of the pasture, the system recovers in a natural way from the outputs linked to uses.
• With the **intensive grazing planned at specific times the pasture produces the maximum in each season.** Using this method, the grass is subjected to a significant impact when the animals are present, but once they have move on, the plots have a long time to recover.
• **The level of labour that the pasture requires once established is low,** since it is maintained by the grazing of animals and there is only minor clearing or reseeding work every several years.
• **A lack of water can be a limiting factor of the system,** since it conditions the growth of the pasture. At Planeses, depending on the annual rainfall, the cattle can pass through each plot up to seven times in rainy years and less than five in dry years.

Fruit trees on pasture

• Fruit trees are planted in spring and require a **good irrigation system** and individual protection for each tree.
• When there are livestock, **individual protection is essential for each tree**, in order to avoid damage that the animals may cause.
• When the animal used is large, **a tall fruit tree should be chosen, such as walnut, apple or chestnut trees**. When medium or small animals are used, the grazing height is not so high and shorter fruit trees can be planted.
• **Placing trunk beds at the base of the fruit trees during planting** improves the environment of the fruit trees, as logs offer a reserve of water and microorganisms to keep the soil alive and increase the soil carbon content.
• The fruit tree plantation should have an **extended irrigation system that drips into each tree**, especially in the first few years and later in drier seasons.

Extensive crops

• In extensive crops there are no outside inputs, because fertility is maintained with the **incorporation into the soil of the plant remains** of the species that grow in the field and the presence of legumes as nitrogen fixers.
• To achieve greater production and biological activity of the system, **associations and rotations of species are used in time and space**, such as that of cereal crops on permanent pastures with which cereal grain and pasture forage are obtained.

Garden without tillage

• An orchard without tillage (**Figure 2**) **improves the content of organic matter and the structure of the soil**, with a reduction in the cost of fertilisation and water consumption.
• In a no-till garden, **all structures can be permanent**, they can be maintained from one year to the next.
• The garden beds consist of a series of elements: the permanent path through which the garden workers can move, the groove through which the main hose passes that leads the water to the plants, and the two rows of plants of the crop.
• It is best to **fill the irrigation ditch with BRF or compost**, since this way the water does not escape and, in addition, the hose is protected from the sun.
• **Planting is a slow process** because a planter cannot be used, since the soil is not loose, it is not ploughed.
• **Adventitious plant control is one of the most expensive jobs** in managing a garden without tillage and is done only by cutting, without pulling the plants.
• The **contributions of organic matter** in an orchard without tillage are produced with the cut part of the adventitious plants, the BRF and biochar, and the vegetable fertilisers, both green and dry.

Lessons learned after the implementation of the Polyfarming system II. Animals and Polyfarming as a whole

This sheet summarizes the main lessons learned about the management of large and small animals, and about the Polyfarming system as a whole, including aspects of installation, operation and the combinations between elements. The application of a production system such as Polyfarming requires having examples of pilot farms that work according to this model.

Lessons learned about animal management and Polyfarming as a whole

This sheet summarises the most outstanding aspects and learning after having applied different techniques to managing large and small animals, and after having implemented the Polyfarming system as a whole. Thus, from the monitoring and studies carried out at the Planeses farm and taking advantage of the exchanges of valuable information with other researchers and producers, both ranchers, farmers and foresters, we have been able to extract the following lessons.

Figure 1. Cows on the Planeses farm. Photo: MJ Broncano.

Cow management through intensive controlled grazing

• Intensive controlled grazing is characterised by using **very high livestock densities in small spaces** (**Figure 1**) with a very short stay and a very long recovery period.
• It is essential to have **permanent plots** because it helps manage the system better and collect information in a much more precise way.
• In intensive controlled grazing, **cows only spend one day in each plot** and therefore do not have time to eat the sprouts of the first plants that were eaten, nor do they cause significant trampling compaction.
• In intensive controlled grazing**, the farmer can divide the herd into two smaller herds**, one with the highest nutritional needs (in this case, dairy cows), and the other with individuals with the least nutritional needs (calves for fattening). First, the herd with the highest nutritional requirements enters the plot and, once it leaves, the second herd enters for grazing it.
• With the intensive controlled grazing the cows consume the pasture at the best possible time at each time of the year.
• **The return time to the same plot varies**: in spring it usually takes around 25 days for the animals to return to it, while in summer and winter it takes longer, between 60 and 70 days.
• For the proper functioning of the system, there should be at least as many plots as days with the longest return period.
• Herd movements between plots can be daily or twice a day and the **animals can occupy an entire plot or only part of it**, depending on the state of the vegetation.
• Cows are herbivorous animals, so **they get all their food from plants**. During most of the year they must obtain it directly from the pasture, although in some months the grassland does not grow and they need to receive additional forage.

Managing calves for fattening

• Calves for fattening are normally **managed as a second herd**, which has less demands than cows, especially if they are dairy cows, and which enter the pasture plots behind them.
• Calves are **perfectly adapted to being in the forest and in the dehesa** during winter months. However, in these months their production decreases, since the resources they find available are not of the same quality as those of the pasture.
• **They have very low labour requirements**, as they only have to be moved between different plots of pasture, dehesa or forest.

Managing rabbits on pasture

• **Rabbit fattening is exclusively carried out in the pasture**, since their diet is 100% herbivorous.
• **Shelters should protect animals** from bad weather and predators, and should **be easy to move around**.
• Animals are kept in a delimited plot of the pasture, with a high density, but only for one or two days (depending on the time of year). The time it takes to return to the same plot can vary between 60 and 80 days.
• **It is much more profitable to raise one's own young**

Figure 2. Mobile shelters for chickens placed in the meadow of the Planeses farm. Photo: MJ Broncano.

Figure 3. Hen house located next to the garden. Hens are allowed to go out to the terraces every day for two or three hours at the Planeses farm. Photo: Ángela Justamante.

rabbits on the farm than to buy them, as it requires minimal setup for both females and males.
• With this type of management, **it is the use of antibiotics is virtually unnecessary** and only vaccines are used for viral diseases.

Managing chickens on pasture

• Chickens are omnivores, in the meadow they consume a lot of grass and seeds, and they also obtain high amounts of live protein in the form of worms and insects.
• Chickens are managed in a **pasture divided into corridors that allow the animals to be moved daily** through a system of fences and mobile shelters (**Figure 2**).
• For a batch of **400 chickens in a 60-day rotation**, an area of approximately **1 ha** is considered adequate.
• Chickens are susceptible to predation by birds of prey and some mammals such as foxes. A good way to protect them is to **place an electric shepherd around the enclosure** and have trained dogs in the field.
• With this system, chicken production with a high nutritional value is obtained.

Managing hens in the garden

• The presence of hens in the garden (**Figure 3**) **contributes to adventitious plant control**, fertilisation with excrement and the elimination of pests.
• The hens can go out to the garden beds every day for a **maximum of 2-3 hours** because if they remain in the garden for a longer time, they could disturb the soil excessively and attack some crops.

Lessons learned about the Polyfarming system as a whole

• The Polyfarming system proposes an **integrated system of forestry, livestock and agricultural uses** (including fruit trees and orchards) that interact and complement each other.
• The Polyfarming system promotes various **combinations** based on the fact that at least two elements of different uses interact in the same place. These combinations generate important synergies.
• At farm level, the spatial and temporal planning of the different uses makes it possible to establish a **complementarity of products and labour,** in order, among other things, to reduce the external resources needed and the production costs, and to increase the efficiency of the system as a whole.
• **The outputs of the system are the final products**, which include: firewood, wood, fruits, forage, vegetables, meat, milk and eggs.
• The **inputs to the system** are mainly products from other elements of the system itself, such as grass, forage, grain, leaves, biochar, BRF and wooden beds. However, a series of products from outside the system are also required, such as feed, forage and grain (the latter two if the internal production of the farm is not enough), seeds and seedlings.
• In order to apply the Polyfarming system, **it is important to learn to observe and interpret** the whole system in a different way, and this means being in the field a lot and discussing the different aspects of each element in the field.
• The application of a production system such as Polyfarming requires having examples of **pilot farms** that work according to this model.

Returns of the different activities

- Costs of forest-related activities
- Costs of activities related to livestock on pasture
- Costs of activities related to crops
- The Polyfarming system as a whole

Returns of the different activities

Costs of forest-related activities

- Costs and key points of forest harvesting
- Costs and key points of producing and applying BRF
- Costs and key points of producing and applying biochar
- Costs and key points of producing and applying trunk beds
- Costs and key points of producing and applying Bocashi-type organic fertiliser
- Costs and key points of producing and applying biofertilisers

Costs and key points of forest harvesting

Forest harvesting mainly has three types of costs: (1) costs of felling and limbing the trees, which can vary considerably depending on the size and species of the trees cut; (2) costs of dragging the logs to the track, which is performed with an adapted agricultural tractor from the track; and (3) product preparation costs, which include cutting the logs to size for use and transportation.

Figure 1. Dragging logs out of the forest largely determines the total cost of forest harvesting. Photo: AV Video.

Quantification of the costs of forest harvesting

The quantification of forest harvesting (**Figure 1**) is based on calculating three different types of costs:

1. Cost of felling and limbing the trees.
2. Cost of dragging the logs to the track.
3. Cost of preparing the logs.

Globally, it is possible to estimate in 2 h the total time that it takes to carry out all these processes for 1 Tm placed on track. Below are described the different alternatives we have analyzed for each one, indicating their costs and variability (**Table 1**).

1. Cost of felling and limbing the trees. All the materials necessary for felling and limbing the trees (chainsaw, protective equipment, etc.) are considered to be already **available on the farm**, otherwise the corresponding costs to obtain them should be included. The time for felling and delimbing obviously depends on the size and the species. Thus, the yields obtained in the use of holm oak are lower compared to those of other species, especially conifers, where the scarcity of branches and the straightness of the trees facilitate processing works. Guideline values can range from 10 to 12 min (10% of the total time) to cut the trees necessary to obtain 1 Tm, and around 50 min (40% of the total time) to limb them.

2. Cost of dragging the logs to the track. This cost includes dragging the logs from where they were felled to the track. This cost **depends on the availability or not of a good network of tracks**. If the dragging of the logs to the track is long, the total cost of extracting them will be higher. This is done with an agricultural tractor adapted from the track. Two situations can occur:

• **If the farm has an agricultural tractor**, the time used to drag the logs is around **40-45 min** (35% of the total time) to obtain 1 Tm.

• **If the farm does not have an agricultural tractor**, the cost of renting the tractor must be added to the above costs, which can be **€50/day**.

3. Cost of preparing the logs. This cost includes preparing the product and placing it on the track. When the job is finished, **the wholesaler pays for the kg that he/she loads onto the truck**, but these costs are not included in forest harvesting at farm level. The logs are left as necessary for use and transport. The time to do it can be estimated at **15-20 min** (15% of the total time) to obtain 1 Tm.

Based on these considerations, we can establish a series of simple calculations to estimate the total costs of forest harvesting in the Mediterranean forest. This quantity **corresponds to 1 Tm**. **The overall cost is the sum of the three costs described above**:

$$C_{total} = C_{felling} + C_{dragging\ the\ logs} + C_{preparation}$$

Felling and limbing trees (for 1 Tm):
$C_{felling}$ = 0.20 h / Tm x Salary/h
$C_{limbing}$ = 0.80 h / Tm x Salary/h

Trunks delimbing:
$C_{dragging\ the\ logs}$ = 0.75 h / Tm x Salary/h + 0.25 day x 50 € / day (tractor cost if necessary)

Trunk preparation:
$C_{preparation}$ = 0.25 h / Tm x Salary/h

Considerations on the optimal strategy for forest harvesting

We must consider the following key points in forest harvesting:

• The **size** and, above all, the **species of the felled trees** largely determines the costs incurred, especially for delimbing and dragging the logs.

• **The network of tracks** is essential to determine if the exploitation is viable or not. If the network of tracks is insufficient, **dragging the logs is sometimes infeasible**. This activity is more appropriate to subcontract to forest harvesting experts.

• The **final use of the product**: whether it is for poles, wood or firewood, can considerably condition the costs of preparing the product on the track.

Parameter	Unit	Value used	Variability and causes
Total time of laying 1 Tm of wood on the track	h / Tm	2	It varies depending on whether it is near or far from the track and the slope between 1 and 4
Tree felling time	h / Tm	0.20	It varies slightly depending on the size and species of the trees cut
Tree limbing time	h / Tm	0.80	It varies slightly depending on the size and species of the trees cut
Log dragging time	h / Tm	0.75	If the track is far away, the cost of dragging the logs increases
Farm tractor rental cost	€ / day	50	It depends on the availability or not on the farm
Time to prepare the logs on the track	h / Tm	0.25	It may vary depending on whether the product is prepared for wood or firewood

Table 1. Parameters used to calculate the costs of forest harvesting, indicating the values used in Polyfarming and any variability that can occur in these values.

Costs and key points of producing and applying BRF

There are mainly three types of costs for the production and application of BRF: (1) costs of obtaining the base material, which are branches <7 cm in diameter; (2) shredding costs, which includes the use of a shredder and transportation to the location of the pile of branches; and (3) field application costs, which includes transporting the BRF from the crushing zone to the field and distributing it in the field.

Figure 1. Decomposition process of BRF in the forest. Photo: J. Luis Ordóñez.

Quantification of production and application costs of BRF

The quantification of BRF production and application (**Figure 1**) is based on calculating three different types of costs:

1. Cost of obtaining the BRF base material.
2. Cost of crushing BRF.
3. Cost of placing BRF on the field.

Next, we will describe the different alternatives analysed for each of these processes, indicating the costs they represent and their variability (**Table 1**).

1. Cost of obtaining the BRF base material. This cost includes cutting the branches that will be used as raw material. All the necessary materials for felling (chainsaw, etc.) are already available on the farm, otherwise the corresponding costs will have to be included. **Branches of <7 cm are obtained from the traditional forestry cuttings** that are made in the agro-silvo-pastoral farms. So, its **cost** can be considered **0**, since it is work included in obtaining wood or firewood.

2. Cost of crushing BRF. This cost includes crushing the branch biomass using a shredder. It is considered that the farm has **a shredder**, otherwise the cost of hiring it would have to be counted. In principle, the shredder is taken to the place where the branches are and not the other way around, since transporting the volume of branches would be much more expensive than transporting the BRF directly. Approximately 10 m^3 of branches are needed to obtain 1 m^3 of BRF. **The cost of crushing is that of two people working for approximately 1-2 hours**: one drags the branches to the crusher and the other introduces them. If the branches are large (5-7 cm) it takes longer than if they are than if they are smaller (2-4 cm).

3. Cost of placing BRF on the field. This cost includes transporting the BRF from the crushing area to the field and distributing it on the ground.

- In the case of **transport**, the cost depends on the time spent loading the trailer and moving the BRF to the application area. In the farm where the Polyfarming system is implemented, the trailer has a capacity of 2 m^3, so it only takes one trip to transport all the BRF obtained from 10 m^3 of branches. It is considered that the farm has a jeep with a trailer, otherwise it is necessary to include the **costs of renting it**. If the BRF is left in the field for a year before transporting it (one of the possible options), then it is still more compact and more BRF can fit on the trailer.

- Regarding the application, **it is essential that the vehicle arrives right next to the field**, so that transporting the BRF with a wheelbarrow to the application area is very quick. A pile is mounted near the facilities that require it, which the chicks and the garden area.

• In the case of the **chick litter**, the BRF is placed directly in a very short time, so the **cost** is practically **0**.

• In the case of the **vegetable garden**, the BRF is placed in the irrigation ditches. In the trenches of 15 cm x 20 cm section (0.03 m^2), the hose is placed and the top is covered with BRF. Approximately 0.5 m^3 of BRF is placed on each 70 m long line, like those at Planeses. One worker takes approximately 0.75 hours to apply BRF to one of these lines.

Considerations on the optimal strategy for producing and applying BRF

The **key points** to consider in the production and application of BRF are the following:

- In BRF production, it is essential to **place the shredder close to where the freshly cut branches are**.
- The crushing of the branches depends on their size: **when they are large (5-7 cm), much higher yields are obtained** than if the branches are small (2-4 cm).
- The BRF can be transportd to the farm once it has been crushed or, more advisable, **leave it in the forest for a few months** and then transport it to the area of the farm where it will be applied.

From these considerations, we can establish a **series of simple calculations to estimate the total costs** of applying BRF in agricultural farms. These calculations are based on 1 m^3 of BRF. **The overall cost is the sum of three costs:**

$$C_{total} = C_{obtaining} + C_{crushing} + C_{placing}$$

Obtaining the BRF base material:

$C_{obtaining}$ = 0 (<7 cm branches are obtained from forest harvesting)

Crushing del BRF:

$C_{crushing}$ = 10 m^3 branches x 1 m^3 BRF / 10 m^3 branches x 2h / 1 m^3 BRF x Salary / h (shredding with 2 workers)

Placing the BRF, the sum of two costs:

$C_{transport}$ = N h (depends on the distance from the crusher to the field) x Salary / h (load and transport of BRF)
$C_{application\ (1)}$ = 0 (application in the chick litter)
$C_{application\ (2)}$ = 0.5 m^3 BRF x 0.75 h/m^3 x Salary/h (application in the orchard, in a 70 m-long line)

Parameter	Unit	Value used	Variability and causes
Shredding time of 10 m^3 of branches	h	2	Two people take 1 h when the branches are large (5-7 cm), if they are small (2-4 cm) they take twice as long
Quantity of BRF obtained from 10 m^3 of branches	m^3	1	When it is left in the field for a year it ends up occupying a smaller volume
BRF trailer loading time	h	0.5	It varies with trailer size
Trailer transfer time	h	-	It depends on the distance
Time of application of BRF in the chick litter	h	0	A small amount of BRF is added and this does not take very long
Amount of BRF applied to the orchard (per 70-m line)	m^3 BRF/ line	0.5	It may fluctuate slightly depending on how deep the trench is
BRF application time	h/line 70 m	0.75	It may vary depending on where the BRF stack is

Table 1. Parameters used to calculate the costs of producing and applying BRF, indicating the values used in Polyfarming and the possible variability that can occur in these values.

Costs and key points of producing and applying biochar

Biochar production and application mainly has three types of costs: (1) costs of obtaining the base material, which are branches <7 cm in diameter; (2) biochar production costs, which include the use of self-transporting boilers; and (3) field placement costs, which includes transporting the biochar from the production area to the field and distributing it to the chick litter and chicken feed.

Figure 1. Biochar. Photo: iStock, orkrip.

Quantification of the costs of producing and applying biochar

The quantification of biochar production and application (**Figure 1**) is based on calculating three different types of costs:

1. Cost of obtaining the biochar base material.
2. Cost of biochar production.
3. Cost of biochar application.

Next, we will describe the different alternatives analysed for each of these processes, indicating the costs they represent and their variability (**Table 1**).

1. Cost of obtaining the biochar base material.
This cost includes cutting the branches that will be used as raw material. All the necessary materials for the cuts (chainsaw, etc.) are already available on the farm, otherwise the corresponding costs should be included. **Branches of <7 cm are obtained from the traditional forestry cuttings** that are made in the agro-silvo-pastoral farms. So its cost can be considered 0, since it is work included in obtaining wood or firewood.

2. Cost of biochar production.
Biochar production can be done using different methods. In the Polyfarming system we make it **using self-built transportable boilers**. They are cheap self-built infrastructures with oil drums connected with screws. Therefore, **their cost can be considered 0**. If they are bought, their price can be very high. Those used at Planeses have a diameter of 1.75 m and a height of 0.9 m, i.e. a volume of about 2.2 m^3. Normally, the boiler is taken to the place where the branches are and not vice versa, since transporting the volume of branches would be much more expensive than transporting the boiler. Approximately 8-9 m^3 of branches are needed to fill the boiler that we use to produce biochar. **The staff cost of loading the boiler is that of two people for 2 hours**: one drags the branches to the shredder and the other cuts them to size and introduces them into the fire. Later they spend another half an hour putting out the fire and sealing the boiler. The next day, the two workers return and it takes half an hour to uncover the boiler, let the biochar cool down and load it onto the trailer. Around 0.7 m^3 of biochar is obtained in each of these boilers.

3. Cost of placing biochar on the ground.
This cost includes transporting the biochar from the pyrolysis area to the farm, and its subsequent treatment in the chick litter and chicken feed.

- In the case of **transport**, the cost depends on the time spent loading the trailer and transferring the biochar to the application area. In the Polyfarming system, the trailer has a capacity of 2 m^3, so it takes one trip to transport all the biochar produced in a boiler, and there is still more than half the trailer left. It is considered that the farm has a jeep with a trailer, otherwise it is necessary to include the costs of renting it.

- **As regards subsequent treatment, it is important that the vehicle arrives right next to the field**, so that the transport of the biochar by wheelbarrow to the application area is very quick. Biochar is applied to the chick litter and chicken feed, so it is part of other farm work and cannot be considered an added cost.

Considerations on the optimal strategy for producing and applying biochar

We must consider the following **key points** in the production and application of biochar:

- The branches must be easily accessible, i.e. the **boiler must be placed near a large accumulation of branches.**

- The **branches** used **must be dry**, from the previous year. In this case, the process is more efficient and faster. If the leaves are green, they must be burned first and this causes a significant loss of carbon and minerals.

- Other methods besides boilers can be used in the forest. **The branches can be lowered to the farm and there using a more efficient boiler** that allows the waste heat to be used. But transporting the large number of branches that are necessary causes the costs to go up a lot.

- The use of **biochar can be applied to the chick litter or any composting process** carried out on the farm.

From these considerations, we can establish a series of **simple calculations to estimate the total costs of applying biochar in agricultural farms**. These calculations are based on the content of a biochar boiler. The overall cost is the sum of three costs:

$$C_{total} = C_{obtaining} + C_{production} + C_{placing}$$

Obtaining the biochar base material (to fill a boiler):
$C_{obtaining}$ = 0 (<7 cm branches are obtained from forest harvesting)

Biochar production:
$C_{production}$ = 0 € (self-built boiler) + 2 hx Salary / (hour x worker) x 2 workers (loading a boiler) + 0.5 hx Salary / (h x worker) x 2 workers (sealing of a boiler) + 0.5 hx Salary / (h x worker) x 2 workers (discharge from a boiler)

Transport and application of biochar:
$C_{placing}$ = Transport of biochar (depending on distance from the boiler to the farm) + 0 (application of biochar in the chick litter or the chick feed)

Parameter	Unit	Value used	Variability and causes
Cost a self-built pyrolysis boiler	€	0	If it is not self-built it can be worth more than €10,000
Volume of branches to fill a boiler	m^3	9	It depends on the size of the boiler
Time to load a boiler	h/2 people	2	It may depend on whether the branches are near or far from the boiler, if they are far away this time can be doubled
Boiler sealing time	h/2 people	0.5	-
Boiler discharge time	h/2 people	0.5	-
Amount of biochar produced per boiler	m^3	0.7	It can vary in a range of 0.5-0.9
Time to transport the biochar	h	variable	It depends on the distance between the boiler and the farm

Table 1. Parameters used to calculate the costs of producing and applying biochar, indicating the values used in Polyfarming and any variability that can occur in these values.

Costs and key points of producing and applying trunk beds

Producing and applying trunk beds mainly has two types of costs: (1) costs of obtaining the base material, which are logs of more than 20 cm cut to the appropriate size; (2) costs of laying in the field, which includes the transport of the logs from the cutting area to the field and their distribution on the ground, which is different if it is done in a fruit tree plantation or in the garden.

Figure 1. Placement of the trunk beds on the garden plot. Photo: AV Video.

Quantification of the costs of producing and applying trunk beds

The quantification of the production and application of trunk beds (**Figure 1**) is based on calculating two different types of costs:

1. Cost of obtaining the base material of the trunk beds.
2. Cost of laying the trunk beds on the ground.

Next, we will describe the different alternatives that we have analysed for each of these processes, indicating the costs they represent and their variability (**Table 1**).

1. Cost of obtaining the base material of the trunk beds. This cost includes obtaining the logs that will be used as raw material. All the necessary **materials for felling** (chainsaw, etc.) are already available on the farm, otherwise the corresponding costs will have to be included. In principle, it is understood that the logs are obtained from a traditional forest harvest, so that **the cost of cutting them can be considered 0**, since it is a work included in the cutting itself. However, since the large logs used for trunk beds could otherwise be used as firewood, the cost of not selling them must be considered as obtaining the base material for the trunk beds. This cost depends on the volume used in each case and the price of firewood in each location.

2. Cost of transport and placement of the trunk beds on the ground. This cost includes the transport of logs from the felling area to the field and their distribution on the ground.

• As regards transport, the **cost depends on the time spent loading the trailer, moving the logs, and unloading the logs in the application area**. In Planeses, the trailer has a capacity of 2 m^3. The average time to fill the log trailer is 0.33 h. Each trip is loaded with about 24 logs 2 m long and around 15 cm in diameter. To this cost should be added the **transport time** (which varies with distance) and the time to unload the logs, which can be considered the same as loading them. The time is always calculated for two workers. It is considered that the farm has a jeep with a trailer, otherwise it is necessary to include the costs of renting it.

• As regards the application, it is essential that the vehicle arrives right next to the field, so that the transport of the logs with a wheelbarrow to the application area is very quick.

- A hole to plant a fruit tree has an approximate volume of 0.5x0.5x0.5 m^3, in which between 4-5 trunks of 40-50 cm are introduced at the bottom. This means that with **each 2-m**

log we prepare the bed of a fruit tree. The average time used to transport and **place the logs is 0.1 h (6 minutes)**, although it varies with the distance from the fruit tree to the pile of logs. The rest of the calculations referring to the hole for the fruit tree are given in the corresponding file.

- In the orchard, digging the furrow where the logs will be placed to make the wooden bed requires several activities. Let's consider the values for 100 linear m of furrow. First, a worker spends twice as long making the ditch with a rented **motor trencher (€250/day)**, he walks at a normal walking speed (5-6 km/h, 1 km every 10 min), i.e. it takes a minute to travel 100 m. The average 50-m long log are then carried along the 100-m line, and 3-4 standard logs 2 m long are placed every 2 m. This makes about **200 trips over an average distance of 50 m** (10,000 m in total), in total about 100 minutes. Finally, it takes half a minute to cover the logs of every 2 m, i.e. in total 25 minutes to cover the entire line.

Quantification of the costs of producing and applying trunk beds

We must consider the following **key points** in the production and application of trunk beds:

- In the case of **planting fruit trees,** the calculation depends on whether the ground is stony and, therefore, it takes more or less time to make the holes.
- The calculations **the fruit trees and the orchard** are based on the fact that the trunks are cut and close to the holes. Their transportation can be a significant cost.

From these considerations, we can establish a series of simple calculations to estimate the **total costs of applying trunk beds in agricultural farms. The calculations obtained are based on 1 m³ of logs**. The application cost depends on whether it is applied to fruit trees (1, data per fruit tree) or the orchard (2, data per 10 linear m of furrow). The total cost is the sum of both costs after correcting the amount required in each case:

$$C_{total} = C_{obtaining} + C_{placing}$$

Obtaining the base material of the trunk beds (per 1 m³):

$C_{obtaining}$ = 1 m³ logs x € 60 / m³ firewood (price of firewood that is not sold to make wooden beds)

Transport and placing of the trunk beds, the sum of two costs:

$C_{transport}$ = 0.33 h x Salary / (h and worker) x 2 workers x 2 (loading and unloading of logs) + N h x Salary / (h and worker) x 2 workers (transport, variable according to the distance to the cutting area)

$C_{placing\ (fruit\ trees)}$ = 0.1 h / fruit tree x Salary / h (per fruit tree)

$C_{placing\ (orchard)}$ = 100m x 0.03 h / 100 mx Salary / h (make the 100 m trench) + 2 h x Salary / h (place and cover the logs) + 2 h (approximately) x 250 € / 24h (rent motor ditcher)

Parameter	Unit	Value used	Variability and causes
Cost of logs for firewood	€ / m³ firewood	60	It is a totally indicative price, it depends on the place and the species, with a range of €50-80/m³
Time to load the trailer with logs	h/2 workers	0.33	It may depend on the distance of the log stacks
Time of transfer of the logs from the forest to the field	h	-	It depends on the distance
Time for transporting, cutting and placing the logs in a fruit tree hole	h	0.1	It is very fast, but the logs have to be transportd to the hole
Renting the motorised machine to make furrows in the orchard	€ / day	250	The price may depend on the specific offer in the area
Time to dig a furrow in the orchard (100-m line)	min	2	The time it takes to walk 100 m twice (two trips)
Time to place the logs and cover them in the orchard (100-m line)	h	2	There is the time to transport the logs (100 min) and another to cover the trench (25 min) in the 100 m considered. These are guide values

Tabla 1. Parameters used to calculate the production and application costs of the bed trunks, indicating the values used in Polyfarming and any variability that can occur in these values.

Costs and key points of producing and applying Bocashi-type organic fertiliser

The production and application of Bocashi-type organic fertiliser mainly has three types of costs: (1) costs of the ingredients to produce Bocashi-type organic fertiliser, there are up to ten different ones; (2) production costs of the Bocashi-type organic fertiliser, which includes the time it takes to turn the entire mass first with a shovel and then with a grower until it is mixed; and (3) the costs of applying Bocashi-type organic fertiliser to the ground, which includes the time spent applying it to crops.

Quantification of the costs to produce and apply Bocashi-type organic fertiliser

The quantification of the production and application of Bocashi-type organic fertiliser (**Figure 1**) is based on calculating three different types of costs:

1. Cost of ingredients to produce Bocashi-type organic fertiliser.
2. Cost of preparing the Bocashi-type organic fertiliser.
3. Cost of applying Bocashi-type organic fertiliser to the field.

Next, we will describe the different alternatives that we have analysed for each of these processes, indicating the costs they represent and their variability (**Table 1**).

1. Cost of ingredients to produce Bocashi-type organic fertiliser. The main ingredients and quantities used to make **100 kg of Bocashi-type fermented organic compost** are: **self-produced charcoal** (13.7 kg, €0), **self-produced manure** (27.4 kg, €0), **rice husk** (27.4 kg, €0.09/kg), **rice bran** (1.2 kg, €0.2/kg), **molasses** (1 l, €0.5/l), **forest humus** (1.2 kg, €0), **common soil** (27.4 kg, €0), **rock and ashes meal** (1.2 kg, €0) and **water** (in a variable quantity in order to homogenise the humidity of all the ingredients of the compost). These values are indicative, they only indicate the proportions for the different ingredients.

2. Cost of preparing the Bocashi-type organic fertiliser. The ingredients are mixed by turning the entire mass with a motor grower until mixed. Once finished, it is turned twice a day during the first three days with a shovel (approximate time 0.5 h every time). Afterwards, it is spread to about 30 cm in height and turned over with a rototiller once a day (10 min each time) until **15 days** later, when the Bocashi-type organic fertiliser is finished.

3. Cost of applying Bocashi-type organic fertiliser to the soil. This cost includes the time spent applying it to crops. Just before transplanting, at the base of the hole where each plant will be placed, an amount between **50 and 100 g of Bocashi-type fertiliser** (depending on the needs of the crop) is applied and covered with soil before planting the plant. The time spent performing this action can be **half a minute per plant**, including the entire process.

From these considerations, we can establish a series of simple calculations to **estimate the costs global production and application of organic fertilizer Bocashi type in agricultural land**. The overall cost is the sum of three costs:

$$C_{total} = C_{ingredients} + C_{production} + {}_{application}$$

Ingredients for making Bocashi-type organic compost (to produce 100 kg of compost):

$C_{ingredients}$ = 13.7 kg x € 0/kg (charcoal) + 27.4 kg x € 0/kg (manure) + 27.4 kg x € 0.09/kg (rice husk) + 1.2 kg x € 0.2/kg (rice bran) + 1 lx € 0.5/l (molasses) + 1.2 kg x € 0/kg (forest humus) + 27.4 kg x € 0/kg (soil) + 1.2 kg x € 0/kg (rock and ashes meal)

Production of organic fertiliser Bocashi type:

$C_{production}$ = 0.5 h / turn x 6 turns x Salary/h (turning the mix with a shovel for the first three days) + 0.15 h/turning x 12 turns x Salary/h (turning the mix with a walking tiller until day 15)

Application of organic fertiliser Bocashi type:

$C_{application}$ = 0.83 h x Salary/h (half min per plant, application for 100 plants)

Figure 1. Bocashi-type organic compost. Photo: Marc Gràcia.

Considerations on the optimal strategy for producing and applying Bocashi-type organic fertiliser

We must consider the following key points for the production and application of Bocashi-type compost:

- One of the main advantages of Bocashi-type fertilisers is that the **materials** they **are made from are widely known by producers**, easy to obtain locally and at a very low cost.

- There are many types of organic fertilisers and, within the Bocashi-type, the ingredients and quantity of each one can vary considerably.

- Bocashi-type organic fertiliser can be applied to the bottom of each hole, but also in the rows of crops.

Parameter	Unit	Value used	Variability and causes
Amount of charcoal to produce Bocashi-type compost	kg/100 kg	13.7	There are many ways and ingredients to prepare Bocashi. This is one of them.
Amount of manure to produce Bocashi-type compost	kg/100 kg	27.4	There are many ways and ingredients to prepare Bocashi. This is one of them.
Amount of rice husk to produce Bocashi-type compost	kg/100 kg	27.4	There are many ways and ingredients to prepare Bocashi. This is one of them.
Amount of rice bran to produce Bocashi-type compost	kg/100 kg	1.2	There are many ways and ingredients to prepare Bocashi. This is one of them.
Amount of molasses to produce Bocashi-type compost	l/100 kg	1	There are many ways and ingredients to prepare Bocashi. This is one of them.
Amount of forest humus to produce Bocashi-type compost	kg/100 kg	1.2	There are many ways and ingredients to prepare Bocashi. This is one of them.
Amount of common soil to produce Bocashi-type compost	kg/100 kg	27.4	There are many ways and ingredients to prepare Bocashi. This is one of them.
Amount of rock flour to produce Bocashi-type compost	kg/100 kg	1.2	There are many ways and ingredients to prepare Bocashi. This is one of them.
Amount of water to produce Bocashi-type compost	l/100 kg	variable	Variable volume to homogenise the final mixture
Time to turn the mixture with the shovel	h	0.5	It has to be done twice a day during the first three days
Time to turn the mixture with a grower	h	0.15	It has to be done once a day until day 15
Time to place the Bocashi-type compost in the planting hole	h/100 seedlings	0.3	0.2-0.4

Table 1. Parameters used in the calculation of the costs of the production and application of Bocashi type fertilizer, indicating the values used in Polyfarming and the possible variability that can occur in these values.

Costs and key points of producing and applying biofertilisers

The production and application of biofertilisers mainly has three types of costs: (1) costs of obtaining mountain microorganisms as the basis of the biofertiliser, which are obtained from forest humus and are produced in closed containers; (2) costs of producing the biofertiliser, which is obtained from these mountain microorganisms in a closed container; and (3) costs of applying the biofertiliser to the ground, which can be done by foliar application or via irrigation.

Quantification of the costs of producing and applying biofertilisers

The quantification of the production and application of biofertilisers (**Figure 1**) is based on calculating three different types of costs:

1. Cost of obtaining mountain microorganisms as a basis for the biofertiliser.
2. Cost of producing the biofertiliser.
3. Cost of applying the biofertiliser in the field.

Next, we will describe the different alternatives that we have analysed for each of these processes, indicating the costs they represent and their variability (**Table 1**).

1. Cost of obtaining mountain microorganisms as a basis for the biofertiliser. This cost includes the time it takes to collect the humus sample that will be used as a raw material for the microorganisms in the forest, the materials needed to achieve the mixture, and the time dedicated to obtaining the homogeneous mixture. In Polyfarming, these mountain microorganisms are produced in 200-l containers and all subsequent calculations refer to producing a complete container.
• To produce a container of mountain microorganisms like the one described, about **120 l of humus from the forest floor** is needed (slightly more than half because it is then compacted). The time spent collecting the humus sample from the forest floor can be estimated at **0.5 h of work** by one person. The forest must be close to the farm, because otherwise we have to count the time to look for and transport the humus sample.
• In addition to humus, which in principle has no cost, for the production of the mixture that fills the used container (200 l), a similar amount of **rice bran** is needed (**120 l**, which is equivalent to about 28 kg, €0.2-0.3/kg), and **10-20 l of molasses** as an energy source (at €0.5/l).
• These three ingredients (sometimes water is added) are combined until a homogeneous mixture is obtained. The time required to get it and fill the entire container with it is **2 h of work** for two people. After a month of being hermetically sealed, the product is obtained.

2. Cost of producing the biofertiliser. In this case, the biofertiliser is obtained from mountain microorganisms. The costs of producing it include the drums in which they

Figure 1. Applying biofertilisers at Planeses farm. Photo: Ángela Justamante.

are produced, the remaining ingredients required and the time to prepare the biofertiliser.
• Biofertilisers are produced in 200-litre **plastic drums**, with a hose connected to a valve with the end inside a bottle filled with water, to evacuate the gases formed. The cost of each of these structures is **€60-70 if they are new** and **€10-15 if they are recycled**.
• To complete the content of a drum, a mesh bag is required into which a **40 kg sample of mountain microorganisms** and the following ingredients are introduced: **20 l of cow's milk serum**, which in our case is self-produced (if not, it can be obtained free from a cheese factory**, 4 l of molasses (€0.5/l), 4 kg of rock flour** (obtained free from a quarry), **4 kg of ashes** (obtained from a wood stove) and **180 l of water.**
• The **time to mix** all the ingredients and obtain a homogeneous mixture, and the **time to fill the drum** contents in closed containers is **0.25 h for each 200-l drum**.

3. Cost of applying the biofertiliser. This cost includes the time spent applying it to crops, which can be done by foliar or irrigation means.
• **The foliar application of the biofertiliser** is carried out by spraying with a full backpack up to 20 l (if not, it weighs too much), which, if the orchard is large, must be with a motor. We have estimated that with the backpack the biofertiliser can be applied at a speed of **1 ha/h**, counting **a speed of 6 km/h** (one-person walking) and a **width of 1.5-1.6 m**. To this should be added that each time the backpack is emptied, it must be refilled (20 minutes in total each time).
• The application of biofertiliser through irrigation is very fast, it simply requires a pump to inject it into the irrigation water pipe.

From these considerations, we can establish a series of simple calculations to estimate the **costs global production and application of bioertilisers** in agricultural land. **The overall cost is the sum of three costs:**

$$C_{total} = C_{obtaining} + C_{production} + C_{aplication}$$

Obtaining mountain microorganisms as the basis of the biofertiliser (for a 200 l container):
$C_{obtaining}$ = 0.5 h x Salary/hour (collection of 120 l of humus) + 28 kg x 0.2 €/kg (rice bran) + 15 lx 0.5 €/l (molasses) + 2 h/worker x 2 workers x Salary/h (preparation of the mixture)

Production of biofertiliser (per 200 l drum):
$C_{production}$ = € 15 (reused drum) + 20 lx € 0/l (cow serum) + 4 lx € 0.5/l (molasses) + 4 kg x € 0/kg (rock meal) + 4 kg x € 0/kg (ash) + 0.25 h x Salary/h (preparation of the mixture and packaging)

Application of the biofertiliser (in one ha of crops), can be in two ways:
$C_{aplication\ (foliar\ way)}$ = 1 h/ha x Salary/h (foliar application with a backpack filled up to 20 l)
$C_{aplication\ (irrigation)}$ = 0.25 h x Salary/h (application through irrigation)

Considerations on the optimal strategy for producing and applying biofertilisers

We must consider the following key points in the production and application of biofertilisers:

- **There are many types of biofertilisers**, so costs and techniques can vary depending on the biofertiliser produced.
- In general, the key point of biofertilisers is that they are produced by the farmers themselves with very **low costs and from materials from the environment or at a very low price**.
- There are very important differences in the mode of application and the total amount of biofertilisers to apply, and in general the information found on their impact on crops is not very extensive.

Parameter	Unit	Value used	Variability and causes
Amount of soil humus to produce mountain microorganisms	l/drum 200l	120	It may be something more because it compacts a lot.
Time to collect soil humus	h	0.5	It depends on the distance to the forest
Amount of rice bran to produce mountain microorganisms	l/drum 200l	120	As in the case of humus, when compacting it can accommodate more
Amount of molasses to produce mountain microorganisms	l/drum 200l	15	It can range from 10 to 20
Time to get the homogeneous mixture of the container	h/2 workers	2	2-3 range if lacking experience
Cost of the drum prepared to produce biofertiliser	€/drum 200l	15	This is the price of the reused drum, if it is new it can be worth €60-70
Amount of microorganisms to produce biofertiliser	kg/drum 200l	40	-
Amount of cow's milk serum to produce biofertiliser	l/drum 200l	20	Milk can also be used
Amount of molasses to produce biofertiliser	l/drum 200l	4	-
Amount of rock meal to produce biofertiliser	kg/drum 200l	4	-
Amount of ashes to produce biofertiliser	kg/drum 200l	4	-
Amount of water to produce biofertiliser	l/drum 200l	180	It must be chlorine-free water
Time to produce the fertiliser	h/drum	0.25	-
Speed of applying fertiliser by spraying with a backpack	ha/h	1	It is a fully estimated calculation that can vary considerably depending on the applicators and the application conditions
Time to apply biofertiliser to the irrigation system	h	0.25	It is very quick, just a pump connection to inject it into the irrigation water.

Table 1. Parameters used to calculate the costs of the production and application of biofertilisers, indicating the values used in Polyfarming and any variability that can occur in these values.

Returns of the different activities

Costs of activities related to livestock on pasture

- Costs and key points of setting up a pasture
- Costs and key points of raising young chicks and rabbits
- Costs and key points of chicken production on pasture
- Costs and key points of the production of rabbits on pasture
- Costs and key points of managing cows on pasture through intensive controlled grazing

Costs and key points of setting up a pasture

The development of a pasture has three main types of costs: (1) costs of adapting the field and removing the current vegetation, which includes the time to remove remains and previous vegetation; (2) costs of sowing the pasture, which include the price of the seeds and the time to sow with the no-till seeder or, if not possible, broadcast; and (3) costs of irrigation and other post-planting activities, including watering if possible, reseeding if necessary, and removing sprouts of trees and shrubs in the area.

Quantification of the costs for setting up a pasture

The quantification of what the set-up represents a pasture (**Figure 1**) is based on calculating different costs:

1. Costs of adapting the field and removing the current vegetation.
2. Costs of sowing the pasture.
3. Costs of irrigation and other post-planting activities.

The various alternatives that we have analysed for each of these processes are described below, indicating the costs they represent and their variability (**Table 1**). The cost of the cattle that will graze in the meadow is not included, since it is part of a different element of Polyfarming.

1. Cost of adapting the field and removing the current vegetation. This cost has two components:
• The cost of adapting the field is very difficult to assess, as it depends entirely on the situation it is in, the amount of stones, logs and other debris to be removed. **An average value cannot be given because it can** vary according to the initial situation: if it is an old crop field, if they are old terraces occupied by forest (in which case the trees and stumps must be removed because if they are there, they cannot be planted with a direct seeding seeder) or if it is a degraded area.

• In the **case of vegetation, it also depends on the previous state**. In this sheet we take into account more or less complete coverage of the herbaceous or small shrub layer. If the farm has livestock to graze that vegetation, then the cost can be considered 0. If it is not available, it must be removed with a forest hammer brush cutter, which has an approximate speed of 0.6 km/h (yield of about 8 h/ha). The cost of renting can be estimated at €80/h.

2. Cost of planting the pasture. The first cost to consider is the price of the seeds, which can vary considerably depending on what is sown. We must count about 20-40 kg/ha and a price per kg of €5/kg. Altogether it can be estimated at **€100-200 of seed per ha**. It can be sown in two ways:
• Whenever possible, sowing should be done with a direct seeding seeder. If it is not available at the facility, it can be rented, estimating an approximate cost of €350/day. Given this price, it is only justified if we have a large area to sow.

Figure 1. Pasture in the Planeses farm. Photo: MJ Broncano.

• If this is not possible, sowing should be broadcast. This type of sowing requires approximately 3-4 h of work per ha by one person.

3. Cost of irrigation and other activities after planting. The costs after planting depend on the situation that is created after it. There are three possible costs that should be considered:
• If it does not rain enough during the first few days, whenever possible, **it is convenient to have a system prepared to irrigate the surface of the future pasture**. Therefore, the cost of the system to irrigate the pasture surface must be counted. This system includes about 75-100 m of main pipe per ha (price around €1.5/m), about 400-450 m of smaller pipe per ha (€0.5/m) and a sprinkler in each 1000-m^2 plot, about 10 sprinklers per ha (€10-12/sprinkler). This gives a cost of around €500/ha.

• If the sowing has very low coverage, it is necessary to re-sow, especially in areas where there are patches without vegetation. It is difficult to estimate this cost because it depends on how the pasture is, but an approximate estimate of half the time and the number of seeds can be made with respect to the first sowing.

• **The cost of removing regrowth of tree and shrub stumps** in the area that have resprouted after initial clearing is not easy to estimate either, because it depends on the number of tree and shrub stumps there were. It is done with a **manual brush cutter** and can be estimated at a maximum of **one hour per 1000 m plot, 10 h/ha**.

Once the pasture has been installed**, the cost of maintaining it can be considered 0**, since the movement of animals allows the grassland to be conserved at no additional cost.

Based on these considerations, we can establish a series of simple calculations to estimate the total costs of setting up a pasture in an agricultural field. The overall cost is the sum of three costs:

$$C_{total} = C_{adequacy} + C_{sowing} + C_{postsowing}$$

Field adequacy, the sum of two costs:

C_{field} = highly variable
$C_{vegetation\ (1)}$ = 0 (if done by the farm's livestock grazing)
$C_{vegetation\ (2)}$ = 1 ha x 8 h/ha x € 80/h (if done with a forest hammer brush cutter)

Sowing (per ha), the sum of two costs:

C_{seeds} = 5 kg/ha x € 30/kg
C_{sowing} = 1 ha x 4 h/ha x Salary/h (broadcast sowing)

Post-sowing (per ha), the sum of three costs:

$C_{irrigation}$ = 100 m x 1.5 €/m (main pipe) + 400 m x 0.5 €/m (smaller pipe) + 10 x 12 €/sprinkler (sprinklers)
$C_{resowing}$ = ½ x (1 ha x 4 h/ha x Salary/h)
$C_{re\text{-}sow}$ = 1 ha x 10 h/ha x Salary/h

Considerations on the optimal strategy for operating a pasture

We must consider the following key points when setting up a pasture:

- The **starting situation of the area** where the pasture is going to be established determines all the subsequent costs. The fewer actions that have to be done, the sooner the pasture will be profitable.
- The **cost of the seeds** varies completely depending on the species, the price per kg and the amount of kg to be sown. **It is necessary to perform a detailed study of the most suitable mixture to sow in a pasture**, considering all the possible conditions (climate, species, exploitation objectives, etc.).
- If it is possible to **sow with a direct seeding seeder, it is recommended**, although the cost is higher, since the process is much more controlled. With broadcast seeding, if there is no rain or no flocks of birds come, a very small emergence occurs and it is necessary to re-sow.
- **Irrigation has a significant cost**, but if there is water nearby, it ensures that the production of the pasture is much higher.

Parameter	Unit	Value used	Variability and causes
Time to prepare the land	h/ha	very variable	It is very variable but it completely determines the costs that will be in putting the pasture ready
Efficiency to clear the previous vegetation with a hammer brush cutter	h/ha	8	It again depends on the starting situation. It also varies considerably on the type of machine
Rental cost of a forestry hammer brush cutter	€/h	80	It depends on the offer in the area
Cost of seeds for sowing	€/ha	100	It ranges from €100 to €200/ha
Cost of the direct seeding seeder	€/day	350	It is a very high cost that is only justified if the surface is large
Broadcast sowing time	h/ha	4	It can range from 3 to 5 depending on the skill of the workers
Irrigation system including tubes and sprinklers	€/ha	500	It may vary slightly depending on the models of tubes or sprinklers
Re-seeding time	h/ha	2	Estimated as half of the sowing time
Time to remove the sprouts of shrubs and trees	h/ha	10	It can also vary depending on the number of resprouting species in the area

Table 1. Parameters used to calculate the costs of the setting up a pasture, indicating the values used in Polyfarming and any variability that can occur in these values.

Costs and key points of raising young chicks and rabbits

Chick rearing has two main types of costs: (1) costs of the rearing structures, which include the box with the outside patio, the infra-red lamps, feeders and drinkers; and (2) daily care costs, which include food and cleaning. The rearing of young rabbits also has two main types of costs: (1) installation costs of the cages, both for males and females; and (2) reproduction and rearing costs, which include mating and caring for the kits from hatching until they are transferred to the pasture.

Quantifying the costs of rearing chicks

The quantification of the installation and rearing of the chicks (**Figure 1**) until they are transferred to the pasture is based on calculating two different types of costs:

1. Cost of breeding structures.
2. Cost of daily chick care.

Next, we will describe the alternatives that we have analysed for each of these processes, indicating the costs they represent and their variability (**Table 1**).

1. Cost of breeding structures. Each rearing structure consists of **a large temperature-controlled box**, which is self-constructed from recycled insulating sandwich panel, and a front yard delimited with chicken wire on all sides (including the roof). In addition, there must be **two infra-red lamps** (**€25 for each one**, including installation), **two feeders** (**€12** each) and **drinkers** (**€8** for an initial one for when they are small, and **€23 for the bell drinker** that is then put on the patio when they are bigger).

2. Daily cost of feeding and caring for the chicks. The daily running costs of chick rearing include chick **feed for the 30 days before they are moved to the pasture**, and the staff to feed them and keep the structure clean.

From these considerations, we can establish a series of simple calculations to estimate the **overall costs of raising chicks before transferring them to pasture**. These calculations are based on raising a batch of 200 chicks. **The overall cost is the sum of two costs:**

$$C_{total} = C_{structure} + C_{daily\ operation}$$

Installation of a rearing structure:

$C_{structure}$ = 2 x € 25 (infrared lamps) + 2 x € 12 (feeders) + (8 + 23) € (drinkers) + drawer and patio (self-built)

Daily operation, **the sum of two costs (per batch of 100 chicks):**

$C_{feeding}$ = 1 month x 0.75 kg feed / (month and chick) x € 0.34 / kg x 100 chicks + 0.25 h/day x Salary/h x 30 days

$C_{cleaning}$ = 0.25 h / day x Salary/h (3 days per week)

Figure 1. Structure for chick rearing at the Planeses farm. Photo: Marc Gràcia.

• The chicks are fed for 30 days with a monthly quantity of 0.75 kg per chick of feed at a cost of **€0.32-0.36/kg**. Other materials used such as biochar, apple cider vinegar, fermented garlic and straw for the bed have a very low cost or are products generated directly on the farm at no additional cost.
• To this must be added the **time spent by a worker** feeding and cleaning the chick cages (about **0.25 h** per day and per cage, in total **2-3 days per week**).

Quantification of the costs of rearing young rabbits

The quantification of the installation and rearing of young rabbits until they are moved to the pasture is based on calculating two different types of costs:

1. Cost of installing the cages.
2. Cost of reproducing and rearing young rabbits.

Next, we will describe the alternatives that we have analysed for each of these processes, indicating the costs they represent and their variability (**Table 1**).

1. Cost of cage installation. This cost includes the cost of individual cages for males and females. The cages that we used are commercial metal galvanised wire cages, which have a market price (€50 per cage) but can also be obtained second-hand at a cheaper price. The cages for the males are cylindrical cages so that the female does not escape, and they cost about €90 per cage.

2. Cost of reproducing and rearing young rabbits. The production of young rabbits includes reproduction by adult rabbits and the feeding and care of the young rabbits for 30 days until they are ready to move to the pasture.

• Rabbit reproduction requires keeping **male and female in separate cages**. The transfer of the female to the male's cage, courtship and copulation are very fast, and **in less than 0.25 h the female is back in her cage.**

• Female rabbits should be fed **during the 31 days of pregnancy and 30 days of weaning** with a monthly amount of **8 kg of feed** with an approximate **cost of €0.5/kg**. An equivalent amount is needed to feed the male that performs the copulation. To this must be added the time spent by one worker feeding the rabbits and cleaning the cages (about 2 h per week for 25 rabbits). Finally, the cost of the vaccines for the average 10 young rabbits produced at each farrowing must be considered, but it is a small cost compared to the others.

From these considerations, we can establish a series of simple calculations **to estimate the total costs of raising rabbits until they are transferred to the pasture**. These calculations are based on raising a batch of 10 rabbits produced in a single parity**. The overall cost is the sum of two costs**:

$$C_{total} = C_{infrastructure} + C_{operation}$$

Installation of infrastructure, sum of two costs:

C_{cages} = € 50/cage (female) + € 90/cage (male)

Operation (per month), the sum of two costs:

$C_{reproduction}$ = 0.25 h x Salary/h (preparation and copulation)

$C_{feeding}$ = 8 kg feed/month x 2 months x 0.5 €/kg (the same for males as for females) (feeding) + 8 h/(25 cages and one month) x Salary/h (cleaning and food)

Considerations on the optimal strategy for rearing young chicks and rabbits

The **key points** to consider when raising chicks and young rabbits are the following:

Chicks

- It is convenient to bring the chicks to the farm when they are one day old: they are cheaper than if they are brought in later and they work perfectly.
- There are many breeds of chickens, **the Planeses farm works with the Broiler breed**. There are other breeds that get bigger or have slower growth. In these cases, the parameters that have been given in this sheet may vary.
- When working in **larger spaces with more chicks, it is often more cost-effective to use gas heating** instead of infra-red lamps.

Young rabbits

- In the breeding of young rabbits, a key point is to **control the pregnancy and delivery of the female rabbits**. It must be very clear when each female is going to be covered and when it is going to give birth. For this reason, it is essential to have a detailed file with all the information on each rabbit.
- During reproduction, **if the male does not fertilise the female in less than 5 minutes**, it is not worth continuing and it is **better to separate them both** to their cage.

Parameter	Unit	Value used	Variability and causes
Chick raising			
Maintenance time in the rearing structure	Day	30	It depends on the time of year, it may be less time, 3 weeks in spring and summer
Amount of feed to feed the chicks	kg/(month and chick)	0.75	-
Price of chick rearing feed	€/kg	0.34	There is a range according to the companies and cooperatives that sell it
Time to clean and feed a batch of 100 chicks	h	0.25	Time may be longer if it rains
Young rabbit breeding			
Cost of an individual cage for a female rabbit	€/cage	50	They are commercial cages, there are multiple models on the market
Cost of an individual cage for a male rabbit	€/cage	90	They are commercial cages, but bigger and cylindrical
Time to get the rabbit pregnant	h/attempt	0.25	This is the total time from when the female is caught in her cage, but if there is no copulation in 5 min it is better to separate them again.
Amount of feed to feed the female until weaning	kg/(month)	8	It is the same quantity to feed the female or the male.
Price of rabbit feed	€/kg	0.5	There is a range according to the companies and cooperatives that sell it
Time to feed the rabbits and clean the cages	h/month and 25 cages	8	-
Age at which young rabbits are placed in the pasture	week	4	Not less, if they are not, they are very small

Table 1. Parameters used to calculate the costs of raising chicks and young rabbits, indicating the values used in Polyfarming and any variability that can occur in these values.

Costs and key points of chicken production on pasture

The production of chickens on pasture has mainly two types of costs, since the costs of setting up the pasture are considered external to the system followed: (1) costs of installing the infrastructure, which include permanent external fencing, interior fences and mobile shelters; and (2) daily running costs, which include workers' time to move and feed the animals, the time to clear the plot before the chickens move on (only in spring), and the price of the feed for the animals.

Quantification of the costs of chicken production on pasture

The quantification of what is involved in the production of chickens on pasture (**Figure 1**) is based on three different types of costs:

1. Cost of setting up the pasture.
2. Cost of installing the infrastructure.
3. Daily running costs of the system.

Next, we will describe the different alternatives that we have analysed for each of these processes, indicating the costs they represent and their variability (**Table 1**).

1. Cost of setting-up the pasture. This cost includes defining a breeding area where there is or will be a pasture. The cost of installing the grassland depends on its surface. For a batch of **400 chickens in a 60-day rotation, an approximate area of 0.96 ha** is considered adequate, corresponding to the area per day for the **400 chickens (160 -16x10-m^2) for 60 days**. Therefore, two situations arise:

• In the case that the chicken farm is to be located in **an area where there is already a pasture, the cost can be considered 0**, since the activity of moving the chickens itself allows the grassland to be maintained at no additional cost. Once the chickens have moved on, it is a good idea to clear the brush from time to time to restore the grassland. In spring we must clear the brush even earlier, because the large amount of grass makes it difficult for the cages to be moved and the animals to move around the plot.
• If there is no pasture in the area chosen for exploitation, costs are incurred to develop it. These costs can be found in the sheet corresponding to the development of a pasture. In any case, **chickens in particular do not need a large pasture to start their production**, because they do not depend excessively on grass for their food and their presence ends up improving the pasture.

2. Cost of installing the infrastructure. This cost includes the exterior fencing of the entire pasture area, the interior fences to separate the daily plots, and the mobile shelters. The costs of such infrastructure are the following:

• **The permanent external fence is approximately 650 m for the area calculated for 400 chickens**. This can vary

Figure 1. Chickens on pasture in the Planeses farm. Photo: Ángela Justamante.

depending on the shape of the plot used. As there are dogs on the farm protecting against predators, it is done with **hunting mesh** (€3/m). If not, you should look for a stronger mesh (such as single-twist mesh), which also costs more. We make the interior mobile fences ourselves that delimit the daily plots. In total there are 10 units 3x0.9 m, which each cost about €15.
• A **shelter** consists of an iron structure without a floor (3 x 4 m) with a raised structure and wheels so they can be moved by hand every day. On the top is a canvas roof with cane that protects against water and sun. The **price** of each shelter of this type is **€200**.

3. Daily running costs of the system. The daily running of the entire chicken rearing system includes the **daily movement of the animals in the corridors established in the pasture**, and the **feeding of the chickens for a total of 60 days** until they have grown and ready to be sold. It starts with four-week-old chickens that have been raised on the farm from 1-day-old chicks (see the sheet "Costs and key points of raising young chicks and rabbits").

• Moving the animals includes **moving the mobile fences, shelter, feeders and drinkers**. This represents a total of **1 h per day of a farm worker** during the 60 days in which the chicks are growing.
• In **spring** the grass grows a lot and gets very tall. At this time, another **cost** must be considered: **the time to clear the plot**, which is 0.5 h of a worker per plot. In other seasons this cost does not exist.
• **Grass represents approximately 30-40% of the chicken's diet**. The rest must be provided in the form of feed. It is calculated approximately 7 kg of feed per chicken for the total of the **60 days of growth**. **The price of the feed may vary, but the organic one is around €0.58/kg**. The time spent by a worker feeding the chickens is included with that of moving the shelters.

From these considerations, we can establish a series of simple calculations to estimate the overall costs of chicken production on pasture in agriculture fields. These calculations are based on raising a batch of 400 chickens. The total cost is the sum of two costs, since the third, that of preparing the pasture, is considered in the corresponding card:

$$C_{total} = C_{infrastructure} + C_{daily\ operation}$$

Installation of infrastructure, the sum of two costs (per plot where there is a batch of 400 chickens):
C_{refuge} = € 200/refuge
C_{fences} = 650 m x € 3/m (outdoor fence) + 10 units x € 15/unit (mobile fences)

Daily operation, the sum of three costs (for each batch of 400 chickens):
$C_{movement\ /\ feed}$ = 1 h/day x Salary/h (from a batch)
$C_{clearing}$ = 0.5 h/day x Salary/h (per plot, only in spring)
C_{feed} = 400 chickens x 7 kg feed/(2 months and chicken) x 1 month/30 days x € 0.58/kg

Considerations on the optimal strategy for chicken production on pasture

We must consider the following **key points** in the production of chickens on pasture:

- As mentioned, **these costs do not include preparing the field for pasture**, which is a significant cost when starting a project. The details of these costs are in the sheet corresponding to the pasture.
- The **area of pasture per chicken is conditioned by the size of the animals**. If larger chickens are wanted, the number of chickens per batch would be lower and the area of pasture per chicken would increase.
- When chickens can grow larger, their droppings make the grass dirtier and it takes more time to return to the same plot.
- The data given in the file refer to the **Broiler breed**, which is a breed that grows very fast, but is not very large. If larger breeds of chickens are used, they will need more space on the pasture.
- **The proposed fencing is simple because there are dogs at Planeses and a more protected fencing system is not necessary**, which is also more expensive.
- The cost of having the chick from one day of age (when it arrives at the farm) until it is four weeks old and goes to pasture has not been considered in this sheet, since it is contemplated in another (Costs and key points of raising young chicks and rabbits).

Parameter	Unit	Value used	Variability and causes
Pasture area per chicken	m^2/chicken and day	0.4	It may be less. Salatin gives a value of 0.2 (70 chickens in 12 m^2)
Rotation	day	60	It may be shorter (up to 40 days), depending on whether the density of chicks is lower
Clearing the plot	h/plot	0.5	In spring, when the grass is very tall, it takes time to clear the plot. At other times it is 0.
Chicken shelter cost	€/shelter	200	These are self-built with a galvanised tube structure. They can be made of wood, which is somewhat cheaper
Cost of exterior fence with hunting mesh (includes mesh and bars)	€/m	3	It is a fence made with hunting mesh because there are dogs on the farm. If there are no dogs, the type of fence must be more resistant (e.g. simple torsion mesh) and the cost can increase up to €8-10/m
Cost of mobile fences 3x0.9 m	€/fence	15	These are self-built with a galvanised tube structure and chicken wire.
Time to move the plot	h	1	If it rains, it takes a bit longer. When there is a raven attack on small chickens (in spring) an aerial protection must be placed, which represents 0.5 h
Age at which chickens are placed on pasture	weeks	4	Some farmers do so at 3 weeks
Amount of feed to feed the chicken	kg/(2 months and chicken)	7	The total amount of feed that a chicken of average weight (2 kg) needs during the two months it is on the pasture is given. Not all seasons see the same consumption. In winter, consumption is higher than in summer
Time of chicken growth in the pasture	day	60	It varies slightly between summer and winter, because it takes a little longer in winter

Table 1. Parameters used to calculate the costs of producing chickens on pasture, indicating the values used in Polyfarming and any variability that can occur in these values.

Costs and key points of the production of rabbits on pasture

The production of rabbits on pasture mainly has two types of costs, since the costs of setting up the pasture are considered external to the system followed: (1) costs of installing the infrastructure, which includes permanent external fencing, interior fences and mobile shelters; and (2) daily running costs, which include time for workers to move the animals on the pasture, and time to clear the plot before the rabbits pass through (only in spring).

Quantification of the costs of producing rabbits on pasture

The quantification of producing rabbits on pasture (**Figure 1**) is based on calculating three different types of costs:

1. Cost of setting up the pasture.
2. Cost of installing the infrastructure.
3. Cost of daily maintenance of the system.

Next, we will describe the different alternatives that we have analysed for each of these processes, indicating the costs they represent and their variability (**Table 1**).

1. Cost of setting up the pasture. This cost includes defining a breeding area where there is or will be a pasture. The cost of installing the pasture depends on its area. For 40 rabbits in a rotation of 60 days, an approximate area of 0.96 ha is considered adequate. This corresponds to a **daily area of 160 m^2 (plots of 16x10 m) for the 40 rabbits**. Therefore, two situations arise:

• If the exploitation of rabbits is to be carried out in an **area where there is already a pasture, the cost can be considered 0**, since the activity of moving the rabbits itself allows the pasture to be maintained without an additional cost.
• If there is no pasture in the area chosen for exploitation, costs are incurred to develop it. These costs can be found in the sheet corresponding to the set-up of a pasture (see the "Costs and key points of setting up a pasture").

2. Cost of installing the infrastructure. This cost includes the exterior fencing of the entire pasture area, the interior fences to separate the daily plots, and the mobile shelters. The costs of such infrastructure are the following:

• The permanent exterior fence is approximately **650 m for the area calculated for 40 rabbits**, although it varies depending on the shape of the plot. This fence is made with **hunting mesh** (€3/m) because there are dogs protecting the rabbits from predators. If there were no dogs, we would have to look for a more resistant mesh. For its part, the **interior mobile fences** that delimit **the daily plots are made by us**, a total of 10 units of 3x0.9 m, each costing about €15.

Figure 1. Rabbits on pasturein the Planeses farm. Photo: Marc Gràcia.

The design is the same as for pasture chicken production.
• **A shelter consists of a self-built iron structure without a floor** (3 x 4 m) with a raised structure and wheels so that it can be transported by hand every day. It has a canvas roof with cane on top that serves as protection (in total €200 per refuge). A piece of wood is placed at the bottom of each shelter to protect the animals that hide underneath (€90).

3. Daily running costs of the system. The daily running of the entire rabbit system basically includes: the daily movement of the animals to the corridors established in the pasture. Food has practically no cost. The starting point is 4-week-old rabbits that have been raised on the farm by their own mothers (see the corresponding sheet on the production of young rabbits).

• Moving the animals includes **moving the mobile fences and the shelter**. This represents a total of 0.5 h of a farm worker during the 60 days in which the growth of the rabbits is maintained.
• In spring, it is often necessary to **clear the brush** before the rabbits' pass, because the large amount of grass makes it difficult for the cages to move and the animals to move around the plot. **Rabbits easily eat cut grass.**
• Rabbits feed mainly on grass, which represents between 80 and 100% of their diet. Therefore, there is no additional cost of feeding the rabbits.

From these considerations, we can establish a series of simple calculations to estimate **the total costs of the production of rabbits on pasture**. These calculations are based on raising a batch of 40 rabbits. The total cost is the sum of two costs, since the third cost, that of preparing the pasture, is considered in the corresponding sheet:

$$C_{total} = C_{infrastructure} + C_{daily\ operation}$$

Installation of infrastructure, the sum of two costs:

C_{fences} = 650 m x € 3/m (outdoor fence) + 10 units x € 15/unit (mobile fences)
$C_{shelter}$ = € 200 (shelter) + € 90 (wooden base)

Daily operation:

$C_{movement}$ = 0.5 h/day x Salary/h(per batch)
$C_{clearing}$ = 0.5 h/day x Salary/h
$C_{feeding}$ = 0

Considerations on the optimal strategy for rabbit production on pasture

We must consider the following **key points** in the production of rabbits on pasture:

- These **costs do not include preparing the land for pasture**, which is a significant cost when starting a project. The details of these costs are in the sheet corresponding to the pasture.
- It is **much more profitable to raise our own young rabbits on the farm than to buy them**, it requires minimal installation for females and males, but it pays off quickly.
- **It is proposed that the rabbits remain on the farm for up to three** months (one month with their mother and two in the pasture). At that time, they are not very big, but in general consumers prefer them rather small.
- At certain times we can add some **vegetable supplements**: if the grass is very tender, it is advisable to put something with more fibre **such as oak leaves**.
- A key point in the breeding of rabbits is that **they are very susceptible to predators**, Therefore, we must protect them well, even the dogs that watch them can harm them.
- Another fundamental point is that **they are also sensitive to many viral diseases**. Therefore, we must be very aware of when and what to vaccinate them with.

Parameter	Unit	Value used	Variability and causes
Pasture area per rabbit	m^2/rabbit and day	4	-
Rabbit shelter cost (includes the structure and the protective wood)	€/shelter	290	These are self-built with a galvanised tube structure. They can be made of wood, which is somewhat cheaper.
Cost of exterior fence with hunting mesh (includes mesh and bars)	€/m	3	It is a fence made with hunting mesh because there are dogs on the farm. If there are no dogs, the type of fence must be more resistant (e.g. simple torsion mesh) and the cost can increase up to €8-10/m.
Cost of mobile fences 3x0.9 m	€/fence	15	These are self-built with a galvanised tube structure and chicken wire.
Time to move the plot	h	0.5	If it rains, it takes a bit longer.
Age at which rabbits are placed in the pasture	week	4	It could be done a bit later but not before because they are too small.
Number of days of growth of rabbits on pasture	day	60	It may vary slightly between seasons.

Table 1. Parameters used to calculate the costs of producing rabbits on pasture, indicating the values used in Polyfarming and any variability that can occur in these values.

Costs and key points of managing cows on pasture through intensive controlled grazing

Managing cows in pasture through controlled intensive grazing has two types of costs because the costs of setting up the pasture are considered external to the system: (1) costs of installing the infrastructure, which include installing the electric fences, the system to bring water to the plots, and the barn; and (2) the daily running costs of the herd, which include workers' time to move and feed animals, time to clear the field after the cows pass (only in spring), forage price and milking time, if they are dairy cows.

Quantification of the costs of managing cows on pasture using intensive controlled grazing

The quantification of what it means to manage cows on pasture is based on three different types of costs:

1. Cost of setting up the pasture.
2. Cost of installing the infrastructure.
3. Daily running costs for the herd.

Next, we will describe the different alternatives that we have analysed for each of these processes, indicating the costs they represent and their variability (**Table 1**). The cost of the cows, which can range between **€1200 and €2500 per cow** (for the Simmental breed, which is the one we have used in the Polyfarming system), is not included and this is a mandatory initial cost if we start from 0.

1. Cost of setting-up the pasture. This cost includes defining the pasture area needed to manage the cow herd. The cost of producing the pasture depends on its area, the initial conditions and the possibility of mechanisation to perform direct sowing. Two situations arise:
• **If the cows will be used in an area where there is already pasture**, the **cost can be considered 0**, since moving the cows itself allows the pasture to be maintained at no additional cost.
• If there is no pasture in the area chosen for exploitation, **costs arise from setting it up**. These costs can be found in the sheet corresponding to the development of a pasture.

2. Cost of installing the infrastructure. This cost includes the exterior fencing of the entire pasture area and the electric fences to separate the plots. The costs of such infrastructure are the following:
• **The cost of placing the electric fence for the plots** includes the material and staff. The materials per 100 m of fence are: metal bars (€1/bar) every 6 m, 2 insulators (approximate price €32/100 units) and two electric wire lines (€15/200 m). These costs are about €41/100 m of fence (€16 for bars + €10 for insulation + €15 for wire). The **time for two workers to lay 100 m** would be **0.75 h**. For the system to work properly, it is necessary to consider in each case how many plots are needed to feed the cows throughout the year. This depends on the number of cows, the productivity of the pasture and the seasonality of the area.
• **The cost of installing the system to bring water** to all the plots depends on the design of the pasture. It includes the **hose system** (about 150 m of pipe per ha-price around €0.5/m and five taps to connect the hoses to the drinkers €12/tap) and the drinkers, which for less than 30 cows can be made with plastic drums at a very low cost (no more than €20 per drinker).
• A set of **permanent infrastructure is required, such as a stable** (which costs around **€6000** when there are no more than 20 cows), which is necessary both for health reasons, in case it is necessary to separate animals with a specific treatment, and for milking the cows when they are for milk.

3. Daily running costs for the herd. The daily running of the cow herd includes the following aspects.
• **Moving the animals** includes moving cows from one plot to the next. This represents a total of **0.5 h per day for a worker on the farm** every day of the year.
• The **clearing of the non-consumable vegetation** of each plot (mainly in spring) represents an average dedication of 1 hour per day of a worker in plots of 1000 m^2.
• The **pasture represents between 30% and 100% of the cows' diet** depending on the months, as indicated in the sheet for herd management on a pasture. The rest must be provided in the form of forage. Calculating an average of **27% forage each month**, each cow should receive an average of **5 kg of forage per day**, although distributed in different ways throughout the year. The price of forage can vary, but **small bales (20-30 kg)** cost around **€7/bale**, and **large bales (300-400 kg)** around **€60/bale**. When the forage comes from farm surpluses in times of high pasture production, there is no cost.
• To this must be added the **time spent by a worker feeding the cows: about 0.5 h per day**. When this contribution must be made, the forage must be loaded onto the trailer, taken to the field and distributed.
• **If the cows are dairy cows**, they are taken to the barn every day to be milked. **The milking time per cow is 5-10 min** (includes cleaning the teats, milking and sealing the teats). The total herd time is highly variable because it depends on the number of cows milked at the same time.
• **Other occasional costs are:** inseminating the cows (once a year) and carrying out a sanitary control (also once a year). These are basically veterinary costs, but also for the workers accompanying the veterinary and facilitating their work.

From these considerations, we can establish a series of simple calculations to estimate the **overall costs of managing cows on pasture through intensive controlled grazing. These calculations are based on a herd of 10 cows**. The total cost is the sum of two costs, since the third, that of setting up the pasture, is considered in the corresponding sheet:

$$C_{total} = C_{infrastructure} + C_{daily\ operation}$$

Installation of infrastructure (per 1000 m2 plot), the sum of three costs:

$C_{electric\ fences}$ = 120 mx 41 €/100m (electric fence per plot approximately 30x30 m -1000 m2-, includes poles and wires) + 120 mx (0.75h x 2 workers) / (100m) x Salary/h (work to assemble the wire around the 1000 m^2 plot).

$C_{irrigation\ system}$ = 15 m x € 0.5/m (pipe) + € 12 (tap) + 20 € (trough)

C_{stable} = 6000 € (complete stable, it is used for all plots)

Daily operation, the sum of four costs:

$C_{movement}$ = 0.5 h/day x Salary/h

$C_{clearing}$ = 11 h/day x Salary/h (only in spring)

C_{feed} = 5 kg forage/day and cow x € 0.3/kg x 10 cows (external forage) + 0.5 h/day x Salary/h (placement of forage on the plot) (only at certain times of the year)

$C_{milking}$ = 0.12 h/day and cow x Salary/h

Considerations on the optimal strategy for managing a herd of cows through intensive controlled grazing

The key points that we must consider in the management of cows on pasture are the following:

- **The preparation of the land for the pasture is not included**, the pasture should be available from the start.

- There are **very important differences in some of these calculations depending on the breed of the cows**, and if they are intended for milk or meat.

- **A key point is deciding how the calves are managed**. They normally work as a second herd, which has less demands than cows, especially if they are dairy cows. They can go behind them in the pasture plots.

- **Water is a very limiting factor**, since it **determines the growth of the pasture** and the amount of forage that must be obtained to supplement diet.

Parameter	Unit	Value used	Variability and causes
Cost of cows	€/cow	2000	There is a lot of variety, it depends on the breeds and their use.
Pasture area per cow	m^2/cow and day	75	50 in spring when there is a lot of grass, 100 in other seasons, some months the feed should even be supplemented.
Number of plots for the system to function all year round	plot	60	The best would be to have as many plots as days that have the longest optimal resting point in a year, it ranges between 60-80.
Cost of the fencing material of the plot	€/100m	41	It includes iron bars, insulators and wires. The fences that are next to roads have a higher cost because they are reinforced
Time to fence the plots	h/100 m and 2 workers	0.5	-
Stable cost	€	6000	This would be for 20 cows, it can vary greatly depending on use and size.
Drinker cost	€/drinker	20	It may vary according to the models. When there are many cows, large and expensive infrastructure are required
Installation of water	€/plot of 1000 m^2	40	It depends on where the water is to be drawn from. It includes the assembly, which is simple, of pipes, taps and drinkers.
Time to move the cows from one plot to another	h	0.5	It varies according to the distance between plots, and how long the cows take to respond
Time to clear non-consumable vegetation	h/1000 m^2	1	Mainly in spring. It depends on how much vegetation is left, so it can vary (0.5-1.5 h)
Amount of forage to feed the cows	kg/(day and cow)	5	It is a totally variable value between months, some should receive 15 and others do not need anything.
Forage price	€/bale	€7/small bale, €60/large bale	It is highly variable, the price per kg is higher for small bales (20-30 kg) than for large bales (300-400 kg)
Time to feed the cows	h	0.5	As has been said, in each month the amount is different and so too is the time therefore
Time to milk the cows	h/cow	0.12	The total time for the entire herd is variable because it depends on the cows that can be milked at the same time

Table 1. Parameters used in the calculation of the costs of the production of cows in pasture, indicating the values used in Polyfarming and the possible variability that can occur in these values.

Returns of the different activities

Costs of activities related to crops

- Costs and key points of managing fruit trees on pasture
- Costs and key points of managing a non-tillage orchard

Costs and key points of managing fruit trees on pasture

Managing fruit trees on pasture mainly has three types of costs: (1) costs of planting fruit trees, which is the price of young trees and that of planting them; (2) costs of irrigation and protection, which include an irrigation system extended throughout the plantation and individual protection of each tree; and (3) costs of the subsequent care of the trees, which include the corresponding phytosanitary checks and annual pruning, including those of the initial formation and those of the subsequent fruiting.

Quantification of the costs of managing fruit trees on pasture

The quantification of managing fruit trees on pasture (**Figure 1**) is based on calculating different costs:

1. Cost of planting fruit trees.
2. Cost of irrigation and protecting fruit trees.
3. Cost of after-care for trees.

Next, we will describe the different alternatives that we have analysed for each of these processes, indicating the costs involved and their variability (**Table 1**). The cost of installing the pasture or the livestock that will graze on it is not included, as they are part of other Polyfarming elements.

1. Cost of planting fruit trees. This cost has two components:

• The price of young trees planted varies greatly between **species**, but it also depends on the size within the same species. Any nursery can give very detailed values of these prices.

• The cost of planting the fruit trees first includes the **cost of making the holes to plant them** in: they have an approximate volume of 0.125 m^3 (0.5x0.5x0.5 m) and must be made with an excavator. The **excavator rental is €45/h** and includes the person who drives it. In each hole, 4-5 logs about 40-50 cm long are first introduced at the bottom (following the technique of trunk beds described in the corresponding sheet), branches and small trunks, a layer of earth and the fruit tree. Then the hole is plugged until it is filled again with the excavator. The complete time to finish this process is a maximum of 4-5 min per tree, depending on the rocks on the ground and therefore the time it takes to make the hole.

2. Cost of irrigation and protecting fruit trees. Once planted, there are two more costs to consider:

• There should be an **extended irrigation system that drip feeds all the planted trees**. This system has a large main pipe with a diameter that depends on the number of connected trees. The small tubes are connected to this pipe with the droppers **(€0.36/m tube + €0.2/dropper**) that carry the water to the fruit trees.

• An individual **protection system must also be installed for each tree**. The cost of the materials (three iron stakes and the wire) is **€3/protection** and the time to **install it is 5 min.** if there are no rocks, otherwise it costs more to drive the stakes.

Figure 1. Fruit tree on the Planeses farm. Photo: Javier Retana.

3. Cost of after-care for trees. After-care for fruit trees basically includes two aspects:

• **Periodic reviews** should be carried out to identify possible pests or diseases. The time required per tree is small, but it depends on the number of trees in the plantation. They must be repeated once every two months or once a month during the growing season. Products to treat pests or diseases are not included because the cost depends on the treatment that must be applied in each case.

• **Fruit trees should also be pruned annually.** The time devoted to each pruning depends on whether they are the initial formation prunings, which are very fast (**1-2 min per tree**) or whether they are subsequent fruiting prunings, in which case it depends on the diameter and height of the trees and may sometimes require lifting platforms to reach the top of the crown.

From these considerations, we can establish a series of simple calculations to estimate t**he total costs of managing fruit trees on pasture in an agricultural field**. The data are given per fruit tree planted. The overall cost is the sum of three costs:

$$C_{total} = C_{planting} + C_{irrigation\ /\ protection} + C_{after\text{-}care}$$

Planting fruit trees, the sum of three costs:
C_{fruit} = Price/tree (depends on the species and size)
C_{fruit}= 0.08 h x 45 €/h (excavator cost) + 0.08 h x Salary/h (farm worker) (following the process described above)

Irrigation and protection of fruit trees, the sum of two costs:
$C_{irrigation}$ = Main pipe price + (N m x € 0.36/m + € 0.2 (dropper) (tree pipe)
$C_{protección}$ = € 3/protection (materials) + 0.08 h x Salary/h (staff)

Cost of after-care for trees, the sum of two costs:
$C_{revisions}$= not evaluable (depends on the number of trees
$C_{pruning}$ = 0.03 h/tree x salary/h (formation pruning) or N h/tree x Salary/h (fruit pruning, depends on the size and the tree height)

Considerations on the optimal strategy for managing fruit trees on pasture

We must consider the following **key points** in the management of fruit trees on pasture:

- **The selection of the species depends on the farm's needs** and the climate of the area.
- If the trees are to grow in combination with animals, it is crucial to know if these animals will be large (**cows**) or not (**chickens, pigs**) to choose large or medium-sized fruit trees.
- We must bear in mind that, during the **first 5-7 years, fruit trees need care, but they do not produce.**
- **When the holes are made with the excavator, the cost of the excavator must be considered**, including its driver and a worker from the farm who is supervising and doing some of the work, such as placing the fruit tree or finishing caking the soil.

Parameter	Unit	Value used	Variability and causes
Price of the young fruit tree to plant	€/fruit tree	-	It varies completely according to the species and size of the trees
Volume of the hole to place the fruit trees	m^3	0.125	We make a hole the size of 0.5x0.5x0.5 m, although it can vary depending on the size of the fruit tree to be planted
Time to excavate and fill the hole of the fruit tree	min	4-5	It includes the whole process: making the hole, placing the logs, applying soil, placing the fruit tree and covering the hole
Rent of the excavator	€/h	45	This includes the person who operates it
Time for filling the hole for the fruit tree	h	23	This includes the whole process, trunk beds
Irrigation system	€/fruit tree	-	The cost of the main pipe depends on the number of trees connected, and that of the small pipe depends on the distance from the tree to the main pipe
Materials for the fruit tree protection structure	€/fruit tree	3	This includes wire and stakes
Installation time of the protection structure	min/fruit tree	5	The time may be longer if there are rocks in the ground that make it difficult to drive the stakes
Time to check for pests and diseases	min/fruit tree	-	This is very quick, but the total time depends on the number of fruit trees in the plantation
Number of revisions per year	number	8-12	Once per month in the growing season and two per month outside of it

Table 1. Parameters used in the calculation of the costs of the management of fruit trees on pasture, indicating the values used in Polyfarming and the possible variability that can occur in these values.

Costs and key points of managing a non-tillage orchard

Running a non-tillage orchard mainly has four types of costs: (1) irrigation costs, which include the cost of installing the hoses for the first time, the time to adjust them at the start of each growing period, and the time of the irrigation itself; (2) costs of planting, which include the price of the plant and the time to plant; (3) costs of controlling adventitious plants, including time to remove them on roads and between crops; and (4) costs of applying forest products and compost, including the time it takes to apply them.

Quantification of the running costs of a non-tillage orchard

The quantification of the functioning of a non-tillage orchard is based on calculating the various costs:

1. Cost of irrigation.
2. Cost of plantation.
3. Cost of controlling adventitious plants.
4. Cost of applying forest products and vegetable fertilisers.

Next, we will describe the different alternatives that we have analysed for each of these processes, indicating the costs they represent and their variability (**Table 1**). **The cost of livestock that can graze in the orchard is not included**, as it is part of a different element of Polyfarming.

1. Cost of irrigation. This cost includes four components:
• The first cost is the irrigation material. The most common system is based on having a **central pipe** (63 mm in Planeses) from which the smallest 40 mm **perforated hoses** come out for each line. In the Planeses orchard this system includes about 80 m of main hose pipe (price around €1.5/m) plus the variable distance to where the water source is, and 75 m of smaller pipe per line (€0.5/m).
• To this is added the cost of **making the trenches to introduce the hoses of the lines**. It can be done with a motor trencher (rented, €250/day), the worker walks at a normal walking speed (5-6 km/h, 1 km every 10 min), i.e. it takes 1-2 min to travel the 75 m. **If done manually, it takes longer,** approximately 30 min to dig the 75 m.
• At the start of each growing period it is necessary to **prepare the hose system**: dig them up, clean the holes, start watering, test that water comes out of all the holes and uncover those that are closed. In total, the time needed to prepare 100 m of hose can be estimated at half an hour.
• Finally, **the irrigation time itself is also considered**. In the first few days we should water every other day and after this time we should water depending on the weather. At Planeses, with the required flow rates, up to 4 lines can be watered at the same time for 20-30 minutes. **The time to change lines is very short**, but it forces a worker to be vigilant throughout the irrigation, although he/she may be doing other work.

2. Cost of plantation. The first cost to consider is the price of the plants, which can vary considerably depending on what is planted. The price of the plants depends on the species of plant that is planted, ranging between €0.1 and €0.2. Then there is **the time to plant them**. Normally, it is done manually, and it takes one garden worker 40 min for every 100 plants planted.

3. Cost of controlling adventitious plants. The costs of removing adventitious plants depend on where they grow in the garden:
• **Adventitious plants that come out on the main roads** or on the paths of the lines are cut with a brush cutter. In this case, it takes workers 2 minutes for each 75 m line, since they are walking slowly (about 3 km/h) and cutting the vegetation as they go.
• **Plants growing in the line or between crops have to be removed manually with scissors** so as not to disturb the crops. In this case, the yield is much lower: 1-1.5 h per 75 m line.

4. Cost of applying forest products and plant fertilisers. In all cases, the products are obtained directly from the orchard (manures) or from other uses of the farm such as the forest or animals (BRF, compost, biofertilisers), so **their cost can be considered 0**. There may be a cost for their application.
• The manures that are added to the orchard are the result of cutting dry crops or adventitious plants. Therefore, **no extra time dedicated to its application should be counted**.
• **BRF or compost is placed in the orchard trenches** early in the production period. The BRF takes approximately 0.75 hours to apply to the trench of a 75 m line.
• **Biofertilisers** should be applied every 2 days for the first 10 days, and each time it takes 4 min per 75 m line, including the time to recharge the backpack.
Once the orchard is working**, maintaining it involves other costs such as training some crops** (such as beans or tomatoes) **or harvesting the products obtained**. We have not included these costs, because they depend on the crops planted and the procedure followed at each farm.

From these considerations, we can establish a series of simple calculations to estimate the overall costs of running a non-tillage orchard. The overall cost is the sum of four costs:

$$C_{total} = C_{irrigation} + C_{planting} + C_{adventitious\ plant\ control} + C_{application}$$

Irrigation, the sum of four costs:

$C_{material}$ = 80 m x € 1.5/m (main hose, cost to be distributed among the different lines) + 75 m x € 0.5/m (smallest hose) (per 75 m bed)
$C_{installation\ (motor\ trencher)}$ = 0.03 h x Salary/h + 0.03 h x € 250/24h (per 75 m line)
$C_{installation\ (manual)}$ = 0.5 h/75 m line x Salary/h (per 75 m line)
$C_{adequacy}$ =0.5 h/100 m x Salary/h (every 100 m of hose)
$C_{irrigation}$ = 0 (if compatible with other jobs)

Planting, the sum of two costs:

C_{plants} = € 15/100 plants
$C_{plantation}$ = 0.66 h/100 plants x Salary/h (manual planting of 100 plants)

Control of adventitious plants, it depends on where they are:

C_{paths} = 2 min/line of 75 m (on paths)
$C_{trenches}$ = 60 min/75 m line (in the trench or between plants)

Products application (per 75 m bed), it depends on the prouduct we apply:

C_{BRF} = 0.75 h/75 m line x Salary/h
$C_{biofertilisers}$ = 0.06 h/75 m line x Salary/h (per application)
$C_{vegetable\ fertilizers}$ = 0

Considerations on the optimal strategy for operating a non-tillage orchard

We must consider the following **key points** in the functioning of a non-tillage orchard:

- The **installation and adaptation of irrigation** is key in an intensive cultivation such as an orchard, so irrigation is essential for its operation.
- The **cost of the plants** is totally variable, it will depend on the species and the quantity that is planted, as well as the time it takes to plant them.
- **Controlling adventitious plants** is one of the most important costs in a non-tillage orchard. And it is especially important to do it just before they can affect the crops, although in general it is a task that is performed almost continuously throughout the entire period of the orchard's operation.
- **The application of products**, such as **BRF** at the beginning, **vegetable manures** when they are produced, or **biofertilisers** at different times of crop growth, allow a healthy soil to be maintained with a high level of fertilisation.

Parameter	Unit	Value used	Variability and causes
Irrigation material – central hole	€/m	1.5	The total amount needed varies according to the layout of the orchard and the distance from the water source
Irrigation material – line hole	€/m	0.5	The cost per line depends on the length of the bed, in the case of Planeses they are 75 m long
Rental of the motor-trencher to make furrows in the orchard	€/day	250	The price may depend on the specific offer in the area
Time to make the 75 m trench with a motor trencher	min	2	It is the time it takes to slowly walk 100 m
Time to make the 75 m trench manually	min	30	We have to stop often and remove the soil that falls into the trench
Preparation time of the hoses at the start of the orchard season	h/100 m	0.5	It includes digging up the hose, cleaning the hole and testing that water comes out of all the holes
Cost of plants for planting	€/100 plants	15	It varies considerably depending on the species planted, and can vary between €10 and €20 per 100 plants
Cost of plants for planting	h/100 plants	0.66	This is the time it takes to do it manually, several tools may reduce it
Time to eliminate adventitious plants on the paths of the lines with a brush cutter	min/75-m line	2	We must progress slowly and cut the vegetation continuously
Time to remove the adventitious plants between the plants on the lines manually	min/75-m line	60	It can be more, up to 90 min, if there are lots of adventitious plants and they are in close contact with the crops
BRF application time	min/75-m line	45	Only applied once at the start of the production period
Biofertilisers application time	min/75-m line	4	They are applied every two days after planting, and then every 5-7 days as needed
Plant manures application time	min/75-m line	0	The manures are the result of cutting dry crops or adventitious plants, so there is no extra time for their application

Table 1. Parameters used in the calculation of the operating costs of a no-till orchard, indicating the values used in Polyfarming and the possible variability that can occur in these values.

Returns of the different activities

The Polyfarming system as a whole

• Balance of costs and incomes at farm level of the Polyfarming system I. Costs
• Balance of costs and incomes at farm level of the Polyfarming system II. Incomes and balance sheet

Balance of costs and incomes at farm level of the Polyfarming system I. Costs

In a model farm in which the different elements of the Polyfarming system work, the balance of costs and incomes obtained at farm level has been calculated. The annual costs of the different elements are around €148,666, broken down into the following four categories: labour (59.0% of the total, corresponding to 4.5 full-time workers), mechanisation (7.0%), external inputs (15.1%) and internal inputs (18.9%), which are inputs that need a certain element that come from another element within the farm itself.

A model farm to value the Polyfarming system

We have evaluated the main costs and incomes at the farm level of the Polyfarming system in a **model farm** in which the different elements of Polyfarming would operate. This **model farm consists of**: a) a 50-ha holm oak forest; b) a 7-ha dehesa obtained by intense forest thinning; c) a 7-ha pasture divided into plots where a herd of 10 cows and 20 calves graze (Pasture 1); d) a crop of 700 fruit trees (almond trees) already in production installed on the separation lines of the pasture plots; e) a pasture of 2 ha, where 960 rabbits and 2,400 chickens graze (Pasture 2); f) a 2-ha extensive crop in which there is an active perennial pasture in summer, and a winter cereal crop and g) a 1-ha no-tillage garden where there are two mobile poultry houses with 200 hens in total.

Costs of the different elements in the Polyfarming system

The annual costs of a farm like the one described are around €148,666. The costs have been broken down into four categories (**Table 1**): **labour, mechanisation, external inputs and internal inputs from the farm itself.**

- **The labour costs** are €87,655, which represents 59.0% of the total annual expenses of the farm. In total they represent 4.5 workers hired full time.
- **The mechanisation costs** are €10,450, 7.0% of the total annual expenses. They include the tractor to remove the logs when the farm does not have one, the seeder for direct seeding and the combine harvester for extensive crops, and the transport and external slaughterhouse for calves.
- **The costs of external inputs** to the farm represent €22,497, 15.1% of the total. They include diesel and oil for the chainsaw, seeds, seedlings, forage, feed, grain and new-born chicks.
- Finally, **the costs of internal inputs** of the farm itself are €28,064, 18.9% of the total, mainly grass. They are expenses that are produced in elements of the farm itself, so they do not represent an additional cost.

By elements, the highest annual costs are those of the garden (€25,376), chickens (€22,269) and forest (€19,500), in all cases without counting the costs of internal farm inputs. On the other hand, the lowest costs are those of extensive crops (€682), dehesa (€1,218) and chicken and rabbit pasture (€2,508).

Labour (a)	Mechanisation (b)	External inputs (c)	Internal inputs (d)	Annual costs (a+b+c+d)
		FOREST		
Log cutting, limbing and dragging: 2 workers * 100 days * 8 h/day * €12[(1)]/(h and worker) = €19,200	**Tractor for dragging logs** (if it not available on the farm): €50/day * 100 days = €5,000	**Chainsaw gasoil:** 1 tank/h * 0.37 l/tank * €1.2/l *2.5 h/day * 100 days = €111 **Chainsaw oil:** 1 tank/h * 0.25 l/tank * €3/l *2.5 h/day * 100 days = €188	0	€24,500 or €19,500 (not counting the tractor)
		DEHESA		
Movement of animals (included in each animal) **Reseeding** (broadcast and every 5 years): 7 ha x 2 h/ha * €12(1)/h = €168	0	**Seeds for reseeding:** 7 ha * 5 kg/ha x €30/kg = €1,050 (every 5 years)	0	€1,218 (every 5 years)
		PASTURE 1		
Movement of animals (included in each animal) **Clearing of unconsumed vegetation** (in the establishment phase): 1 h/plot * 365 plots of 1,000 m² * €12/h [(1)] = €4,380 **Mowing with a brush cutter** (when there is excess grass): 1.5 h/1.5 h/plot of 1,000 m² * 40 plots/month * 3 months * €12/h [(1)] = €2,160 **Reseeding** (broadcast and every 5 years): 7 ha x 2 h/ha * €12 [(1)]/h = €168	Due to the size of the Pasture 1, it is not profitable to use a direct seeding seeder for reseeding, it must be done manually.	**Seeds for reseeding:** 7 ha * 5 kg/ha x €30/kg = €1,050 (every 5 years)	0	€7,758
		PASTURE 2		
Movement of animals (included in each animal) **Clearing of unconsumed vegetation** (separating one ha for chickens and one ha for rabbits): 0.25 h/plot of 160 m² * 80 plots/month * 3 months * €12/h [(1)] = 720 **Mowing with a brush cutter** (when there is excess grass and separating one ha for chickens and one ha for rabbits): 0.5 h/plot of 160 m² * 80 plots/month * 3 months * €12/h [(1)] = €1,440 **Reseeding** (broadcast and every 5 years) 2 ha x 2 h/ha * €12/h[(1)] = €48	Due to the size of the Pasture 2, it is not profitable to use a direct seeding seeder for reseeding, it must be done manually.	**Seeds for reseeding:** 2 ha * 5 kg/ha x €30/kg = €300 (every 5 years)	0	€2,508

Mano de obra (a)	Mechanisation (b)	External inputs (c)	Internal inputs (d)	Annual costs (a+b+c+d)
EXTENSIVE CROPS				
Seeding: 2 ha * 2h/ha * €12/h [1] = €48 **Harvest:** 2 workers * 1 h * €12/(h and worker) [1] = €24	**Direct seeding seeder:** 2 ha * 0.5 days/ha * €350/day = €350 **Combine harvester:** 2 ha * 0.5 h/ha * €100/h = €100	**Seeds** (with half density) 2 ha * 4 kg/ha x €20/kg cereal = €160	0	€682
FRUIT TREES				
Plantation: 0.1 h/ fruit tree * 700 fruit trees [2] * €12/h = €840 **Pruning** (annual pruning + collection of remains) (0.25 h+0.1 h)/fruit tree * 700 fruit trees * €12/h [1] = €2,940 **Harvest** (manual, with rod and canvas): 0.15 h/fruit tree * 700 fruit trees * €12/h [1] = €1,260	**Excavator** (renting): 0.08 h/fruit tree * €45/h * 700 fruit trees = €2,520	**Seedlings** (almonds): €12/fruit tree * 700 fruit trees = €8,400	**Log beds** (production): 0.25 m^3 (1 trunk of 20 cm diameter and 2 m length)/ fruit tree * 700 fruit trees * €60/m^3 = €10,500	€4,200 (without plantation) €22,260 (only plantation)
GARDEN CROPS				
Irrigation (preparation): 0.5 h/100 m * 7,500 m * €12/h [1] = €450 **Planting:** 0.66 h/100 plants * 24,200 plants [3] * €12/h [1] = €1,916 **Adventitious plant control**: (three times per plantation) (on the roads) 2 min/(line and day) * 100 lines * 6 days * 1 h/60 min * €12/h = €240 (in the ditch or between crops) 60 min/(line and day) * 100 lines * 6 days * 1 h/60 min * €12/h [1] = €7,200 **Application of BRF and biofertilisers:** (BRF) 0.75 h/line * 100 lines * €12/h [1] = €900 (biofertilisers) 0.06 h/(line and time) * 100 lines * 20 times (once every two weeks) * €12/h [1] = €1,440 **Harvest:** (mean estimation between May and December): 4 h/day * 200 days * €12/h = €9,600	0	**Seedlings** €15/100 plants * 24,200 plants = €3,630	**BRF** (production): 0.5 m^3/line of 75 m*100 lines * 3 h/m^3 BRF * €12/ day = €1,800	€27,176 (counting internal inputs) €25,376 (without counting internal inputs)
COWS				
Functioning: 3 h/day including movement (0.5 h/day), feeding (0.5 h/ day, several months), clearing the plot (1 h/day), milking (1 h/day) * 365 days * €12/h [1] = €13,140	0	**Forage:** [4] 10,746 kg/DM * ((0.6 * 1 bale/150 kg DM grasses * €35/bale) + (0.4 * 1 bale/200 kg DM alfalfa * €60/bale)) = €2,794	**Grass:** 12.5 kg DM/(cow and day) [5] * 365 days * 10 cows * ((0.6 * 1 bale/150 kg DM grasses * €35/bale) + (0.4 * 1 bale/200 kg DM alfalfa * €60/ bale)) [6] = €11,862	€27,796 (counting internal inputs) €15,934 (without counting internal inputs)
CALVES				
Functioning: movement (0.5 h/day) * 365 days * €12/h [1] = €2,190	**Transport and slaughterhouse** (external): €500/calf * 10 calf = €5,000	0	**Grass** (calves in Pasture 1, dehesa and extensive crops): 200 kg weight/calf * 0.025 kg DM/(kg weight and day) [7] * 20 calves *365 days * 1 bale/150 kg DM grasses * €35/bale = €8,516	€15,706 (counting internal inputs) €7,190 (without counting internal inputs)
RABBITS				
Functioning Rabbits: movement (in combination with the transport of chickens) 0.5 h/day * 365 days * €12/h = €2,190 **Young rabbits:** feeding and cleaning of breeding individuals 8 h/(25 cages and month) * 12 months * €12/h [1] = €1,152 **Slaughterhouse** (own): 1 h/6 rabbits * 960 rabbits * €12/h [1] = €1,920	0	**Feed** (breeding individuals, both males and females): €0.5/kg * 8 kg feed/month and rabbit * 12 months * 20 rabbits = €960	**Grass** (rabbits in pasture 2): 2 kg weight/rabbit * 0.15 kg DM/(kg weight and day) [8] * 960 rabbits * 60 days * 1 bale/150 kg DM grasses * €35/bale = €4,032	€10,254 (counting internal inputs) €6,222 (without counting internal inputs)
CHICKENS				
Functioning Chickens: movement, feeding 1.5 h/day * 365 days * €12/h = €6,570 **Chicks:** feeding and cleaning 0.25 h/day * 155 days * €12/h [1] = €465 **Slaughterhouse** (own): 2,400 chickens * 1.5 €/chicken = €3,600	0	**Feed** (chickens): €0.58/kg * 7 kg/chicken * 2,400 chickens = €9,744 **Feed** (chicks): €0.36/kg * 0.75 kg/chick * 3000 chicks = €810 **Chicks** (of one day): €0.36/chick * 3,000 chicks = €1,080	**Grass** (30% of the diet of chickens in pasture 2): 3 kg DM/chicken * 2400 chickens * 1 bale/150 kg DM grasses * 35 €/bale = €1,680	€23,949 (counting internal inputs) €22,269 (without counting internal inputs)
HENS				
Functioning: opening to the garden, feeding 0.5 h/day * 365 days * €12/h [1] = €2,190	0	**Grain:** 0.32 €/kg * 0.11 kg/ hen and day * 365 days * 200 hens = €2,570	0	€4,760

[1] A salary of €9/h (plus Social Security) is considered for an agricultural worker.
[2] The fruit trees are distributed every 10 m along the separation lines of the plots, in a density of about 100-120 per ha, in total 700 trees.
[3] Sum of the annual planting of all the products broken down in **Table 2** of the following sheet.
[4] It is the forage necessary to complete the feeding of cows and calves in times when there is not enough grass in the meadow.
[5] Value obtained from Wattiaux (1996) for 500 kg cows and a production of 10 l of milk per day.
[6] Dairy cows are fed a 60:40 ratio of grass and legume forage (alfalfa). When bales are supplied, grass bales weigh about 350 kg and are priced around €35/bale, while alfalfa bales weigh about 400 kg and are priced around €60/bale.
[7] In Perramón (2016) it is indicated that each calf consumes 2.5% of its weight in kg of DM every day.
[8] In the FAO report (1996) it is indicated that each adult rabbit consumes 15% of its weight in kg of DM every day.

Table 1. Expected costs for labour, mechanisation, external inputs and internal inputs of the different elements of the Polyfarming system in the model farm described in this sheet.

Balance of costs and incomes at farm level of the Polyfarming system II. Incomes and balance sheet

In a model farm in which the different elements of the Polyfarming system operate, the annual income from the outputs of the different elements is around €214,415. The total balance sheet at farm level between income and total costs is positive whether the intermediate products produced in elements of the farm itself are included (+ €65,749) or not (+ €93,773). These results are based on optimal yields that allow minimising expenses and maintaining the expected income in all the elements, but they can be greatly modified when not all the elements proposed are available or when climatic variations occur that can affect the mortality of animals and plants.

Incomes in the different elements of the Polyfarming system

The expected annual income from the outputs of the different elements of the Polyfarming system reaches a total of €214,415 (**Table 1**). In some cases, estimates have been made based on information published in the literature, since they have not yet been measured at the Planeses farm. **By type of output**, the highest incomes are those from vegetables from the garden (€53,515), milk from cows (€42,000), chicken meat (€33,600), fruit from fruit trees (€28,000) and firewood from the forest (€24,000). In addition to external outputs, **there are a number of intermediate products,** mainly grass, but also grain, which are produced on the farm and used on the farm itself. These represent a total of €23,918 that must not be bought externally.

Balance of costs and incomes at farm level

The total balance sheet for the entire model farm is the difference between the **total costs** (calculated in the previous sheet) and the **total income** (calculated in the previous section). If all the costs that the farm would have incurred are included, **including those of intermediate products** that are produced in elements of the farm itself to be consumed in other elements of the farm, the balance sheet is as follows:

$$\text{Farm}_{\text{balance}} = \text{Farm}_{\text{incomes}} - \text{Farm}_{\text{costs}} = €214,415 - €148,666 = €65,749$$

Element	Output	Quantity in time (a)	Number of times per period (b)	Price per unit (c)	Annual income (a*b*c)
Forest	Firewood	4 Tm/day	100 days	60 €/Tm	€24,000
Dehesa	Forage	3000 kg MS/month [1]	3 months	Grasses: €35/150 kg DM	€2,100
Pasture 1	Forage	62,379 kg DM annually [3]	1 year	Grasses (60%): bale €35/150 kg MS Legumes (40%): bale €60/200 kg MS	€16,218
Pasture 2	Forage	17,822 kg DM/ha annually	1 year	Grasses: bale €35/150 kg DM	€4,158
Extensive crops	Forage	,719 kg DM/ha * 2 ha	1 time	Grasses: bale €35/150 kg DM	€802
Extensive crops	Grain (wheat)	1,000 kg/ha [3] * 2 ha	1 crop	€0.32/kg	€640
Fruit trees	Fruits (almonds)	110 kg/tree with irrigation[4] * 700 trees	1 crop	€4/kg [5]	€28,000
Garden crops	Vegetables	The amounts by crops are in Table 2 [6]	6 months	€8,919/month	€53,515
Cows	Milk	7 l/cow and day * 10 cows (one milking per day)	300 days (10 months per year)	€2/l [7]	€42,000
Calves	Meat	0 calves/year * 400 kg/calf * 0.33[8]	1 year	€10/kg meat	€13,200
Chickens	Meat	200 chicken/month * 2 kg/chicken	12 months	€7/kg meat	€33,600
Rabbits	Meat	80 rabbits/month	12 months	€10/rabbit	€9,600
Hens	Eggs	200 hens * 180 eggs/hen per year	1 year	€3.5/12 eggs	€10,500

(1) Only the amount consumed by the calves during the months they spend in the dehesa is counted.
(2) The amount of grass produced in the meadow by adding the production of each of the seven periods per year and using the following equation for each one: Production (kg DM/ha) = 52.7 + 1.6 * Pasture height (cm).
(3) The average production of wheat in rainfed ranges between 2,800 and 3,000 kg/ha. One third of this harvest is given because the sowing is done at one third density.
(4) Average production of 10 to 15 kg of almonds per tree, in irrigated fields or in fresh drylands.
(5) Average price of the Lonja de Reus in November 2020.
(6) Table 2 details the indicative quantities of the different crops installed in the orchard, their prices and the income obtained from each one.
(7) This is the sale value for the subsequent production of yogurt, it is not the sale value of milk directly.
(8) Carcass live weight yield is estimated at 50% (although it can reach 60% with great differences according to breeds and weights at the time of slaughter) and finally 33% of the meat remains.

Table 1. Expected annual income from the outputs of the different elements of the Polyfarming system in the model farm described in the previous sheet. Intermediate products that are not sold, but are used in other elements of the farm are in red.

CROP	LINES	PLANTATION	PRODUCT	PRICE PER UNIT	TOTAL INCOME
Lettuce	10	Every 25 cm, 300 per line, 3,000 overall	3,000 units	€0.9/unit	€2,700
Tomato	10	Every 40 cm, 190 per line, 1,900 overall	4 kg/plant	€1.8/kg	€13,680
Pea	5	Every 40 cm, 190 per line, 950 overall	1 kg/plant	€4.3/kg	€4,085
Broad bean	5	Every 60 cm, 125 per line, 625 overall	2 kg/plant	€1.7/kg	€2,125
Aubergine	10	Every 40 cm, 190 per line, 1,900 overall	2 kg/plant	€2.2/kg	€8,360
Bean	5	Every 40 cm, 190 per line, 950 overall	1 kg/plant	€4.5/kg	€4,275
Cabbage	20	Every 60 cm, 125 per line, 2,500 overall	2,500 units	€1.3/unit	€3,250
Celery	5	Every 50 cm, 150 per line, 750 overall	5 u/ bunch	€0.9/bunch	€135
Beet	10	Every 25 cm, 300 per line, 2 per hole, 6,000 overall	5 u/ bunch	€1.2/bunch	€1,440
Chard	5	Every 25 cm, 300 per line, 2 bunches per plant, 3,000 overall	0.5 kg/bunch	€1.0/bunch	€1,500
Pumpkin	20	Every 100 cm, 75 per line, 1,500 overall	3 units of 1.5 kg each	€1.4/kg	€9,450
Leek	5	Every 20 cm, 375 per line, 2 per hole, 3,750 overall	5 units/bunch	€1.5/bunch	€1,125
Onion	5	Every 10 cm, 750 per line, 2 per hole, 7,500 overall	7 units/kg	€1.3/kg	€1,390

Table 2. Indicative quantity of plants installed in the orchard of the different crops throughout a year, and annual incomes obtained from each one. The prices per unit have been obtained from the catalogues of the farmers' associations Xarxa Pagesa and Hortec for 2020.

However, the balance sheet **not considering the cost of these intermediate products** is quite different, as seen below:

$$Farm_{balance} = Farm_{incomes} - Farm_{costs} = €214{,}415 - €120{,}642 = €93{,}773$$

Considering the **different elements** that have a product that is sold outside the farm separately, we obtain the following:

- In the case of the **forest**, and considering that the farm has a tractor, so its rent does not have to be recorded, the income from firewood (€24,000) considerably exceeds the annual costs (€19,500).
- The balance of the **fruit trees** is very positive, since the annual income (€28,000) is much higher than the expenses (€4,200), although it must be taken into account that the initial planting costs are very high (€22,260) and that the fruit trees take quite a few years to enter production.
- In the case of the **garden**, the costs are very high (€25,376), but they are offset by high income too (€53,515).
- The balance sheet of the **cows** is clearly positive between income from milk (€42,000) and costs (€15,934), even if the grass they consume was counted (€11,862).
- Calves also have a positive balance **sheet** between income (€13,200) and costs (€7,190), although without accounting for the grass they consume (€8,516).
- In the case of **rabbits**, the expected income from the sale of meat (€9,600) exceeds the annual costs (€6,222), provided that the costs of the grass they consume in the meadow (€6,048) are not counted.
- Regarding **chickens**, the expected income from the sale of meat (€33,600) considerably exceeds the annual costs (€22,269), and in this case the costs are not greatly increased by internal inputs (€1,680).
- Finally, for **hens**, the expected income from eggs (€10,500) also considerably exceeds the annual costs (€4,760).

Aspects to consider about variations in the balance sheet at farm level

The above values are based on optimal returns that allow us to minimise expenses and maintain expected incomes in all elements of the farm. However, in many cases the internal or **external conditions of the farm do not allow the project to be developed in optimal conditions:**

- First, it must be considered that **only production costs have been included**, but that a farm has other management and marketing expenses that, in this case, have not been taken into account. The costs until the production of the raw material have been considered, the possible costs of processing the products have not been included, which also have a different sale price. Furthermore, all products have been considered to be sold at the proposed price, which is often not possible.
- **Frequently, it is not possible to have all the elements** proposed in this pilot farm and, on occasions, not all are in production due to various circumstances. Depending on which is not in operation at a certain time or a certain farm, the result of the balance is obviously different.
- On the other hand, **the possible climatic variations** that may occur, such as periods of extreme heat or extreme cold that can greatly affect the survival and growth of animals, or periods of extreme drought that can limit the growth of plants, mainly those of the pastures, should be considered. Major natural catastrophes like the recent Gloria storm can also cause significant facility losses.

In any case, the results of costs, income and balances of Polyfarming as a whole and of the different elements separately allow us to quantify the factors that can modify them and to know that it can be more or less profitable for the farm, depending on the situation that arises at each moment. These calculations incorporate the idea that, in Polyfarming, with the same staff, work is optimised in time and space, and, in addition, the by-products of one element are used for others within the farm.

Benefits of the Polyfarming system

- Environmental, productive and economic benefits

Benefits of the Polyfarming system

Environmental, productive and economic benefits

- Main benefits of the Polyfarming system
- Improvement of soil conditions
- Increase in biodiversity I. Soil organisms
- Increase in biodiversity II. Birds
- Reversal of rural abandonment

Main benefits of the Polyfarming system

The application of the Polyfarming system has important benefits on an environmental, productive and economic level. Specifically: (1) improving soil conditions, (2) increasing carbon sequestration and combatting climate change, (3) reducing fire risk, (4) increasing biodiversity, (5) greater diversity and quality of the products obtained, and (6) reversal of the tendency to abandon the rural environment.

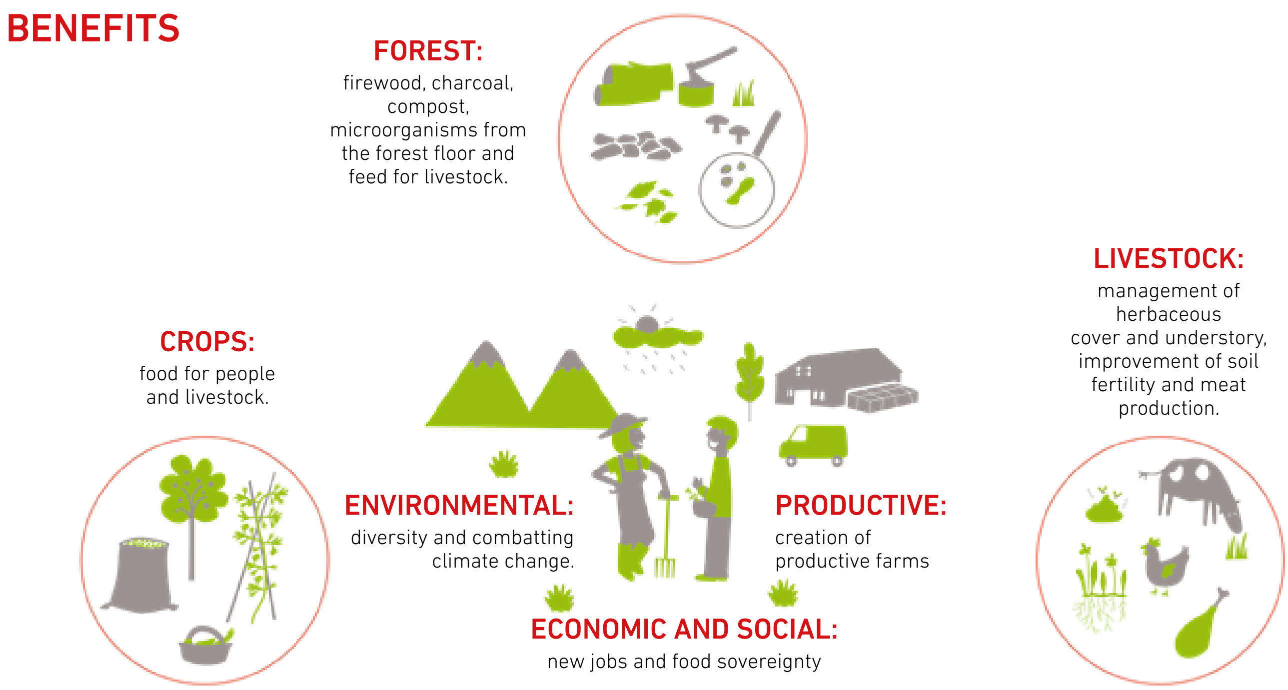

Figure 1. Scheme that reflects the benefits derived from applying the Polyfarming system

Environmental, productive and economic benefits of the Polyfarming system

The multi-functional management of mountain farms, as is the case of the Polyfarming system, has numerous benefits on all levels (**Figure 1**).

A) Environmental benefits. The Polyfarming system uses techniques that improve soil conditions, this translates into an increase in **carbon sequestration in the soil**, thus contributing to the fight against climate change. In turn, it creates discontinuity at landscape level and at local level, and thus **reduces the risk of fire** and generates habitats, thus increasing plant and animal biodiversity.

B) Productive benefits. The farms managed according to the Polyfarming system become productive. The techniques proposed by this system make it possible to **improve the farm's resources**, creating a new production system in which synergies are established between the different uses and which is managed with less dependence on external inputs. This results in **healthier and more nutritious food**, which is free of pesticides, fertilisers and drugs.

C) Economic and social benefits. The Polyfarming system benefits farmers since it presents an **economically viable** alternative for the recovery of abandoned farms of the Mediterranean mountain.

Here are some of the main beneficial impacts after the application of the Polyfarming system.

• Improvement of soil conditions

The regenerative model has the main objective of improving soil conditions. Therefore, the Polyfarming system focuses on recovering its vegetation **cover and introducing organic matter into the soil**. All this entails a series of improvements in soil conditions, specifically:

- **The structure and fertility** of the soils improves by leaving the plant materials on the surface. This facilitates the recovery of organic matter and the soil trophic network, and allows the reduction of the use of machinery, which also reduces the presence of uncovered soil and the risk of erosion.
- The increase in soil organic matter also leads to an **increase in its water retention capacity** since the organic

fraction of the soil is highly hydrophilic. This increases the usable water for the plants.

• Increase in carbon sequestration and fight against climate change

Climate change is one of the main risks facing the planet, especially in the Mediterranean region. The Polyfarming system achieves a positive carbon balance of the productive system at the farm level:

- On the one hand, there is a **greater sequestration of carbon in the soil** by two different processes: increasing the organic matter in the soil and not tilling it. The application of the different techniques proposed in the Polyfarming system represents an important incorporation of organic matter into the soil. This promotes the creation of stable humus in the soil as a result of its biological activity. But it is also that when the soil is ploughed its structure is destroyed and a large part of the carbon it contains is released. On the other hand, the regenerative model, though not tilling and covering the soil with plants, reverses this process. The regenerative model developed at Polyfarming implies that soils do not lose carbon, but rather store it.
- On the other hand, with the Polyfarming system, **greenhouse gas emissions** are significantly reduced, since the regenerative model does not have inputs of pesticides and synthetic fertilisers, which require a high energy cost to be produced. In addition, it needs much fewer fossil fuels due to less use of heavy machinery.

• Reduction of fire risk

The Polyfarming system, like other agrosilvopastoral systems, **represents a good way to reduce the risk of fire**, which has been increasing in recent decades due to the disappearance of open spaces (crop fields, pastures and dehesas) and the densification of forest stands (horizontal and vertical growth of vegetation).

Maintaining farms by applying a profitable system such as Polyfarming not only **increases landscape diversity**, but also creates landscapes that are less vulnerable to fire. This is because it preserves open areas with low fuel continuity. It achieves this **by farm animals reducing fuel load** from the understory. Furthermore, grazing with an adequate stocking load in the forest or dehesa understory reduces the vertical continuity of the vegetation.

• Increase in biodiversity

The Polyfarming system promotes increased biodiversity directly and indirectly for several reasons.

- **At landscape level**, the recovery of open spaces is promoted, which in Mediterranean areas it is the appropriate environment for many species. Polyfarming also **promotes forest maturity**, which is associated with characteristic fauna and flora.
- On the other hand, at **local level**, the combination of trees, pastures and crops, which characterises the Polyfarming system, favours a greater diversity of habitats with wide gradients of humidity and light that create **environmental heterogeneity** in which many species of microorganisms, animals or plants can find shelter or food.

In the sheets "Increase in biodiversity. I Soil organisms" and "Increase in biodiversity. II Birds" there is a description of the biodiversity patterns of two groups of organisms in the Polyfarming system.

• Greater diversity and quality of the food obtained

The regenerative model developed in the Polyfarming system promotes **optimal nutrition and health**. To do this, it is committed to a balanced, healthy and quality production.
- A system made up of different elements can provide a **great diversification of products**: firewood, wood, forage, grain, fruit, many types of vegetables, meat from different animals, milk and eggs.

- In addition, the food produced has **great nutritional value**. Thus, the meat obtained has a higher density and a higher content of vitamins (A, D and K) and quality fats (Omega-3). Milk from cows raised on pasture also has more Omega-3 fats, vitamin E and beta-carotene than conventional milk. Regeneratively grown vegetables also contain much higher levels of antioxidants than conventionally grown varieties.
- Finally, **regenerative crops do not use agrochemicals**, which are products that have a high cost for human health and the environment, while animals raised in the pasture according to the Polyfarming system also have fewer diseases and need fewer drugs. All this creates healthier environments and food.

• Reversal of the tendency to abandon the rural environment

One of the main objectives of the Polyfarming system is to **reverse rural abandonment**. It achieves this by transforming abandoned agricultural and livestock farms into profitable farms, taking into account the following principles: (i) it **avoids dependence** on market inputs and heavy machinery to manage the system; (ii) it proposes **accessible technologies** for all producers and is applicable on different scales; (iii) it **improves the economic profitability** of farms; (iv) it allows **job creation**, especially for young people; (v) it must be linked to new ways of selling the products; and (vi) it proposes recovering **food sovereignty**, which implies being able to produce quality food for all society, without there being control by large external lobbies. The detailed description of these principles is explained in the sheet 'Reversion of rural abandonment'.

Improvement of soil conditions

The Polyfarming system, based on incorporating plant materials into the soil, improves soil conditions in the places where it is applied. After developing this model to the Planeses farm for three years, the organic matter in the soil has practically doubled in the different elements of the system. This is accompanied by an increase in the amount of nitrogen, a higher C/N ratio and more water in field capacity in these areas, compared to others in which a conventional system is applied.

Changes in the soil as a result of the regenerative model

The most important potential carbon stock in natural systems is the soil. One of the current problems is that the conventional model destroys the structure of the soil with the plough and favours the mineralisation of organic matter by continuously removing it, thus releasing the carbon that was retained in the soil into the atmosphere. In contrast, **the regenerative model seeks to preserve the structure of the soil and feed its trophic web**, reducing carbon from the atmosphere and introducing it into the soil. In this way, the soil becomes a large carbon reservoir again, a function that it has been losing for decades.

The regenerative model ensures that harvesting does not significantly affect the productive potential of the soil, while minimising external contributions and maintaining the main carbon stocks. To do this, **it improves soil conditions by incorporating plant materials into it**. This organic matter incorporated in the surface provides nutrients and plays an important role in covering the soil surface and increasing water reserves for plants.

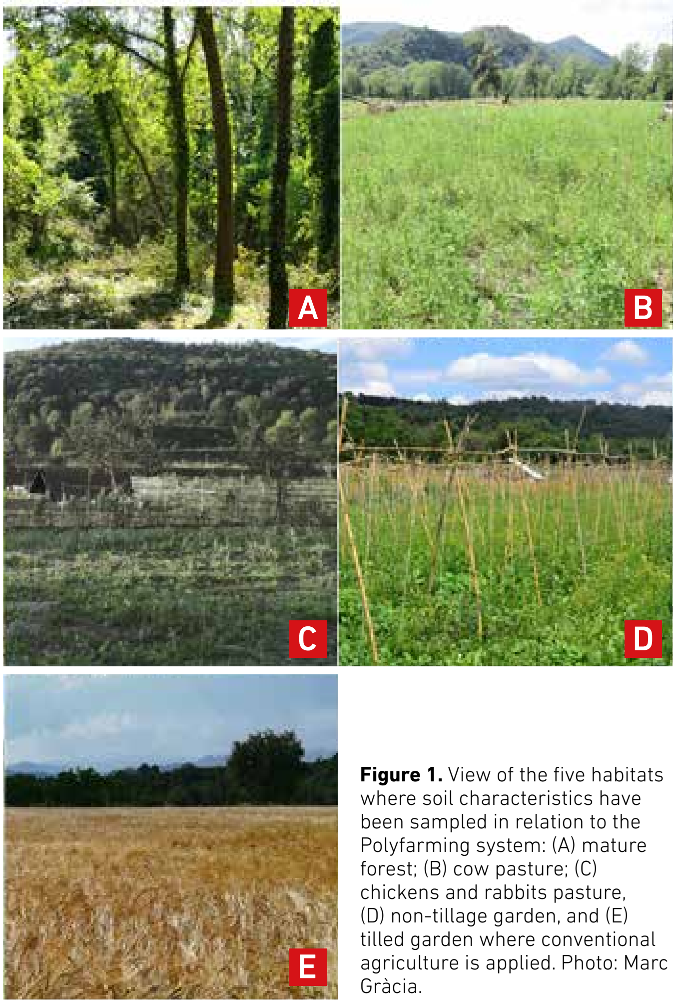

Figure 1. View of the five habitats where soil characteristics have been sampled in relation to the Polyfarming system: (A) mature forest; (B) cow pasture; (C) chickens and rabbits pasture, (D) non-tillage garden, and (E) tilled garden where conventional agriculture is applied. Photo: Marc Gràcia.

Improved soil conditions

In the Polyfarming components, which have been developed on the Planeses farm since 2017, **significant improvements have already been obtained in various soil characteristics**. A study of these characteristics was carried out at the beginning of the application of Polyfarming (2017) and, three years later (2020), **in the following habitats**: (A) mature forest, (B) pasture where cows graze, (C) pasture where chickens and rabbits graze (only in 2020), (D) garden without tillage, and (E) garden of a neighbouring farm where conventional agriculture is carried out (**Figure 1**). Four of the main aspects related to soil fertility and productivity have been analysed.

• Organic matter

Organic matter mostly corresponds to humified organic materials. It presents greater stability than the plant matter from which it comes and represents a very important stock within the system. **It is the main indicator of the amount of carbon that a soil can store** and, indirectly, the amount of water available to plants, not only directly due to the ability of humic substances to retain water, but also indirectly due to the improvement of the structure in the form of a greater abundance of microaggregates. **Figure 2** shows the changes in the **% of soil organic matter between the start of the application of the Polyfarming system (2017) and three years later (2020)** in the four habitats considered (the chicken pasture is not included because it does not have data for 2017). As expected, the highest value of organic matter is obtained in the two samplings in the forest. In the two habitats in which Polyfarming was applied (cow pasture and non-tillage orchard) an **increase of almost double** the amount of organic matter was observed. In contrast, the conventional orchard maintained much lower values both in 2017 and 2020 (**Figure 2**).

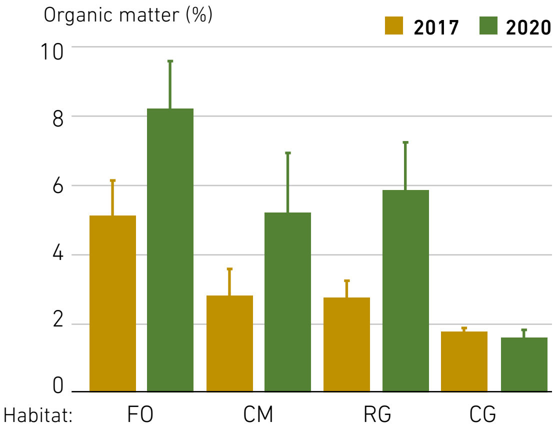

Figure 2. Changes in the % of soil organic matter (mean ± standard deviation) between the beginning of the application of the Polyfarming system (2017) and three years later (2020) in the four habitats considered: forest (FO), cow meadow (CM), regenerative garden (RG) and conventional garden (CG).

• Nitrogen

Nitrogen has been measured through the **Kjeldahl method**, it includes both organic nitrogen and that in the form of NH_4, i.e., nitrogen that is potentially available to plants. High nitrogen values are associated with increased levels of organic matter. **The highest nitrogen values are obtained in the forest and in the non-tillage orchard**, while both in the cow pasture and in that of chickens and rabbits the values are intermediate (**Figure 3A**). The lowest value is found in a conventional garden.

• C/N ratio

The C/N ratio of the soil varies fundamentally according to the C/N ratio of the existing plant organic matter. **A balanced soil in terms of the C / N ratio is around 10** (between 8 and 12), a value that indicates that there are contributions of fresh organic matter while there is a good content of humus-type organic matter.. In the habitats considered in the study, the two that have a value very close to 10 are the forest and the cow pasture (**Figure 3B**), confirming that they are fertile soils. In the other two Polyfarming habitats, the chicken and rabbit meadow and the non-tillage garden, the value obtained is slightly lower, around 8, still in the range of balanced soils. On the other hand, in the conventional orchard the C/N ratio has a value of 6, which indicates that there are few contributions of vegetable matter and a slow mineralisation rate.

• Amount of water in field capacity

The water content in field capacity corresponds to the water that remains in the soil 24 hours after saturating it, and indicates the useful water retention capacity for plants. The highest values of water available for plants are in the forest followed by the non-tillage orchard and the cow

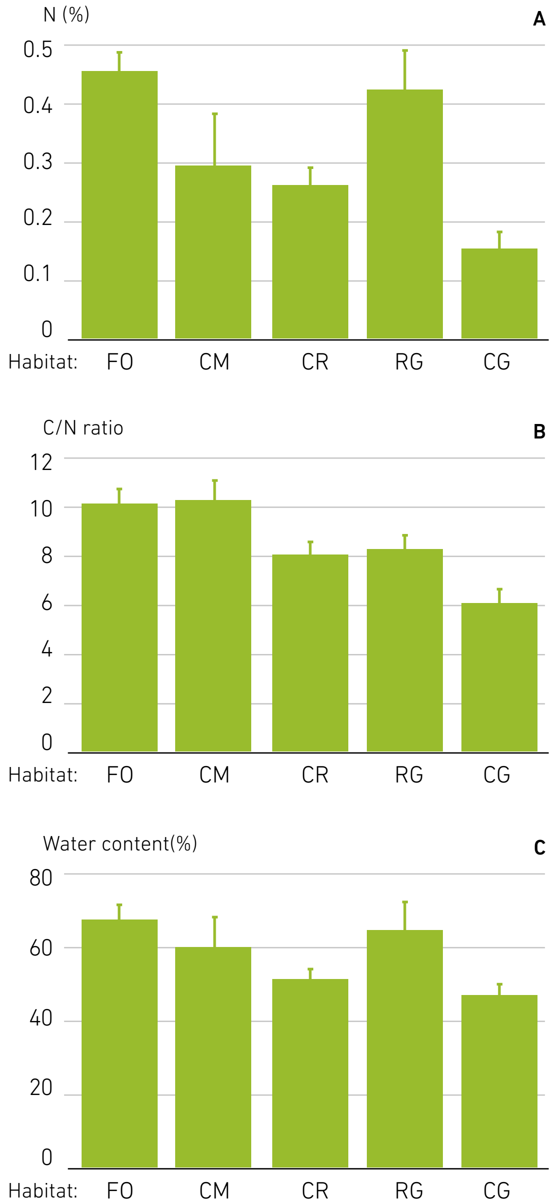

Figure 3. Values (mean ± standard deviation) of (A) total nitrogen (%), (B) C/N ratio, and (C) water in field capacity (%) in the five habitats considered: forest (FO) , cow meadow (CM), chicken and rabbit meadow (CR), regenerative garden (RG) and conventional garden (CG), after three years of operation of the Polyfarming system.

pasture (**Figure 3C**). The chicken and rabbit pasture has an intermediate value and the lowest value occurs in the conventional garden.

From these results, it can be concluded that **the Polyfarming system represents an important improvement of the soils** in which it is applied. Thus, soil organic matter, which is considered an indicator of soil health, practically doubles in three years in areas where the regenerative model is implemented. This is accompanied by an increase in the amount of nitrogen, a higher C/N ratio and a greater amount of water in field capacity in these areas compared to others in which a conventional system is applied.

Increase in biodiversity I. Soil organisms

The study of the biodiversity of soil organisms in relation to the Polyfarming system has been carried out in the following habitats: mature forest, meadow where cows graze, meadow where chickens and rabbits graze, orchard without tillage, and the conventional garden of a neighbouring farm. A large increase in operational taxonomic units (OTUs) is observed when all habitats are considered together, both for bacteria and for fungi and invertebrates. The management analyses show a similar composition of both bacteria and fungi in the forest, the non-tillage orchard and the chicken and rabbit pasture, while the composition of these microorganisms in the cow pasture and the conventional garden is clearly different.

Types of soil organisms

The set of organisms that live in the soil constitutes the soil trophic network. **Healthy soil harbours a complex trophic network**, from microorganisms (bacteria, fungi, protozoa, nematodes), to the meso and macrofauna of the soil (worms, arthropods, molluscs) (**Figure 1**).

• **Bacteria.** Bacteria perform important functions in the soil, including the recycling of nutrients, by decomposing organic matter, and **improving soil structure and aggregation**. Bacteria form microaggregates in the soil, binding the soil particles together with their secretions and creating a structure that increases infiltration and water retention capacity.

• **Fungi.** Fungi participate mainly in the decomposition of plant materials such as cellulose, hemicelluloses, pectin or lignin, before being attacked by bacteria. Thanks to the filamentous structure of their mycelium, **they also play a role in the constitution and preservation of soil structure** since hyphae solidly retain mineral particles and contribute to the formation and stability of soil aggregates.

• **Nematodes.** Nematodes are the most abundant invertebrates in many soils. Most are less than 100 microns in size. **They regulate the populations of bacteria and fungi** by feeding on them and are involved in the recycling of nutrients.

• **Meso and macrofauna.** They are invertebrates of the soil that are around 100 microns and 20 mm. They include different groups of arthropods, molluscs and also annelids.

They have different functions in the soil: they regulate the populations of fungi and microfauna by feeding on them, they fragment plant debris, intervene in the recycling of nutrients and move creating pores and aggregates that improve water infiltration rate and soil aeration.

Presence of the different groups of soil organisms in the different habitats

On the Planeses farm, the implementation of the Polyfarming system has consolidated a series of habitats with highly contrasted characteristics. A study of the biodiversity of soil organisms has been carried out **in the following habitats**: the mature forest, the pasture where the cows graze, the pasture where the chickens and rabbits graze, the garden without tillage, and an orchard of a neighbouring

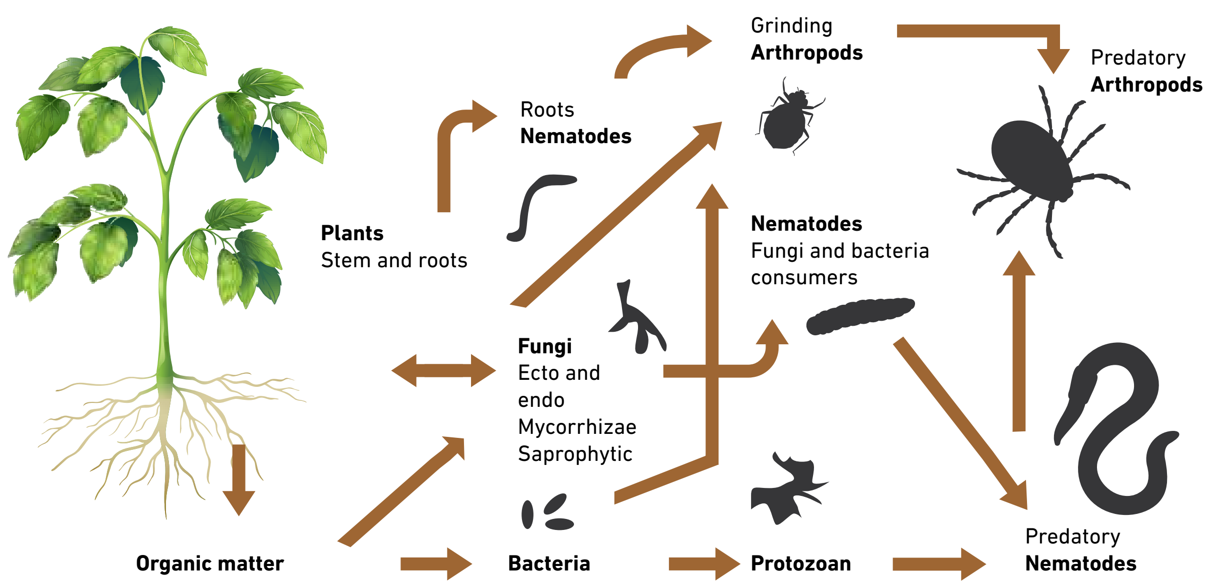

Figure 1. Diagram of the soil trophic network, showing the main groups of organisms that live in it.

farm where conventional agriculture is carried out. They are shown in the sheet “Improvement of soil conditions”. In a soil sample from each habitat, and using the metabarcoding technique in which the DNA present in it is extracted, it has been possible to **estimate the biodiversity of the different groups of soil organisms:** bacteria, fungi and invertebrates (including nematodes, annelids and arthropods), from the sequencing, identification and quantification of taxonomic units or **OTUs (Operational Taxonomical Units)** obtained from the sample. The results of the number of OTUs of each group identified in each habitat and in total are given in Table 1.

• **Bacteria.** In total, **6886** different OTUs have been identified. The number is very high, although to be expected, as recent research estimates that there may be thousands of species of bacteria in a gram of a typical soil sample. **The highest value has been found in the chicken and rabbit pasture** and in the conventional garden, and the lowest in the forest.

• **Fungi. 674 different OTUs** have been identified. The largest number of them are found in the **cow pasture**, followed by the forest and the non-tillage garden. The clearly lower number is found in the conventional garden.

• **Nematodes**. The total number of OTUs of nematodes was 22. The number found **in the different habitats is very similar**, ranging between 5 and 7.

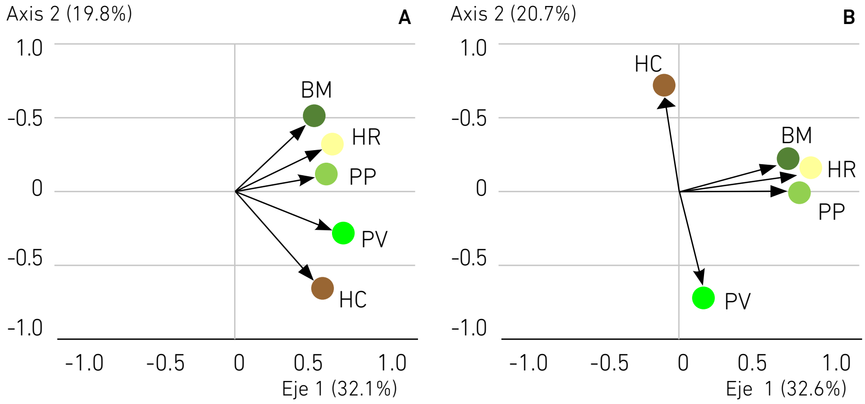

Figure 2. Distribution of the five habitats sampled along the first two axes of the Principal Component Analysis (PCA) carried out for the taxonomic units (OTUs) of bacteria (A) and fungi (B). FO, forest; CP, cow pasture; CR, chicken and rabbit pasture; RG, regenerative garden; CG, conventional garden.

• **Other invertebrates.** Various annelids and arthropods have been identified in soil samples. **Annelids** (in total 11 OTUs) **are most abundant in all Polyfarming habitats** except, surprisingly, in the forest and have not been found either in the conventional orchard. Arthropods (in total 18 OTUs) are found in all habitats, to a lesser extent in the cow pasture.

An ordination analysis (PCA, Principal Component Analysis), performed with OTUs from the different habitats, shows the patterns that appear in **Figure 2** for the bacteria and fungi data separately. In the case of bacteria (**Figure 2A**) a proximity is observed (indicating a similar composition of bacteria) between the forest, the non-tillage orchard and the chicken and rabbit pasture. The cow pasture is further apart, and the conventional orchard is the one that is further along the second axis. The PCA graph of the fungi (**Figure 2B**) shows a similar but even clearer pattern: the forest, the non-tillage orchard and the chicken and rabbit pasture are close together and distributed along the first axis, while the cow pasture remains at one end of axis 2, since it has more fungal OTUs than the other habitats, and the conventional orchard, clearly with fewer fungal OTUs, is located at the other end of this axis. These results show that, in general, **the composition of the conventional orchard is clearly different from that of the other habitats**. This may be related to the fact that conventional agricultural practices are not normally conducive to maintaining high levels of biodiversity of soil organisms.

HABITATS	BACTERIA	FUNGI	NEMATODES	ANNELIDS	ARTHROPODS
Forest	1616	183	6	0	7
Cow meadow	1971	253	6	5	2
Chicken meadow	2274	135	5	4	6
Garden without tillage	2165	187	6	5	7
Conventional garden	2252	112	7	0	5
Total	**6886**	**674**	**22**	**11**	**18**

Table 1. Number of taxonomic units or OTUs (Operational Taxonomical Units) identified from the different groups of organisms in a soil sample from each of the five habitats considered.

Increase in biodiversity II. Birds

The Polyfarming system integrates different uses at farm level and, as a result, generates different habitats for fauna and flora. By establishing contrasting habitats, which include areas of closed forest, very open forest or dehesa, areas of pasture and garden, Polyfarming collectively increases the richness of bird species, since different species coexist in each habitat. In the forest and the dehesa, the typical forest species predominate, while in the pasture and the garden there are species typical of open areas and agricultural areas.

Biodiversity of birds in the different habitats of Polyfarming

In the Polyfarming system, the integration of different uses at the farm level generates **different habitats for fauna and flora**: open pasture or garden areas suitable for many species, and forest areas with different types of management, including stands with characteristics of maturity that also allow the presence of species typical of mature forests. On the Planeses farm, the Polyfarming system has consolidated a series of habitats with highly contrasted characteristics. **In four of these habitats, the composition of birds has been analysed throughout the year over three years** (**Figure 1**): mature forest, dehesa, pasture where cows graze, and garden without tillage.

The total values of the bird samples in the different habitats are presented in **Table 1**. Over three years, 2312 individuals were identified. Of them, **the largest number is found in the pasture zone** (**Table 1**), mainly due to the presence of *Passer domesticus* individuals (**Figure 2A**), which represent more than 50% of the records. The total number of species found in the samplings is high, 41, and it is also high in the pasture where the highest number of them can be found (35), followed by the pasture (25), the orchard (20) and the forest (17). The total diversity (Shannon index) is 1.75. **The highest diversity values** by zones are those of the forest (2.40) and the pasture (2.68), while the lowest are those of the open areas, the meadow (1.27) and the orchard (1.14), mainly due to the great abundance of *P. domesticus*.

COMPONENT	#INDIVIDUALS	RICHNESS	DIVERSITY
Forest	134	17	2.40
Dehesa	219	24	2.67
Pasture	1577	35	1.27
Orchard	382	20	1.14
All	2312	40	1.75

Table 1. Richness and diversity values of the four areas where birds have been sampled at the Planeses farm.

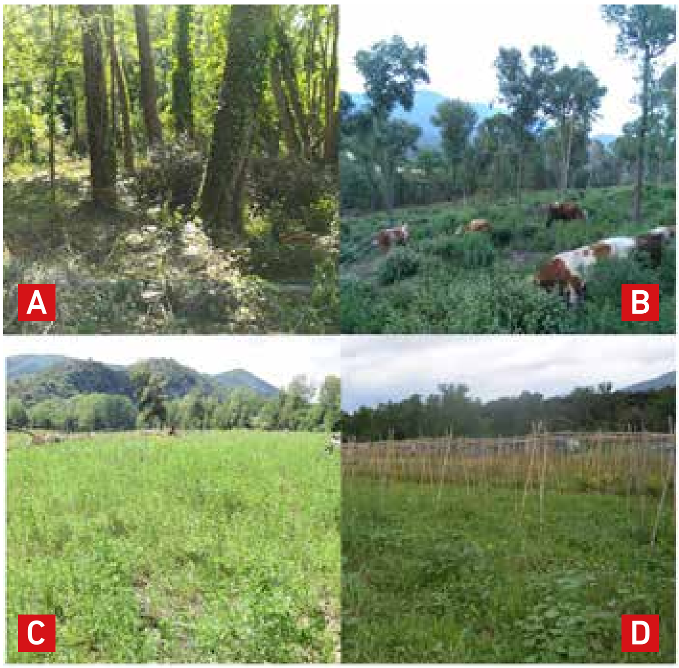

Figure 1. View of the four habitats where bird biodiversity has been sampled on the Planeses farm: (A) mature forest; (B) dehesa; (C) cow pasture; (D) non-tillage orchard. Photo: Marc Gràcia.

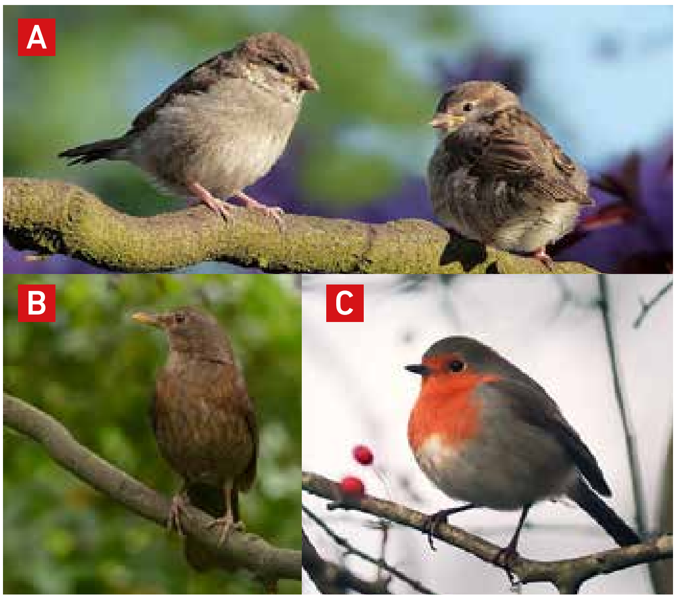

Figure 2. (A) House sparrow (*Passer domesticus*). Photo: Pixabay, Oldiefan. (B) Blackbird (*Turdus merula*). Photo: Pixabay, Oldiefan. (C) Robin (*Eritacus rubecula*). Photo: Pixabay, Manfredrichter. Photo: Pixabay, Manfredrichter.

SPECIES	FOREST	DEHESA	PASTURE	GARDEN
Aegithalos caudatus	0.0	1.8	0.7	0.0
Anthus pratensis	0.0	0.0	0.3	0.3
Carduelis cannabina	0.0	0.0	0.1	0.0
Carduelis carduelis	0.0	1.4	0.9	1.0
Carduelis chloris	0.0	0.0	0.4	0.0
Certhia brachydactyla	9.0	4.6	0.1	0.3
Cisticola juncidis	0.0	0.0	0.1	0.0
Columba palumbus	7.5	1.8	0.2	0.0
Corvus corax	0.0	0.0	0.1	0.0
Corvus corone	0.7	0.0	0.3	0.0
Cyanistes caeruleus	0.0	1.8	0.1	0.0
Dendrocopus major	0.0	1.4	0.0	0.0
Emberiza cirlus	0.0	0.5	0.4	1.0
Erithacus rubecula	17.9	16.9	0.9	1.6
Fringilla coelebs	11.2	9.6	26.7	3.7
Garrulus glandarius	8.2	1.8	0.3	0.3
Hippolais polyglotta	0.0	0.0	0.1	0.0
Hirundo rustica	0.0	0.0	0.1	0.3
Luscinia megarhynchos	1.5	3.2	0.3	1.3
Motacilla alba	0.0	0.0	1.8	0.8
Oriolus oriolus	0.0	0.5	0.2	0.0
Parus major	2.2	6.8	0.3	0.5
Passer domesticus	0.0	1.4	61.4	76.7
Passer montanus	0.0	0.0	0.1	1.3
Phoenicurus ochruros	0.0	0.5	0.6	0.8
Phylloscopus bonelli	1.5	0.0	0.0	0.0
Phylloscopus collybita	0.7	0.9	0.3	0.0
Picus viridis	3.7	2.7	0.1	0.0
Prunella modularis	0.0	0.0	0.1	0.0
Regulus ignicapilla	1.5	0.9	0.0	0.0
Saxicola rubetra	0.0	0.0	0.1	0.0
Serinus serinus	0.0	3.7	0.8	0.8
Sitta europaea	0.7	0.0	0.0	0.0
Streptopelia turtur	0.0	0.0	0.1	0.3
Sylvia atricapilla	10.4	7.3	0.5	2.4
Sylvia communis	0.7	0.0	0.0	0.0
Sylvia melanocephala	0.0	0.9	0.1	0.0
Troglodytes troglodytes	0.7	2.7	0.2	0.3
Turdus merula	18.7	17.8	1.3	1.6
Turdus philomelos	3.0	9.1	0.2	5.0
ALL	100.0	100.0	100.0	100.0

Table 2. Composition of species identified in the four areas of the Planeses farm. The values are the percentages of individuals of the different species identified in all the samplings carried out in each of the habitats.

Table 2 shows the species composition in the four zones. The forest and the dehesa have a similar composition of species, predominantly *Turdus merula* (**Figure 2B**), *Erithacus rubecula* (**Figure 2C**) and *Fringilla coelebs*. The species composition in the pasture and the garden are also similar, with *P. domesticus* standing out in both areas and *F. coelebs* in the pasture. In total, 7 species have been identified only in the pasture, 3 only in the forest and 2 only in the dehesa, while all the species that appear in the garden are also in another area.

Most of the species (94%) and individuals (84%) found in the forest are typical forest species (**Figure 3**). Most species (76%) and individuals (90%) of the dehesa are also forest species. On the other hand, both **in the pasture and in the garden, the majority of individuals are from agricultural areas** (64 and 80%, respectively), while at species level the forest species dominate (46 and 44% respectively), with similar proportions of agricultural species and those of open areas (**Figure 3**).

The conclusion drawn from these results is that the implementation of **the Polyfarming system leads to an increase in the biodiversity of birds.** The reason for this is that generating highly contrasted habitats, including areas of closed forest, very open forest or dehesa, pasture and garden, favours the presence of species typical from forests, open areas and agricultural lands.

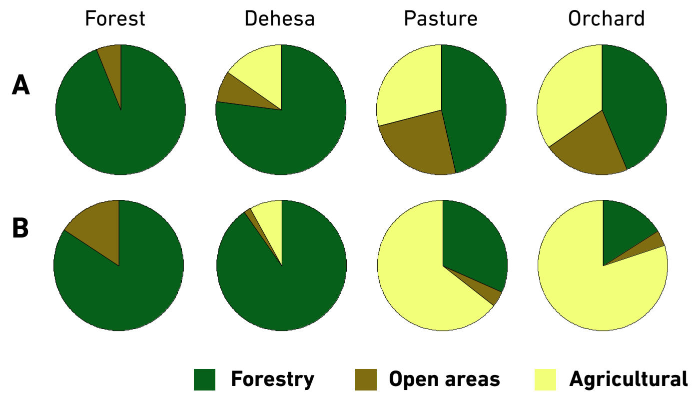

Figure 3. Proportion of (A) species and (B) individuals in three species categories: forest (green), open area (brown) and agricultural species (yellow) in the four Polyfarming habitats sampled.

Reversal of rural abandonment

The Polyfarming system proposes reversing rural abandonment by making farms profitable based on the following principles: (i) avoid dependence on market inputs and heavy machinery for managing the system; (ii) use technologies accessible to all and applicable on different scales; (iii) improve the economic profitability of the farms based on the previous points; (iv) promote job creation, especially for young people; (v) establish new ways of selling products; and (vi) recover food sovereignty, which implies being able to produce quality food for the whole of society without being controlled by large external lobbies.

Figure 1. Garden without tillage of the Planeses farm (Girona), where no external agrochemicals or machinery are used to till the soil. Photo: MJ Broncano.

The Polyfarming system as a tool to reverse rural abandonment

The regenerative model must be **the future driving force in the Mediterranean basin**, since it responds to the main challenges that arise when it comes to recovering activity in rural areas. When the regenerative model is applied, as in the case of the Polyfarming system, it can reverse rural abandonment, making farms profitable, since **it allows you to produce while conserving the environment where the current model is not viable**. The Polyfarming system proposes the production of abandoned or unprofitable agricultural and livestock farms considering the following principles:

• Avoid dependence on external inputs and heavy machinery

The conventional production model depends on the large companies that manufacture the agrochemicals and machinery necessary for the system to function, as well as on oil to produce them and put them into operation. The costs of machinery and agrochemicals are the highest in the production system, which is why a **dependence on external products** (machinery, fertilisers, herbicides and insecticides) is created that causes producers to obtain higher and higher yields to be able to pay them, which is not possible for small farms.

In contrast, the **regenerative model** does not require tilling the soil and does not use agrochemicals (pesticides, fertilisers, etc.) (**Figure 1**). With this model, **production costs related to external inputs are greatly reduced** and, in addition, dependence on both oil and large multinational agrochemical products is largely avoided. In this way, the profitability of small farms is recovered.

• Use technologies accessible to all and applicable at different scales

Polyfarming's proposal is that of a sustainable regenerative model, in which **different techniques are used in the forest, crops and animals** that allow efficient control of the return of organic materials to the soil and the mineralisation/humification balance. This **improves the production per unit area** of the fields without the need for external inputs or machinery. It is not a matter of re-implementing a system from the past, on the contrary, **the Polyfarming system is possible thanks to scientific progress** regarding knowledge of natural processes. This allows you to know how the natural nutrition of plants and animals works and its technical application in an integrated way, i.e., by exploiting the resources of the environment.

A particularly relevant aspect of this model is that it is **scalable**, i.e., it can adapt to any type of conditions. As it does not have large external expenses, **it does not have space limitations**, it can be applied on a small scale, but also on a large scale, for which machinery is needed for sowing or harvesting, but always respecting regenerative principles.

• Improve the economic profitability of farms

The economic profitability of farms based on the regenerative model **is much higher** than those using the conventional model. To begin with, the regenerative model proposed in Polyfarming has **much lower functioning costs than the conventional one**, due to everything that has been mentioned in the previous points: (i) it has a low dependency on oil and nothing on the large multinational agrochemical products; and (ii) it allows working on a small scale, in which the difference in costs can be absorbed, since it can be offset by direct sales strategies.

In addition, this system proposes optimising production by taking advantage of forest, livestock and crop resources through: (i) **a circular economy** in which there is a complementarity of products at farm level that saves costs, since anything left over from one use is applied to another, and (ii) **the complementarity of jobs and labour** between uses in space and time, which also contributes to lower costs.

• Promote job creation, especially for young people

The Polyarming system facilitates the creation of continuous and quality employment, especially for young people and other disadvantaged groups. This is so for two basic reasons: (i) **it makes projects that were not profitable**, or did not even exist, profitable, especially in areas where opportunities to work in rural areas are limited; (ii) in addition, it achieves this because in projects that apply the Polyfarming system **the biggest expense is that of labour**, not infrastructure or machinery (see sheet "Balance of costs and income at the farm level of the Polyfarming system. I. Costs"). It also creates employment in regions with a high rate of rural abandonment, so that old, abandoned farms are recovered.

• Innovate to create new ways of selling products

The Polyfarming system considers that, along with production methods, **selling methods are also important.** Therefore, restoring relationships between people (consumer groups, local markets, direct producer-consumer relationship, etc.) is a basic principle that must be developed (**Figure 2**). The very diversity of products promoted by the Polyfarming system favours the establishment of local markets with a **direct relationship between the producer and the consumer.** This allows both to move forward together to tackle challenges that arise in today's society: reuse of containers (**circular economy**), return and recycling of the organic fraction to the production system (i.e., all the organic waste involved in production and the transformation of food, kitchen scraps, cardboard, etc.), offer of fresh quality products and the possibility for the consumer to know and visit the farms where the products are produced.

Figure 2. Store of the Planeses farm (Girona), where the food produced on the farm is sold directly. Photo: Ángela Justamante.

• Recover food sovereignty

Food sovereignty is the right of each local community to decide on their own food and production system and to protect the local market from international markets. **The value of the regenerative model to regain food sovereignty** is based on several of the aspects that have been discussed in the previous points: (i) it allows the entire population to be fed affordably; (ii) it produces **safe and healthy food** through processes that also **sequester CO_2** and conserve natural resources and biodiversity; (iii) it does not depend on large external lobbies, producers of agrochemicals or machinery; (iv) it establishes a direct way of putting producers in touch with consumers, **promoting local, diversified markets** based on fair prices; (v) it proposes a different way of eating, based on a local diet adapted to the productive characteristics of each zone; and (vi) it proposes direct contact between consumers, administrations and farms, so that the knowledge behind the productive sector and its role in the **fight against climate change** and the conservation of biodiversity can be discovered and valued.

Conclusions

- The future will either be regenerative or it won't be

The future will either be regenerative or it won't be

The global environmental crisis is strongly related to the way we produce, distribute and consume resources, especially in the field of food and energy. The regenerative agro-food model is an environmental alternative to food production and a proposal for the future, both locally and globally. Farms like Planeses and projects like Polyfarming can become reference centres, as real and demonstrable examples of making a change to more environmentally-friendly production systems. The whole of society must push so that models such as regenerative, which benefit us all, can be consolidated.

Global environmental crisis: a consequence of human activity

A **'state of climate emergency'** was declared in December 2020 by the European Union, 14 countries, various cities, entities, and universities. This declaration involves adopting measures to reduce carbon emissions into the atmosphere within a specified time frame, as well as increasing awareness of the existence of a **global environmental crisis**. This crisis also encompasses other emergencies that can become as critical as the climatic one, such as **soil loss and degradation** (erosion, acidification, salinisation, etc.) and the **altered state of the seas and oceans**.

The current environmental crisis is related to the **human productive system**. The concept of an "ecological footprint" is the measure of the impact of human activities on nature and represents the area necessary to produce resources and absorb the impacts of a certain activity. In 2020, to meet the needs of humanity, an amount of natural resources equivalent to 1.75 planets has been consumed, and this footprint will be 2.5 planets in 2050, according to the Worldwide Fund for Nature (WWF). To counteract this trend, it is **urgent and necessary to change and improve the way we produce, distribute and consume resources**, especially in the fields of food and energy. The WWF Living Planet Report (2018) shows that the current food system is unsustainable due to its high environmental and social cost.

1. Environmental. Conventional agricultural production, which occupies 34% of the Earth's land, is responsible for 69% of freshwater withdrawals and is the main cause of soil health degradation. Together with the rest of the food system, it generates almost a quarter of greenhouse gas emissions (IPCC, 2019). Continuing with the conventional production system will cause, in the coming decades, what the scientific community has defined as going beyond the **point of no return**: 450 ppm of CO_2 in the atmosphere. According to a report by the Northeast Organic Farming Association (2015), the current production system has displaced 50-75% of the original carbon content in the planet's soils (136 billion tons of carbon) into the atmosphere and oceans.

2. Social. The current food system is based on three axes: **globalisation, monoculture and control by transnational corporations.** Joel Salatin, a promoter of regenerative agriculture, attributes the **lack of generational change in the agricultural and rural world** that exists today to these axes - the average age of farmers and ranchers in Europe and the US is 60 years old. As he points out in his book "This is not normal", the current paradigm, highly capitalised and based on staple food monocultures, has little to offer the next generations of young people and, hence, the lack of generational change. The current system means that making a living by working the land, producing food and managing the landscape to produce aesthetic and social beauty, is no longer a vocation for young people.

The regenerative production model as an environmental alternative to produce food

Now there are different alternatives that produce healthy food, while looking after the environment. The **regenerative production model** is one of the alternatives that is expanding and, every time, it acquires more relevance. One reason is that their method of producing food has **one of the lowest environmental and social impacts**, or even net positive ones (Rhodes, 2017). While some approaches to its definition focus strictly on outcomes and processes such as improving soil health and its carbon storage capacity, others are broader and based on the regenerative capacity and health of the ecosystem (Newton et al., 2020). There are different aspects that make the regenerative model especially **valuable** currently.

• **It is a solution to carbon sequestration**. The more organic matter there is in a soil, the greater its capacity to sequester carbon. For this reason, regenerative production models, which are based on the **health of the soil** by accumulating organic matter, capture around 50-100 Tm of atmospheric CO_2 per half hectare every year. Regenerative practices maximise the **fixation of carbon** in the soil and minimise its loss once it has been incorporated into the soil, thus reversing the greenhouse effect. Recent data on carbon sequestration in agricultural and pasture systems around the world show that more than 100% of current annual CO_2 emissions could be sequestered with a shift to regenerative production practices (Rodale Institute Report, 2020).

• **It is based on real experiences and scientific advancement in the knowledge of natural processes**. Producers will be able to create better regenerative systems based on basic ecological knowledge such as: knowing how the natural nutrition of plants and animals works and its application in an integrated way, taking advantage of the resources in the environment.

• **It is a synergistic model** that combines a wide range of different well-founded regenerative practices, such as those described in the **'Manual for the design and implementation of a regenerative agri-food model: the Polyfarming system'**, and which can be implemented in each farm to change aspects of management and help productive systems go from being a problem in the climate crisis to being part of the solution.

• **It is a circular production system**, in which there is a complementarity of products at farm level that allows cost savings, i.e., what is left over from one use is applied to another, and where the nutrient cycles are closed because it returns organic matter to the soil while avoiding the consumption of chemicals.

• It is also a **scalable model**, which means that it can adapt to any type of conditions. As it does not depend on external inputs but on the regeneration capacity of the system, it does not have space limitations and can be applied on both small and large scales.

A model for the future both globally and locally

Regenerative production is receiving significant attention from producers, researchers and consumers, as well as from politicians and the mainstream media around the world. Around this system there is an expanding "**regenerative movement**". Both the public and private sectors are currently exploring the possibilities that this model can contribute to climate action plans. Thus, the special report on "Climate change and land" from the IPCC (2019) speaks of the regenerative system as "a sustainable management practice focused on ecological functions, which can be effective in building the resilience of agroecosystems".

On the part of the **public sector**, and with the support of the organisation "The Climate Reality Project" led by Al Gore, various US state governments are committed to its implementation to help achieve local sustainability objectives. In the **non-governmental** sphere, there are several environmental, agricultural and food organisations that work to spread knowledge and promote the **adoption of production systems that incorporate regenerative agriculture and livestock**. Thus, at international level, there are Regeneration International, Rodale Institute, Savory Institute or Kiss the ground, among others. In Spain, Regenerative Agriculture, Alvelal Association or Carne de Pasto, among others, stand out.

At local level, the regenerative system makes it possible to respond to the main challenges that arise when recovering the activity of rural areas. When the regenerative model is applied, as in the case of the **Polyfarming system**, it becomes a model that demonstrates a **real reversal of rural abandonment**: farms become profitable and food is produced while conserving the environment under conditions in which the current model is not feasible. **At global level**, the regenerative system is a model that allows us to **feed humanity** in a more natural way, while helping to **cool the planet** with the massive absorption of CO^2 in regenerated soils.

Polyfarming: a project to promote policies that include the regenerative model

Consolidating a regenerative model, such as the one proposed in Polyfarming, does not require much more than knowledge, experience and support to change practice. However, adopting this new approach can be difficult because the conventional large-scale production system is underpinned by government agricultural policies and large agro-industrial corporations. Consequently, getting out of this system sometimes does not just depend on the will of those who want to change it.

Farms such as Planeses and projects such as Polyfarming can become **centres of reference**, offering real and demonstrable examples that surrounding producers can visit and emulate the model to make a change to more environmentally-friendly production systems.

But not only do producers have to make a change, **it is the society that has to push so that models such as regenerative can happen**. Among the keys to driving this change are: buying regenerative products, supporting local policies of change and lobbying for governments to support international initiatives that implement regenerative agriculture. One of the most significant is the "**4 per 1000**" initiative. This project was launched at COP21 and prompted many governments to include soil carbon sequestration as part of their climate change strategies. The objective of this initiative is to achieve an annual growth rate of 0.4% of the carbon reserves of the first 30-40 cm of soil by the year 2050, thus significantly reducing the concentration of CO_2 in the atmosphere. But **there are many other initiatives** that are aimed at improving soil health to breathe new life into ecosystems, creating a new vocation for farmers and ranchers, producing healthier and more nutritious food, while simultaneously reversing global warming. The first step to promote this change is to know and support the regenerative model. In this way we will head towards **a more hopeful and beneficial future for humanity**.

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Manual for the design and implementation of a regenerative agri-food model:

the Polyfarming system

The 'Manual for the design and implementation of a regenerative agri-food model: the Polyfarming system' is a complete guide for anyone interested to learn about the regenerative model, enjoy while learning it, and replicate it on a small or large scale. It is also an invitation to a truly sustainable agricultural and livestock model change that contributes to mitigating climate change and increasing biodiversity in the soil, as well as increasing food sovereignty and creating local employment.

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