Resources, Conservation & Recycling 223 (2025) 108515

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.sciencedirect.com/journal/resources-conservation-and-recycling

The plastic footprint of U.S. agriculture

Katie A. Malarkey, Callie W. Babbitt *

Golisano Institute for Sustainability, Rochester Institute of Technology, Rochester, NY, USA

A R T I C L E I N F O

Keywords:
Agriculture
Plastics
Material consumption
Horticulture
Mulch films
Circular economy

A B S T R A C T

Agricultural systems face growing demand to support global population growth within sustainable limits of resource consumption and environmental impacts. Plastic use in food production is a complex part of this challenge: plastics can increase crop yields, extend growing seasons, and decrease manual labor, but their production, use, and waste leads to environmental and human health impacts. Circular economy solutions to minimize these impacts are emerging, but are limited by the lack of reliable information about the magnitude and nature of agricultural plastics use. This study therefore aimed to model plastic consumption at each stage of U.S. agriculture and identify priorities for reducing use and waste. A modeling framework was created to account for the annual demand for crops and agricultural commodities that use plastic and the operational practices and functional requirements that govern the type, amount, and lifespan of plastics used. We estimate that 1.56 million tonnes of agricultural plastics are consumed each year in the U.S., representing 2.7 % of total domestic plastic use. The largest demands for plastics are in horticultural containers, mulch films, and silage storage, with LDPE, HIPS, and HDPE making up the most prevalent polymers in use. Even accounting for uncertainties, agricultural plastics represent a significant sustainability challenge due to the magnitude of polymer use, the variability in form and material, and the difficulty recovering plastic products at end-of-life. Results also highlight research priorities for sustainable interventions, including material substitution, reuse, and recycling.

1. Introduction

Feeding a growing global population will require significant expansion of agriculture (Sands et al., 2023) and food production systems (Yang et al., 2024). However, meeting this demand using conventional practices is likely to increase environmental impacts associated with agriculture, including greenhouse gas emissions (Basheer et al., 2024), soil degradation (Sumberg and Giller, 2022), water contamination (Srivastav et al., 2023), pesticide resistance (Mansfield et al., 2024), and on-farm food loss and waste (O'Connor et al., 2023). While new technologies and farming practices offer potential solutions to expand and intensify food production (Adisa et al., 2024; Javaid et al., 2023; Nath, 2024), they may also introduce new environmental risks that are difficult to anticipate.

One such example is the widespread use of plastics in food production. Agricultural plastics, also called “plasticulture” or “agriplastics,” were first used in the 1940s, when cellophane replaced glass panels on greenhouses (Scarascia-Mugnozza et al., 2011). Plastic use has now become integral at every stage of conventional agriculture, driving improvements in production efficiency. For example, thin films of plastic mulch spread across soil can double crop production and improve plant quality (Zhang et al., 2024). Flexible plastic tunnels protect crops from frost damage and regulate soil temperatures (Janke et al., 2017). While 70 % of freshwater withdrawals worldwide are for agriculture (Pérez-Blanco et al., 2020), plastic irrigation systems have helped halve water demand (Chu, 2017) and reduce pollution through targeted fertilizer delivery (Abdi et al., 2021).

However, potential benefits of plastic use may come at a steep sustainability cost. Agricultural plastic production contributes to fossil resource demand (Maraveas, 2020), climate impacts (Sharma et al., 2023), and ozone depletion (Villagrán et al., 2023). Degradation of plastic products during use can form microplastics (Deng et al., 2024), which may harm soil organisms (Tian et al., 2022), interfere with nutrient cycling (Huang et al., 2022), limit soil water holding capacity (Wang et al., 2022), reduce root permeability and growth (Ullah et al., 2021), and become assimilated into plants (Li et al., 2020). Microplastics taken up into fruits and leaves of plants (Tariq et al., 2024) can then be ingested (Mamun et al., 2023), leading to potential impacts to human and animal health (Prata et al., 2021), including respiratory disorders (Winiarska et al., 2024), gastrointestinal and cardiovascular diseases

* Corresponding author.
E-mail address: cwbgis@rit.edu (C.W. Babbitt).

https://doi.org/10.1016/j.resconrec.2025.108515
Received 10 February 2025; Received in revised form 1 May 2025; Accepted 13 July 2025
Available online 8 August 2025

(Yu et al., 2022), and immune responses (Blackburn and Green, 2022). Documented agricultural sources of microplastics include biodegradable mulches (Zhou et al., 2023), plastic films for tunnels or silage wrapping (Jin et al., 2022), and plastic particles in fertilizers (Zhang et al., 2022).

Environmental risks of agricultural plastics are further compounded due to difficulty managing these materials at end-of-life. Although these plastics can technically be reused or recycled (Lawrence, 2017), many are discarded after just a single application or growing season (Empson et al., 2021) due to operational decisions (Briassoulis et al., 2013a, 2013b) or lack of waste management infrastructure (US EPA, 2024). Local material recovery facilities are ill-equipped to handle the extreme organic matter contamination that often accompanies used agricultural products (Baker et al., 2021). Mulch films, for example, can have a total mass at EOL that is 60–80 % adhered soil, causing the cost of cleaning and recycling these plastics to exceed potential profit (Dong et al., 2022; Jones, 2018). Although recycling programs exist in the U.S., their adoption remains low (Hofmann et al., 2023). Farmers store used plastics on-farm, pay tipping fees to landfill plastic waste, or burn remnants on fields (Levitan and Barros, 2003), potentially leading to release of heavy metals (Kim and Lee, 2022), dioxins (Sarpong et al., 2024), and particulate matter (Gullett et al., 2012).

To minimize and manage agricultural plastics, we first need to understand the amount, form, and nature of plastics used, in order to create and prioritize solutions that can meaningfully address the greatest drivers of consumption and waste. For the U.S., no current, comprehensive data about agricultural plastics consumption are available. Because agricultural plastics represent a smaller sector of demand, they are not included in recent studies of U.S. plastic stocks and flows (Di et al., 2021; Hendrickson et al., 2024; Kan et al., 2023). U.S.-specific estimates are "few and inconsistent" (FAO, 2021), and typically extrapolate from global trends (D. Briassoulis, Hiskakis, et al., 2013; FAO, 2021; Levitan and Barros, 2003; Scarascia-Mugnozza et al., 2011), rather than primary data. Current information about U.S. agricultural plastics is from industry-led studies on specific plastic products conducted 30 years ago (Amidon Recycling, 1994; Jones, 2018), but to our knowledge, no current estimates have been generated with recent data that fully reflects the array of plastics used in modern agriculture.

Therefore, this study aims to create a detailed, up-to-date, and data-driven analysis of the plastic footprint of U.S. agriculture. A "plastic footprint" conveys the amount of plastic material consumed, used, and wasted (Boucher et al., 2019; Liu et al., 2023; Senese et al., 2023). Applying this approach to the U.S. agricultural sector responds to calls for quantifying plastic flows (FAO, 2021), increasing material circularity (Gerassimidou and Iacovidou, 2024), and reducing environmental impacts (King et al., 2023). Research presented herein aims to identify the agricultural products and applications responsible for the highest plastic consumption, in order to identify potential circular economy solutions that improve plastic life cycle management.

2. Methods

To estimate the U.S. agricultural plastic footprint, a "bottom-up" model was developed (Fig. 1), which accounted for the annual demand (D) for crops and other agricultural end-use applications that typically use plastic materials, the fraction of those end uses utilizing each plastic (η), and the material intensity (M) of plastic required to meet demand according to material properties and farming practices in the U.S. The total agricultural plastic footprint was calculated according to Eq. (1), as a product of these factors and normalized by plastic product lifespan (L) to provide results on an annualized basis:

$$\text{Agricultural plastic footprint} = \sum_{i \in I} \sum_{j \in J} \frac{M_{ij} D_j \eta_{ij}}{L_{ij}} \quad (1)$$

where I is the set of all plastic products and J is the set of all end-use applications. In total, 26 plastic products and 221 end-use applications (crops and agricultural commodities) were analyzed. The following sections detail data collection and estimation for each of these parameters; additional data are provided in the Supplementary Information (SI) file.

This framework covered five stages of agriculture: 1) preparing soil, 2) planting seed, 3) growing crops, 4) harvesting products, and 5) storing crops and animal feed, which collectively represent the production systems within the oversight of the U.S. Department of Agriculture (USDA). This scope also reflects the definition of modern agriculture as providing sustenance to humans (Harris and Fuller, 2014) through the cultivation of soil for farming (Magdoff and van Es, 1993), growing feed for the rearing of livestock (Mottet et al., 2017), and production of "specialty crops" such as honey and horticultural plants (USDA AMS, 2024). This scope did not include any downstream food processing or manufacturing activities or the packaging and sale of food direct to consumers. To determine which plastic materials and products to include in the analysis, a structured search of academic and trade literature was carried out using a combination of keywords related to plastics, agricultural stages, and specific crops and commodities identified by the USDA Census of Agriculture (see SI). This process identified

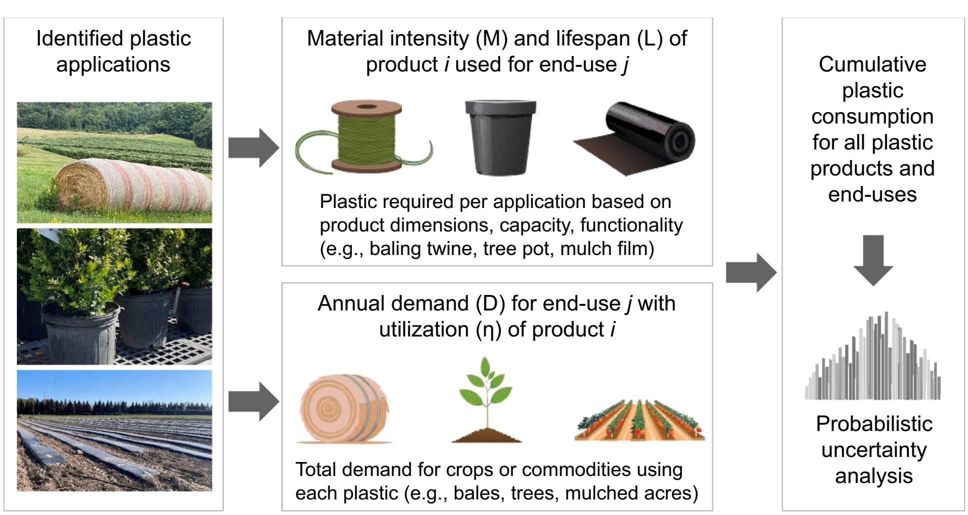

Fig. 1. Methodological framework for estimating the agricultural plastic footprint, including identification of plastic products used by agricultural stage (left), estimation of material intensity, lifespan, demand, and utilization parameters by plastic product and end use (center), and computation of cumulative plastic consumption with uncertainty analysis (right). Photos taken by the authors.

Table 1
Agricultural plastics analyzed, by agricultural stage and product category.

Agricultural stage	Product category	Plastic products	Polymer and form
Soil preparation	Mulch films	Mulch films	LDPE film
	Irrigation tubing	Surface drip tape	LDPE tubing
		Subsurface drip tubing	LDPE tubing
		Microsprinklers with tubing	LDPE tubing
Planting	Seed packaging	Seed boxes	HDPE rigid container
		Seed bags	PP woven fabric
		Seed FIBCs	PP woven fabric
	Chemical containers	Chemical jugs and drums	HDPE rigid container
		Chemical RIBCs	HDPE rigid container
Growing	Horticultural containers	Propagation liners and trays	HIPS semi-rigid container
		Large transplant pots	HIPS semi-rigid container
		Small transplant pots	PP semi-rigid container
	Protection structures	Greenhouses	PC rigid panels
		High tunnels	LDPE film
		Shade structures	HDPE woven fabric
		Low tunnels	LDPE film
Harvest	Sweetener production	Beehives	HIPS rigid panels
		Maple syrup lines	HDPE tubing
	Forage and silage baling	Baling net wrap	HDPE woven fabric
		Baling twine	PP woven fabric
Storage	Silage storage	Silage bale wrap	LDPE film
		Silage silo bags	LDPE film
		Silage bunker tarps	LDPE film
	Grain storage	Grain silo bags	LDPE film
	Animal feed packaging	Animal feed bags	PP woven fabric
		Animal feed FIBCs	PP woven fabric

Table abbreviations: LDPE: low density polyethylene; HDPE: high density polyethylene; PP: polypropylene; PC: polycarbonate; HIPS: high impact polystyrene; FIBC: flexible intermediate bulk container; RIBC: rigid intermediate bulk container.

11 major categories of agricultural plastics mapped across the five agricultural stages and comprising 26 specific plastic products (Table 1).

The above framework was parameterized by the most recent, representative, and reliable public data available at the time of analysis, largely drawn from the 2022 USDA Census of Agriculture (USDA NASS, 2024) and 2019 Census of Horticultural Specialties (USDA NASS, 2020). Because the most recent available data were consolidated from sources published from 2019 to 2024, the presented results are a snapshot of practices and products of this time period. In addition, much of the available data focused only on common polymer types, and thus the model omitted specialty plastics and related materials that may be used in agriculture, such as composites (Huang et al., 2024), multi-layer films (Briassoulis et al., 2018), additives (Cao et al., 2023) and bio-based polymers (Lewis, 2018). While results are certainly sensitive to data quality and availability, the underlying model and code are flexible and freely available (Malarkey and Babbitt, 2025), meaning results can be updated as new data become available.

2.1. Material intensity of plastic use in agricultural applications

The first step in estimating total plastic consumption was determining material intensity, which represents the total mass of plastic needed to meet functional requirements of each end-use application, annualized according to product lifespan. As explained in the following sections, methods of estimating material intensity varied by product category (Table 2), largely according to the nature of available data. For a few products, industry data reported unit mass per product. For the majority of products, however, material intensity was derived from functional properties of the plastic product and typical farming practices. The following sections and the SI provide detail about how this approach is applied for each product, but we illustrate the idea here with the example of plastic mulch films used on row crops to reduce weeds

Table 2
Approaches and key parameters required for estimating material intensity and annual demand.

Product category	Material intensity unit	Material intensity estimation parameters	Annual demand unit
Mulch films	kg/acres mulched crop	Dimensions and number of mulched rows per acre; mulch thickness; LDPE density	Total acres of mulched crops
Irrigation tubing	kg/acres irrigated crop	Dimensions and number of irrigated rows per acre; tubing thickness; microsprinkler mass; LDPE density	Total acres of irrigated crops
Seed packaging	kg/kg seed contained	Dimensions and mass of containers; fabric weight; capacity of container; seeding rate by crop; seed density; storage capacity required	Total mass of seed required
Chemical containers	kg/container	Dimensions and mass of containers; HDPE density; relative usage by container size	Total quantity of containers manufactured
Horticultural containers	kg/container	Mass of container; relative usage by container type and size	Total quantity of containers sold
Protection structures	kg/area crop under protection	Dimensions and surface area of structure; film thickness; polymer density	Total area of crops grown under protection
Sweetener production	kg/quantity of colonies or taps	Mass per frame and foundation; tubing dimensions; HDPE density	Total quantity of colonies or taps
Forage and silage baling	kg/kg baled crops	Dimensions and mass of net wrap and twine; polymer density; storage capacity per bale	Total mass of baled crops
Silage storage	kg/kg silage stored	Dimensions of storage container; capacity of container by type; film thickness; LDPE density	Total mass of silage crops
Grain storage	kg/kg grain stored	Dimensions of storage container; capacity of container; film thickness; LDPE density; storage capacity required	Total mass of grain stored
Animal feed packaging	kg/kg feed stored	Dimensions of container; capacity of container; feeding rate by livestock animal; feed density; storage capacity required	Total mass of animal feed stored

and conserve moisture (Salama and Geyer, 2023): Mulch film material intensity (kg plastic per acre mulched crop) could be estimated from the required mulch thickness; the length, width, and spacing of mulch coverage required for each row crop; and the density and dimensions of commercially-available polyethylene films.

The U.S. produces over 200 crops and agricultural products (USDA NASS, 2020, 2024) in farms that operate at varied scales and locations, where plastic use is influenced by local climate (Anunciado et al., 2021), conditions (Vox et al., 2016), and policies (Church et al., 2020). Data used to calculate material intensity are not sufficiently disaggregated to capture all possible permutations of local plastic use practices. Thus, the approach was to select baseline values representing most commonly observed agricultural practices in regions most representative of an end-use application. Following on the example given above, if plastic mulch films were determined to be used when growing tomato crops, and 90 % of tomato production occurred in five states, then baseline material intensity of mulch films for tomato crops was estimated from average data collected for those states (and so forth for all crops using mulch films). This process was repeated for all plastic products and their respective crops or end uses, as described below, where end uses are discussed according to the agricultural stage in which they occur.

2.1.1. Soil preparation

Preparing soil for planting crops involves the use of mulch films and irrigation tubing. Thin plastic mulch films are used to control weeds, increase soil temperatures, and reduce water loss, generally improving yields, plant quality, and harvest timing (El-Beltagi et al., 2022). Commercially available options are typically made of LDPE (Qi et al., 2020) and most often used on fruit and vegetable cash crops (Lamont, 2017). Material intensity of mulch film is based on crop bed type (which can be flat, raised, or wrapped) (BTC, 2023), the associated bed heights and widths, the "running length" and number of crop rows per acre, required mulch thickness, and polymer density (Table 2, Table SI-2).

Irrigation plastics are typically applied at the same time as mulch films along the lengths of crop rows to convey water from on-farm pumphouses (Zeng and Ren, 2022) in order to increase plant growth, extend growing seasons, provide frost protection, and reduce labor costs (Frisvold and Bai, 2016). Irrigation is common in cultivation of fruit and nut trees (Anderson et al., 2023), perennials (Rogers et al., 2018), and row crops like berries, melons, and herbs (Lamont et al., 2023). The study excluded permanent water infrastructure and other widely-used irrigation systems (e.g., furrow or field sprayers) (Mpanga and Idowu, 2021) that do not typically use plastic (USGS, 2018). The three styles of LDPE irrigation plastics are surface drip tape, subsurface drip tubing, and micro-sprinklers with mainline tubing. Material intensity was based on irrigation style by crop, length and number of crop rows per acre, common tape and tubing dimensions, polymer density, and component mass (Table 2, Table SI-3).

2.1.2. Planting

The planting stage includes sowing seeds and applying chemicals like pesticides and fertilizers (Wang et al., 2024). While farms increasingly use on-site bulk seed drop-offs that do not require plastics (Moore, 2018), seed packaging still includes reusable HDPE bulk seed boxes, durable PP flexible intermediate bulk containers (FIBCs), and single-use woven PP bags. Seed boxes are primarily used to transport corn, cotton, and soybeans (Spangler et al., 2020; W. Dartnell, personal communication, 2022), whereas bags are typically used for fruit, vegetable, and grass seeds (Crowley et al., 2022). Material intensity was determined from industry data for each packaging type relative to polymer type, density, typical dimensions, and seed storage capacity (Table SI-4).

Planting also involves application of chemicals such as fertilizers to augment soil nutrients (Bamdad et al., 2022) and pesticides to control weeds and limit infestations or damage from pests (Tudi et al., 2021). Chemicals are generally packaged in jugs (<5-gallon) or drums (15–55 gallon) (ACRC, 2023) made of rigid HDPE (Ramsay, 2023) or delivered in reusable HDPE rigid intermediate bulk containers (RIBCs) kept on farm. Material intensity was determined from industry-provided container sales and mass data, typical container dimensions, and polymer density (Table SI-5).

2.1.3. Growing

Cultivating or growing crops typically uses plastic to contain and protect plants. Plastic use in horticulture, the agricultural sector that cultivates food crops, medicinal plants, and ornamental plants (Dixon and Aldous, 2014), is primarily for containers used to propagate seeds, grow plants, and transplant trees and plants to soil. Propagation typically uses HIPS liners and trays for growing seedlings (Soulliere-Chieppo, 2020), while transplanting uses small PP pots for foliage plants and large HDPE pots for larger trees and shrubs (Michael, 2017). Material intensity for each container type was adapted from industry data (Schrader, 2013) with in-lab measurements of commercially-available container masses (Table SI-6).

Plastics are also used in protection systems, including greenhouses, high tunnels, low tunnels, and shade structures, which buffer against harsh conditions and provide climate control to extend the growing season (Gerovac et al., 2015). Large greenhouses are constructed with rigid PC panels (Gupta et al., 2024), while high tunnels, sometimes called hoop houses, use LDPE film stretched over a metal frame (Janke et al., 2017). Shade structures have a similar design, but use dark HDPE woven polymers to control lighting (Laur et al., 2021). Low tunnels, or row covers, are designed to seasonally enclose single rows of low-height field crops within a short hoop of LDPE film (Harris et al., 2021). Material intensity of each protection type was estimated from typical structure dimensions, the coverage extent and surface area of plastic components, and polymer thickness and density (Table SI-7).

2.1.4. Harvest

Containing and transporting harvested materials utilizes a variety of plastics. One application is the collection of natural sweeteners (maple syrup and honey). Beehives have used plastics since the 1970s (Tew, 2022) in internal frames and foundations (Cook et al., 2021). Harvesting maple syrup uses flexible HDPE tubing to draw sap from maple trees (Thomas, 2021). Material intensity was determined from manufacturer mass data (Peck, 2022), polymer density, and the dimensions of plastics per collection system (Table SI-8).

Plastics are also used to collect and contain bales of forage crops grown for animal feed, including switchgrass, corn, sorghum, miscanthus, and hay (USDA NASS, 2024). Forage is commonly contained in large round bales (Shinners et al., 2009) with either PP baling twine (75 % of bales) (Jones, 2021) or HDPE woven mesh net wrap (25 % of bales) (Shaffer, 2022). Material intensity was based on the length of material required to encase a standard-size bale and manufacturer data on polymer spool weight, length, and density (Table SI-9).

2.1.5. Storage

The final agricultural stage is storing harvested products for later use. Silage is produced by encasing crops like silage corn, miscanthus, and sugarbeets (USDA NASS, 2024) in plastic to facilitate fermentation for improved storage and nutrient content (van den Oever et al., 2021). Silage is stored in bale wrap (20 %), silo bags (15 %), and bunkers (55 %), with the remainder in non-plastic on-farm silos (Panke-Buisse, 2022) (Table SI-17). Round bales of wrapped silage, or "marshmallows," are first baled with twine or net wrap and then wrapped in LDPE film (Baxter et al., 2019), while silo bags use long air-tight tubes of LDPE plastic (Bartosik et al., 2024). Most silage is stored on farms in open-top concrete bunkers (Amaral-Phillips, 2023) covered with plastic tarps (Saxe, 2016). Material intensity is estimated from bale, bag, or bunker dimensions, storage capacity, polymer density, and wrap or tarp thickness (Table SI-10).

The storage of overflow grains that cannot be accommodated in permanent storage bins is also supported by plastics (Hellevang, 2020).

Grain silo bags are similar to silage bags (Loftness, 2022), and material intensity is estimated comparably, relative to bag dimensions, packing capacities, and LDPE thickness and density (Table SI-11). Plastics are also used to store and deliver compound animal feed to livestock operations (Roy, 2024). While most feed (90 %) is delivered in bulk and stored in permanent structures on farms, the remaining 10 % uses either PP woven bags or FIBCs (Martin, 2022). Material intensity is based on typical container dimensions, storage capacity, and polymer weight or density (Table SI-12).

2.2. Annual demand for agricultural applications that use plastic

Material intensity estimates represent the annualized mass of plastic per unit of end-use application (e.g., kg plastic per acre or per container). To determine cumulative plastic consumption, material intensity values were scaled-up by the total annual demand for each agricultural end use (e.g., acres planted or number of containers) as shown in Table 2. Following the earlier example of mulch films, where material intensity is reported as kg plastic per acre mulched crop, the associated demand would be total acres of mulched crops. Annual demand estimates were made in one of three ways, depending on the nature of available data: 1) total acres of crops that used a given plastic product (e.g., mulch, irrigation), 2) total amount of materials that need to be contained or stored in plastic (e.g., seeds, forage), or 3) total quantities of plastic products manufactured for or used by the agricultural industry (e.g., horticultural and chemical containers). The primary sources of data for annual demand were the 2022 USDA Census of Agriculture (USDA NASS, 2024) and 2019 Census of Horticultural Specialties (USDA NASS, 2020), as well as a limited number of industry reports. Because of the extensive number of end uses included ($n = 221$), the annual demand estimates and references for each are provided in the accompanying data repository (Malarkey and Babbitt, 2025).

Annual demand also incorporated a plastic utilization factor, which reflects the relative extent to which each crop or agricultural application uses a plastic product. In the baseline model, the utilization factor was binary (0 % or 100 %) based on best available information (Table SI-13; Malarkey and Babbitt, 2025). For example, surface drip tape is widely used for irrigating orange trees (Kallsen et al., 2021; Vashisth et al., 2023), so utilization was assumed to be 100 % for this product and crop (i.e., all orange tree acreage contributed to annual demand for this plastic product). On the other hand, forage crops like field corn rarely use drip tape (Sui et al., 2015) and thus were assigned utilization of 0 %. Realistically, agricultural practices are not binary, but since available data were insufficient to characterize every permutation of plastic and crop, this parameter was examined through probabilistic uncertainty analysis (Section 2.3).

2.3. Uncertainty analysis and sensitivity scenarios

Baseline estimates for material intensity and annual demand use the best currently-available data on conventional U.S. agricultural operations, but many underlying parameters may vary by location, crop, material, and practice. For example, thickness of irrigation plastics fabricated by different companies varies by up to 10 mm (Grow Irrigation, 2023; Netafim, 2023), resulting in a 40 % difference in material intensity for irrigation tubing. Plastic baling twine can be applied at rates varying from 20 up to 30 wraps per forage bale (Shaffer, 2022; Shinners et al., 2009), and associated differences in material intensity would be amplified across 246 million t of forage baled in the U.S. annually. In addition, underlying data may have unavoidable uncertainties associated with self-reporting methods used in the USDA Agricultural Census, although this agency verifies data to the extent possible (USDA NASS, 2024).

To understand the implications of such uncertainty, a Monte Carlo sensitivity analysis simulated distributions surrounding key variables, including product lifespan, dimension and mass, and end-use utilization factor. Triangular distributions were applied, with minimum and maximum values corresponding to the practical range of real-world specifications documented for each product (Table SI 2–12). The peak value corresponded to the baseline described in Sections 2.1 and 2.2. Uncertainty analysis was based on 50,000 iterations on all parameters simultaneously, for the full plastic footprint. To determine the influence of individual parameters and the sensitivity of individual product results, these iterations were repeated one-at-a-time and for each plastic product. All calculations were performed in R version 4.2.2 with packages “tidyverse”, “measurements”, and “EnvStats” (Birk, 2023; Millard, 2013; R Core Team, 2021; Wickham et al., 2019), see Malarkey and Babbitt (2025).

The overall results and the sensitivity analyses were used to identify specific products and applications with the highest plastic consumption and the most sensitivity to changes in parameters characterizing material intensity and annual demand. The four plastic products with the highest mass and sensitivity (see Results) were then used for an initial exploration of how circular economy (CE) strategies might reduce plastic consumption. Specific CE strategies examined were: 1) reducing plastic demand by use of non-plastic alternatives; 2) dematerializing plastic use through product choices with the minimum product mass or dimension possible that meets functional requirements; or 3) extending the lifespan of each product by one year. The specific rationale and references for each scenario are provided in SI Table 21. These scenarios are simplistic and theoretical; they do not account for realistic inefficiencies or barriers to adoption. Recycling is treated qualitatively in the discussion, but was not included in a quantitative estimate, as agricultural plastics are likely to be managed in an open-loop system, where recovered materials go into other downstream markets and would therefore not reduce net consumption. While a full analysis of CE strategies applied to all products and end uses is outside the scope of this study and not currently feasible with available data, this initial scenario analysis is intended to highlight emerging opportunities and future research priorities.

3. Results and discussion

3.1. Total annual baseline plastic consumption

The main result of this study is that the U.S. agricultural sector consumes an estimated 1.56 million tonnes of plastics annually. This plastic footprint is 530 % greater than the first estimate of domestic agricultural plastic use made 30 years ago (Amidon Recycling, 1994). This increase is likely due, in part, to the present study having a broader scope (more plastic products covered) and a more comprehensive analysis that links plastic consumption to all crops and activities covered by the USDA (the prior study interviewed a sample of plastics manufacturers and recyclers to estimate amounts produced or recovered at EOL). However, this increase is also likely due to an intensification in agricultural practices that rely on plastic products over the last 30 years. Between 1992 and 2022, total harvested cropland in the U.S. only increased by 1.6 %, while market value of agricultural products grew over 230 % (USDA NASS, 2024). Our estimate of agricultural plastics represents 2.7 % of total reported U.S. plastic demand (Hendrickson et al., 2024), although plastic flow studies don’t typically include this specific sector (Di et al., 2021). Results also suggest that the proportion of agricultural plastics in the U.S. is comparable to available estimates for Europe (about 2–3.5 % of total plastic use) (D. Briassoulis, Babou, et al., 2013; Horodytska et al., 2018) and globally (FAO, 2021; Vox et al., 2016).

Results show that plastics are widely used across agricultural stages, but a limited set of products are responsible for the greatest total mass (Fig. 2). The largest categories of plastic use are horticultural containers (42 %), silage storage (19 %), and mulch films (17 %). All remaining categories contribute less than 7 % each to total annual consumption, with the four smallest categories – chemical containers, grain storage,

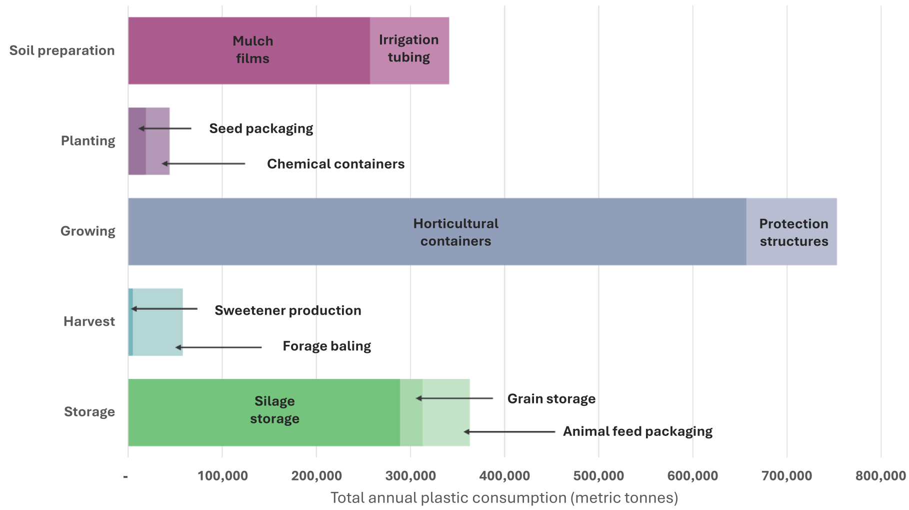

Fig. 2. Total annual agricultural plastic consumption (tonnes) by agricultural stage and usage category.

seed packaging, and sweetener collection – together contributing just 4.6 % (full data provided in SI Tables 18–19). While horticultural containers represent the highest estimated demand for plastics, these products are comparatively understudied, as 89 % of papers on agricultural plastics focus on plastic mulch, tunnels, and greenhouses (Yates et al., 2021). This mismatch suggests a need for future research on solutions that better aligns with agricultural products most responsible for plastic demand.

Within these categories, the largest contributors to the plastic footprint are end-use applications that functionally require more material and/or have shorter lifespans. For example, horticultural containers weigh up to 0.5 kg per large transplant plot (Schrader, 2013), as this application requires sturdy, durable materials to support growing trees (Michael, 2017). While the relative durability of horticultural containers means they could technically be reused, most farms discard them after a single use, increasing waste and materials required for replacement containers (Soulliere-Chieppo, 2020). Conversely, rigid plastic greenhouses have a high baseline mass (>830 kg plastic per structure), but are used for over 10 years (USGR, 2019), leading to low annualized plastic consumption.

3.2. Plastic consumption by agricultural end use

Plastic consumption is also linked to the ultimate demand for agricultural end uses. For most categories, a small subset of crops or products are responsible for the highest plastic use by mass (Fig. 3). For example, almost 50 % of plastic mulch film is attributed to just four crops - sweetcorn, tomatoes, broccoli, and watermelon - mainly due to the vast acreage dedicated to these crops; the remaining 50 % is associated with 36 other crops. The highest irrigation plastic demand is for fruit and nut production - particularly almonds - reflecting the significant land and water required to grow these crops (USDA NASS, 2024) and their use of plastic (as opposed to metal) irrigation (Lamont et al., 2023). Nut crops have previously been implicated for intense agricultural water demand (Marvinney and Kendall, 2021), suggesting the need to further explore a "food-water-plastic" nexus of resource use. Similarly, the largest driver of plastic silage films is acreage of corn and haylage (USDA NASS, 2024), which are used for cattle feed (Ates, 2023; Panke-Buisse, 2022). Thus, curbing beef and dairy consumption would not only cut plastic consumption but also reduce agricultural waste and climate impacts (Putman et al., 2023; Rotz et al., 2019).

End-use demand also dictates the nature of plastic products most commonly used and the mass requirements thereof. For example, most mulched crops use a "wrapped" bed style (110 kg LDPE/acre), rather than flat beds (95 kg LDPE/acre), because it provides greater soil stability and coverage (BTC, 2023; Schrader, 2000). Material intensity of microsprinklers is about seven times that of drip tape, however the two products have comparable net consumption because drip tape is used on more crop acreage and replaced each year, while microsprinklers are primarily used in establishing orchards (Godin and Broner, 2013) and have much longer lifespans. For silage categories, bale wrapping is the most plastic-intense way to contain silage (1.5 kg plastic/bale), while a plastic-covered bunker requires 570 kg of plastic but holds about 3900 bales (about 0.15 kg plastic/bale). Each of these examples underscores the need to design agricultural products that use less plastic but still functionally meet farming requirements.

3.3. Plastic consumption by polymer type and product form

U.S. agricultural plastics are a varied mix of polymer materials and product forms (Fig. 4). LDPE represents the highest share by mass, accounting for 742,000 t, or 48 % of total plastic consumption (Table SI-20), primarily due to flexible films used in plastic mulch, high and low tunnels, and silage wraps, as well as flexible tubing for irrigation. For context, LDPE is also one of the most prevalent polymers in overall U.S. plastic use, although it represents less than 20 % of total domestic plastic flows (Heller et al., 2020). The next highest contributions are from HIPS (26 %), HDPE (15 %), and PP (11 %), respectively, which are primarily associated with horticultural and chemical containers. PC is just 0.3 % of total plastic use, solely associated with rigid plastic greenhouses in this study.

The polymers and product forms used in agriculture directly influence end-of-life management. Polymers like LDPE and HDPE have a high tolerance for recycling (Lahoz, 2023), but actual feasibility depends on product shape (Ding and Zhu, 2023) and cleanliness (Filipe et al., 2023). Woven HDPE fabrics and flexible LDPE films and tubing are particularly challenging to recycle because recovery facilities are ill-equipped to handle lightweight, flexible materials (Reed et al., 2018), especially when they contain adhered dirt and organics (Salama and Geyer, 2023). Recycling and reuse of rigid HDPE is more likely (Gandhi et al., 2021), but many agricultural HDPE containers hold chemicals or plant matter, requiring cleaning and sterilization before reuse or downstream management (Garbounis et al., 2022).

Fig. 3. Plastic consumption by end use and product type. Each chart is scaled to 100 % of total annual mass per category (noted at top of each graph). Highest individual end uses of each product are disaggregated, with remaining crops or products summed under other (n=number of remaining end uses not shown).

3.4. Sensitivity and scenario analysis

Baseline results represent most likely parameters of plastic use, but uncertainties surround plastic properties, lifespan, and use by crop. Underlying data used in the model may also have uncertainties, largely stemming from how government agencies collect agricultural information and the extent to which literature values can represent U.S. practices. Monte Carlo uncertainty analysis shows that over the widest distributions of parameter variability, total plastic consumption could vary from 640,000 to 6 million tonnes (Fig. 5 and SI-1). However, such edge cases reflect extreme scenarios that are unlikely in reality. For example, low estimates are linked to product lifespans up to eight times longer than the baseline. Conversely, extreme high estimates reflect utilization of mulch film on row crops, such as soybeans, which does not widely happen in practice (Knott et al., 2023; Liang et al., 2020). Over 60 % of all iterations return values within 25 % of the baseline result reported above. Future research may be able to further constrain remaining uncertainties, such as including products not yet captured here due to lack of data (e.g., livestock feed tubs; Borreani and Tabacco, 2017).

Sensitivity analysis by product shows that some uses, such as horticultural transplant pots and irrigation surface drip tape, have narrow ranges of uncertainty because underlying data on product mass and utilization are more consistent (Fig. 5, Fig. SI-2). Conversely, products like mulch films, low tunnels, propagation trays, and silage bale wrap have wide distributions of possible results (Fig. 5), due to high variability in product dimensions, lifespans, and utilization factors reported in scientific and agricultural trade literature. One-at-a-time parameter sensitivity analyses (Fig. SI-3) helped identify plastic uses most sensitive to material, behavioral, and operational variables, which represent promising leverage points for reducing plastic consumption and waste, although the extent of change depends heavily on the product and

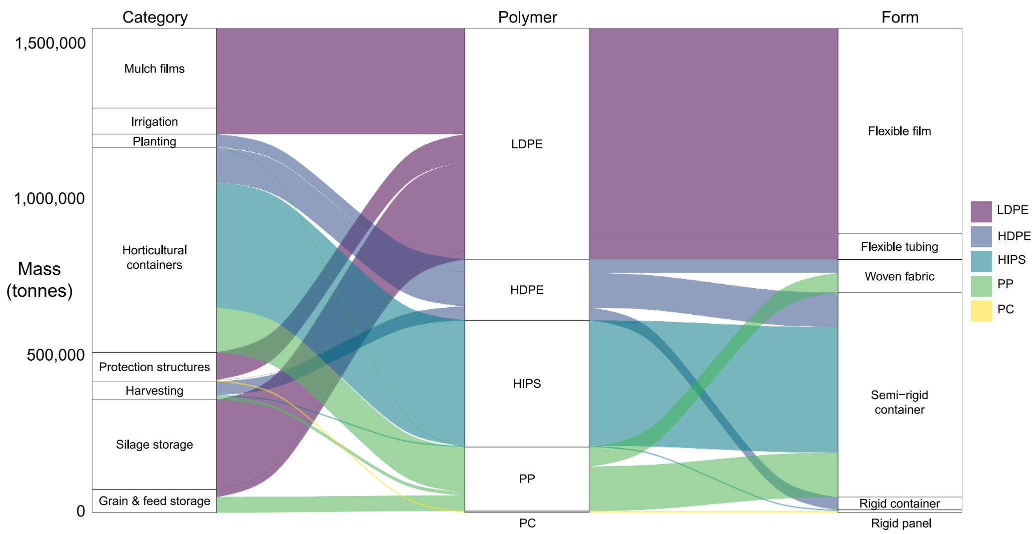

Fig. 4. Disaggregation of the agricultural plastic footprint by product category, polymer type, and material form. All flow lines are scaled relative to 1.56 million tonnes total plastic consumption.

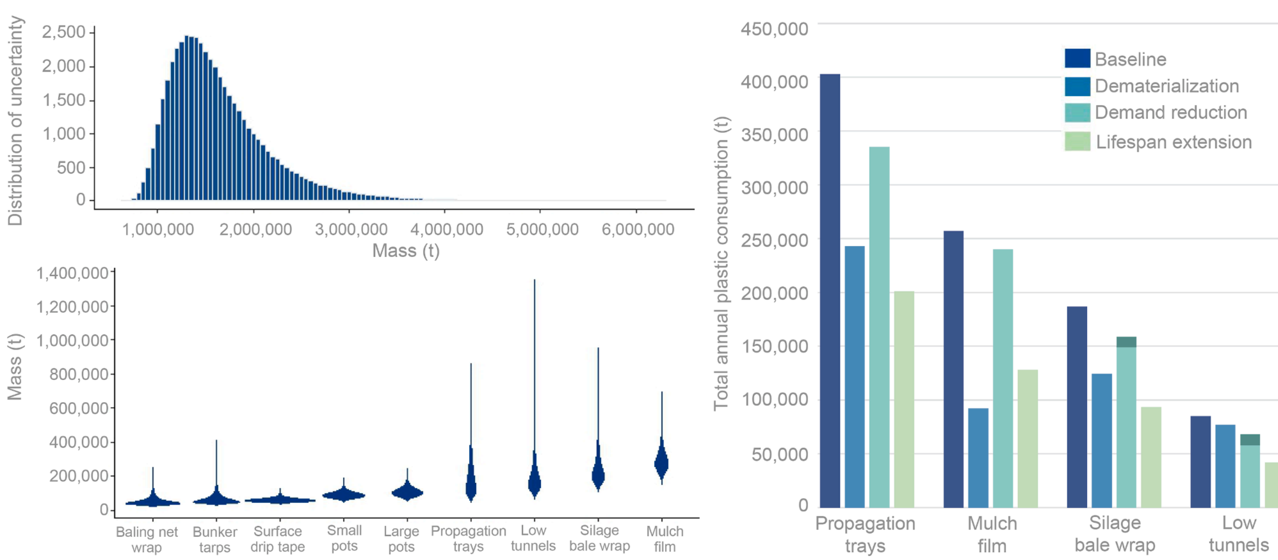

Fig. 5. Plastic consumption sensitivity and scenario analysis. Left: Distributions of total agricultural plastic footprint estimates (top) and product-specific estimates for the nine products with highest mass contributions (bottom); all based on Monte Carlo simulation with 50,000 iterations across parameter ranges. Right: Estimated plastic consumption for the four products with highest mass and sensitivity, for the baseline and three theoretical circular economy scenarios. Note that darker shaded segments of 'Demand Reduction' for silage bale wrap and low tunnels represent marginal demand associated with shifting use to alternative plastic options (bunker tarps and high tunnels, respectively).

application in question.

To theoretically explore how these parameters can be leveraged to reduce the plastic footprint of four high-mass products, three circular economy strategies were explored: dematerialization, demand reduction, and lifespan extension (Fig. 5). For all four products, extending lifespan from the baseline of one to just two years can halve plastic consumption. Reducing consumption by dematerialization is estimated to offer the greatest potential in the case of mulch films, where thinner, lighter options are commercially available and may meet functional needs of the agricultural applications. In the case of demand reduction, non-plastic alternatives are available for horticultural propagation trays and mulch films, such as straw (Muñoz et al., 2022) or paper mulch (Sintim et al., 2022), but low uptake limits the degree to which these options could feasibly reduce plastic demand (Fig. 5). In the case of silage bale wrap and low tunnels, demand can potentially be reduced by shifting usage to other plastic products with lower material intensity, namely storing silage in bunker tarps and growing greens in high tunnels, respectively. While both of these cases show a decrease from the baseline plastic footprint (Fig. 5) because they provide comparable functionality with less plastic, net reduction potential is somewhat offset by the increased use of plastic by the replacement products. These results underscore the need to deploy reusable, non-plastic options (Munch, 2023) that could eliminate plastic storage completely (Smith, 2022).

Even with efforts to reduce, quantify, and explore sensitivities within the underlying data and model, we anticipate that a number of uncertainties still exist. For example, there are few available benchmarks for validating the model, although the 1994 analysis does report similar trends in terms of plastic products with the highest uses (Amidon Recycling, 1994). Results oversimplify the mix of plastics used, as data availability constrained the analysis to common polymers, while many agricultural plastics in use may be composites, have multiple layers, or contain additives. In addition, some end uses or small-scale practices that are not well characterized are omitted from the analysis. However, the current model and estimates provide a practical compromise between waiting for fully refined data and taking action to mitigate the growing impacts of agricultural plastic consumption and waste. The extensive documentation in the SI and data repository (Malarkey and Babbitt, 2025) can be adapted to extend and improve the analysis as more data become available.

4. Implications and future research needs

Results presented herein highlight key opportunities for circular economy strategies to minimize consumption of agricultural plastics and reduce their life cycle impacts (LeMoine et al., 2021). A detailed analysis of CE interventions is not yet possible, as available data do not cover the full extent of how such strategies might realistically be deployed for all the products and end uses analyzed here. However, results can be interpreted in the context of what is currently known about challenges and opportunities associated with applying CE to agricultural plastics by narrowing, slowing, and closing resource loops (Babbitt et al., 2022).

Narrowing resource loops involves reducing net production and consumption of plastics by, for example, decreasing the mass of plastic required per product to provide required functionality (dematerialization), substituting incumbent products with non-plastic alternatives, and cutting demand for the product altogether by reducing demand for the agricultural application in which it is used. For many of the products analyzed, lighter (Willden et al., 2022), plastic-free (LeMoine et al., 2021), bio-based (Kratsch et al., 2015; Fuentes et al., 2021), and waste-derived (Hernandez-Charpak et al., 2024) alternatives are available, but are not widely used at scale. Farmers may perceive such options as unproven technology (Goldberger et al., 2019) having poor cost, aesthetics, and durability (Harris et al., 2020; Shcherbatyuk et al., 2024), and they may create new challenges stemming from incomplete degradation (Samuelson et al., 2022) and increased microplastic release (LeMoine et al., 2021).

Slowing resource loops refers to retaining the value of plastic products in use for as long as functionally possible. The majority of products found to contribute most to total plastics use have a lifespan of just a single year or even a single growing season, after which they are typically landfilled (Soulliere-Chieppo, 2020). Extending product lifespan, therefore, offers a promising pathway to reduce plastic demand. Take, for example, the case of horticultural containers, which represent about 42 % of the total plastic footprint. Extending the lifespan of all containers by one year (doubling the baseline value) would reduce net plastic use by over 300,000 t (about 22 % of the total baseline estimate). Lifespan extension offers direct cost savings from avoiding the purchase of new products, but can potentially increase labor and operational costs associated with collection and cleaning, especially if products contain chemicals or organic matter and must be sterilized before reuse (Garbounis et al., 2022).

Closing resource loops focuses on recovering material and energy value in agricultural plastics at end-of-life, often through recycling products into new agricultural uses (Korol et al., 2021; ACRC, 2023) or other applications, such as plastic lumber (Filipe et al., 2024). While accurate data on recycling rate by product and polymer is challenging to determine (Ritchie, 2018), one estimate suggests that up to 10 % of U.S. agricultural plastics can be recycled (Cassou, 2018), which would correspond to about 156,000 t of the estimated plastic footprint potentially diverted from disposal. Other value recovery pathways include thermochemical conversion of agricultural plastics to biochar (Cisse et al., 2022) and energy recovery (Madrid et al., 2022), which can handle soil-contaminated films (Tan et al., 2023). Chemical recycling methods are also used to recycle materials from agricultural plastics (Chinchkar et al., 2024), and may be better suited to process multi-layer films that are used in greenhouses (Dehbi et al., 2017) and mulch (Wells, 2021), but which are challenging to mechanically recycle (Cabrera et al., 2022; Seier et al. 2024). A European assessment suggests that up to 44 % of agricultural plastic waste can be chemically recycled (Lase et al., 2023), and if that held for the U.S. case, it would correspond to about 680,000 t of plastics diverted from disposal. However, chemical recycling is often viewed to have performance and financial barriers to viability (Schade et al., 2024).

The strategies noted above face a wide array of technical, cost, and behavioral barriers to wider adoption. For example, there are high costs and logistical challenges associated with managing soil and chemical contamination (Sarpong et al., 2024) and transporting EOL plastics from scattered farms (Lark et al., 2021) to centralized recycling facilities (Filipe et al., 2023). Farmers may perceive recycling as costly and inconvenient or lack knowledge of or access to recovery pathways (King et al., 2023). Overcoming these barriers may require policy interventions, such as extended producer responsibility (Leal Filho et al., 2019), tax credits (Galati and Scalenghe, 2021), or "pay-back" programs (Pazienza and De Lucia, 2020) that incentivize farmers to recycle. In the U.S., programs have been funded to increase recycling (Bonhotal, 2020), but ended, in part due to a lack of markets for plastic waste (Bonhotal and Bonacquist-Currin, 2017). There is clearly a need for future research to better understand technical, economic, and stakeholder barriers and then create and scale up circular business models that effectively address the growing challenge of agricultural plastics.

5. Conclusions

This study provides a comprehensive model of the U.S. agricultural plastic footprint and demonstrates that this material system has grown in both mass and complexity over the past three decades. The agricultural sector is estimated to use about 1.56 million tonnes of plastics per year, most of which is concentrated in a limited set of end-use applications, such as horticultural containers, protection structures, and mulch films, which have short lifespans, high functional material requirements, and are associated with significant agricultural activity. In many cases, the highest demands for plastics can be traced to a small set of crops or agricultural commodities. Such results help identify sectors within U.S. agriculture where circular economy strategies may offer the greatest potential to reduce plastic consumption and waste. Scenario analysis suggests that dematerialization, material substitution, and lifespan extension can theoretically reduce demand for certain plastics by up to 60 %, but such strategies face major technical, economic, and behavioral barriers. For example, the majority of plastics used in agriculture are flexible films, tubes, and fabrics, which are challenging to reuse and recycle. There is clearly a need for future research to both resolve remaining uncertainty and better understand how to enable circular management of agricultural plastics. Continued efforts to measure and minimize plastic use and impact in the agricultural sector are critical to future sustainability of food production.

CRediT authorship contribution statement

Katie A. Malarkey: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Callie W. Babbitt:** Writing – review & editing, Visualization, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Callie W. Babbitt reports financial support was provided by National

Science Foundation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This material is based upon work supported by the National Science Foundation under Awards 1639391, 1934542, and 2115405. Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2025.108515.

Data availability

All data and code are published on a public repository cited in the article.

References

Abdi, D.E., Owen, J.S., Wilson, P.C., Hinz, F.O., Cregg, B., Fernandez, R.T., 2021. Reducing pesticide transport in surface and subsurface irrigation return flow in specialty crop production. Agric. Water Manag. 256, 107124. https://doi.org/10.1016/j.agwat.2021.107124.

ACRC, 2023. Recycling—ACRC. Ag Container Recycling Council. https://agrecycling.org/recycling/.

Adisa, O., Ilugbusi, B.S., Adelekan, O.A., Asuzu, O.F., Ndubuisi, N.L., 2024. A comprehensive review of redefining agricultural economics for sustainable development: overcoming challenges and seizing opportunities in a changing world. World J. Adv. Res. Rev. 21 (1). https://doi.org/10.30574/wjarr.2024.21.1.0322, 2329–1241.

Amaral-Phillips, D., 2023. Bunker Silo and Drive- Over Silage Pile Management. University of Kentucky.

Amidon Recycling, 1994. Use and Disposal of Plastics in Agriculture, 106. American Plastics Council. https://www.wastexchange.org/upload_publications/UseandDisposalofPlasticsinAgriculture.pdf.

Anderson, R.G., Girona, J., Gucci, R., 2023. Using water for best product quality in fruit and nut trees and vines. Irrig. Sci. 41 (4), 449–452. https://doi.org/10.1007/s00271-023-00857-8.

Anunciado, M.B., Hayes, D.G., Wadsworth, L.C., English, M.E., Schaeffer, S.M., Sintim, H. Y., Flury, M., 2021. Impact of agricultural weathering on physicochemical properties of biodegradable plastic mulch films: comparison of two diverse climates over four successive years. J. Polym. Env. 29 (1), 1–16. https://doi.org/10.1007/s10924-020-01853-1.

Ates, A., 2023. Feed Grains Sector At a Glance. USDA Economic Research Service. https://www.ers.usda.gov/topics/crops/corn-and-other-feed-grains/feed-grains-sector-at-a-glance/.

Babbitt, C.W., Neff, R.A., Roe, B.E., Siddiqui, S., Chavis, C., Trabold, T.A., 2022. Transforming wasted food will require systemic and sustainable infrastructure innovations. Current Opinion in Environmental Sustainability 54, 101151.

Baker, E., Thygesen, K., Fredrich, C., Heffer, P., Messing, D., Ndegwa, M., Neretin, L., Pradhan, M., Preston-Whyte, F., Tanyi, R., Thompson, R., Zennaro, R., Zhu, S., 2021. Plastics in Agriculture: sources and Impacts. U. N. Environ. Programme. https://www.unep.org/resources/emerging-issues/plastics-agriculture-environmental-challenge.

Bamdad, H., Papari, S., Lazarovits, G., Berruti, F., 2022. Soil amendments for sustainable agriculture: microbial organic fertilizers. Soil Use Manag. 38 (1), 94–120. https://doi.org/10.1111/sum.12762.

Bartosik, R., Cardoso, L., Urcola, H., 2024. Silo bag storage. In: Control and Management of Pests in Stored Products, 32. CRC Press.

Basheer, S., Wang, X., Farooque, A.A., Nawaz, R.A., Pang, T., Neokye, E.O., 2024. A review of greenhouse gas emissions from agricultural soil. Sustainability 16 (11), 4789. https://doi.org/10.3390/su16114789.

Baxter, L., Henning, J., Teutsch, R., Smith, R., Sears, B., Hancock, D., 2019. Baleage: Frequently Asked Questions. University of Georgia Extension. https://extension.uga.edu/publications/detail.html?number=B1508&title=baleage-frequently-asked-questions.

Blackburn, K., Green, D., 2022. The potential effects of microplastics on human health: what is known and what is unknown. Ambio 51 (3), 518–530. https://doi.org/10.1007/s13280-021-01589-9.

Bonhotal, J. (2020). *CornellRAPP* [Personal communication].

Bonhotal, J., Bonacquist-Currin, M., 2017. Agric. Plast. Recycl. N. Y. State.

Borreani, G., Tabacco, E., 2017. 9—plastics in animal production. In: Orzolek, M. (Ed.), 9—plastics in animal production. A Guide to the Manufacture, Performance, and Potential of Plastics in Agriculture 145–185. https://doi.org/10.1016/B978-0-08-102170-5.00003-8.

Boucher, J., Dubois, C., Kounina, A., Puydarrieux, P., 2019. *Review of Plastic Footprint Methodologies: laying the Foundation for the Development of a Standardised Plastic Footprint Measurement tool*. IUCN. International Union for Conservation of Nature. https://doi.org/10.2305/IUCN.CH.2019.10.en.

Briassoulis, D., Babou, E., Hiskakis, M., Scarascia, G., Picuno, P., Guarde, D., Dejean, C., 2013a. Review, mapping and analysis of the agricultural plastic waste generation and consolidation in Europe. Waste Manag. Res.: J. Sustain. Circ. Econ. 31 (12), 1262–1278. https://doi.org/10.1177/0734242×13507968.

Briassoulis, D., Hiskakis, M., Babou, E., 2013b. Technical specifications for mechanical recycling of agricultural plastic waste. Waste Manag. 33 (6), 1516–1530. https://doi.org/10.1016/j.wasman.2013.03.004.

Briassoulis, D., Hiskakis, M., Tserotas, P., 2018. Combined effect of UVA radiation and agrochemicals on the durability of agricultural multilayer films. Polym. Degrad. Stab. 154, 15.

BTC, 2023. Bed & Mulch Configurations Handbook. Buckeye Tractor Company. http://www.buctraco.com/6%20Library/INF–Bed&MulchConfigurations.pdf.

Cabrera, G., Li, J., Maazouz, A., Lamnawar, K., 2022. A journey from processing to recycling of multilayer waste films: a review of main challenges and prospects. Polymers 14 (12), 2319. https://doi.org/10.3390/polym14122319.

Cao, X., Liang, Y., Jiang, J., Mo, A., He, D., 2023. Organic additives in agricultural plastics and their impacts on soil ecosystems: compared with conventional and biodegradable plastics. TrAC Trends Anal. Chem. 166, 117212. https://doi.org/10.1016/j.trac.2023.117212.

Cassou, E., 2018. *Agricultural Pollution Plastics* (No. 124346). World Bank Group. https://documents.worldbank.org/en/publication/documents-reports/documentdetail/122161521208357388/plastics.

Chinchkar, A., Singh, A., Singh, S.V., Kamble, M., 2024. Sustainable Agriculture: Nanotechnology, Biotechnology, Management and Food Security: Vol. Chapter 20. Walter de Gruyter GmbH & Co KG.

Chu, J., 2017. Watering the World. Massachusetts Institute of Technology. https://news.mit.edu/2017/design-cuts-costs-energy-drip-irrigation-0420.

Church, S.P., Lu, J., Ranjan, P., Reimer, A.P., Prokopy, L.S., 2020. The role of systems thinking in cover crop adoption: implications for conservation communication. Land Use Policy 94, 104508. https://doi.org/10.1016/j.landusepol.2020.104508.

Cisse, I., Hernandez-Charpak, Y.D., Diaz, C.A., Trabold, T.A., 2022. Biochar derived from pyrolysis of common agricultural waste feedstocks and Co-pyrolysis with low-density polyethylene mulch film. Waste Biomass Valoriz. 13 (9), 3913–3932. https://doi.org/10.1007/s12649-022-01760-7.

Cook, D., Blackler, A., McGree, J., Hauxwell, C., 2021. Thermal impacts of apicultural practice and products on the Honey Bee colony. J. Econ. Entomol. 114 (2), 538–546. https://doi.org/10.1093/jee/toab023.

Crowley, M., VanDeusen, B., Dawson, J., Lowe, K., 2022. *Standard Values for Amount of Seed Treated and/or Planted Per Day* (No. 15.2; Standard Operating Procedure, p. 23). Science Advisory Council for Exposure. https://www.epa.gov/system/files/documents/2022-01/exposac-policy-15_amount-seed-treated-planted.pdf.

Dehbi, A., Youssef, B., Chappey, C., Mourad, A.-H.I., Picuno, P., Statuto, D., 2017. Multilayers polyethylene film for crop protection in harsh climatic conditions. Adv. Mater. Sci. Eng. 2017, 1–7. https://doi.org/10.1155/2017/4205862.

Deng, Y., Zeng, Z., Feng, W., Liu, J., Yang, F., 2024. Characteristics and migration dynamics of microplastics in agricultural soils. Agriculture 14 (1), 157. https://doi.org/10.3390/agriculture14010157.

Di, J., Reck, B.K., Miatto, A., Graedel, T.E., 2021. United States plastics: large flows, short lifetimes, and negligible recycling. Resour. Conserv. Recycl. 167, 105440. https://doi.org/10.1016/j.resconrec.2021.105440.

Ding, Q., Zhu, H., 2023. The key to solving plastic packaging wastes: design for recycling and recycling technology. Polymers 15 (6), 1485. https://doi.org/10.3390/polym15061485.

Dixon, G.R., Aldous, D.E., 2014. Horticulture: Plants for People and Places, Volume 1: Production Horticulture. Springer, Netherlands. https://doi.org/10.1007/978-94-017-8578-5.

Dong, H., Yang, G., Zhang, Y., Yang, Y., Wang, D., Zhou, C., 2022. Recycling, disposal, or biodegradable-alternative of polyethylene plastic film for agricultural mulching? A life cycle analysis of their environmental impacts. J. Clean. Prod. 380, 134950. https://doi.org/10.1016/j.jclepro.2022.134950.

El-Beltagi, H.S., Basit, A., Mohamed, H.I., Ali, I., Ullah, S., Kamel, E.A.R., Shalaby, T.A., Ramadan, K.M.A., Alkhateeb, A.A., Ghazzawy, H.S., 2022. Mulching as a sustainable water and soil saving practice in agriculture: a review. Agronomy 12 (8), 1881. https://doi.org/10.3390/agronomy12081881.

Empson, L., Eyer, G., Friedl, E., Massion, R., Miyashiro, B., 2021. Reducing Agricultural Plastics' Environmental Impacts. Bren School of Environmental Science & Management. https://bren.ucsb.edu/projects/reducing-agricultural-plastics-environmental-impacts.

FAO, 2021. Assessment of Agricultural Plastics and their Sustainability: a call for Action. Food and Agriculture Organization of the United Nations. https://doi.org/10.4060/cb7856en.

Filipe, S., Mourão, P.M., Couto, N., Tranchida, D., 2023. Towards a sustainable future: advancing an integrated approach for the recycling and valorization of agricultural plastics. Polymers 15 (23), 4529. https://doi.org/10.3390/polym15234529.

Filipe, S., Mourão, P.M., Couto, N., Tranchida, D., 2024. Barriers, drivers and opportunities for valorization of agricultural plastic waste. In: Brito, P.S., Da, J.R., Sanches Galvão, C., Almeida, H., Rosa Ferreira, L.C., Alves Flores De Oliveira Gala, P.E. (Eds.), ICoWEFS 2024 Sustainability Proceedings. Springer Nature, Switzerland. https://doi.org/10.1007/978-3-031-80330-7.

Frisvold, G., Bai, T., 2016. Irrigation technology choice as adaptation to climate change in the western United States. J. Contemp. Water Res. Educ. 158 (1), 62–77. https://doi.org/10.1111/j.1936-704X.2016.03219.x.

Fuentes, R.A., Berthe, J.A., Barbosa, S.E., Castillo, L.A., 2021. Development of biodegradable pots from different agroindustrial wastes and byproducts. Sustain. Mater. Technol. 30, e00338. https://doi.org/10.1016/j.susmat.2021.e00338.

Galati, A., Scalenghe, R., 2021. Plastic end-of-life alternatives, with a focus on the agricultural sector. Curr. Opin. Chem. Eng. 32, 100681. https://doi.org/10.1016/j.coche.2021.100681.

Gandhi, N., Farfaras, N., Wang, N.-H., Chen, W.-T., 2021. Life cycle assessment of recycling high-density polyethylene plastic waste. J. Renew. Mater. 9 (8), 1463–1483. https://doi.org/10.32604/jrm.2021.015529.

Garbounis, G., Karasali, H., Komilis, D., 2022. A life cycle analysis to optimally manage wasted plastic pesticide containers. Sustainability 14 (14), 8405. https://doi.org/10.3390/su14148405.

Gerassimidou, S., Iacovidou, E., 2024. Employing a systems approach to unravelling the complexities of the agricultural plastics value chain. J. Clean. Prod. 478, 143865. https://doi.org/10.1016/j.jclepro.2024.143865.

Gerovac, J.R., Lopez, R.G., Mattson, N.S., 2015. High tunnel versus climate-controlled greenhouse: transplant time and production environment impact growth and morphology of cold-tolerant bedding plants. HortScience 50 (6), 830–838. https://doi.org/10.21273/HORTSCI.50.6.830.

Godin, R., Broner, I., 2013. *Micro-Sprinkler Irrigation for Orchards* (No. 4.703). Colorado State University.

Goldberger, J.R., DeVetter, L.W., Dentzman, K.E., 2019. Polyethylene and Biodegradable Plastic Mulches for Strawberry Production in the United States: Experiences and Opinions of Growers in Three Regions. HortTechnology 29 (5), 619–628. https://doi.org/10.21273/HORTTECH04393-19.

Grow Irrigation, 2023. *Irritec P1 Ultra 7/8" Drip Tape*. Grow Irrigation. March 25. https://www.growirrigation.com/collections/7-8-drip-tape.

Gullett, B.K., Tabor, D., Touati, A., Kasai, J., Fitz, N., 2012. Emissions from open burning of used agricultural pesticide containers. J. Hazard. Mater. 221–222, 236–241. https://doi.org/10.1016/j.jhazmat.2012.04.041.

Gupta, J., Sharma, D., Chauhan, A., 2024. Classification and suitability of protected structures. Protected Cultivation, 1st ed. Apple Academic Press.

Harris, B.A., Florkowski, W.J., Pennisi, S.V., 2020. Horticulture industry adoption of biodegradable containers. HortTechnology 30 (3), 372–384. https://doi.org/10.21273/HORTTECH04563-19.

Harris, D., Fuller, D.Q., 2014. Agriculture: definition and overview. In: Smith, C. (Ed.), Encyclopedia of Global Archaeology. Springer New York, pp. 104–113. https://doi.org/10.1007/978-1-4419-0465-2_64.

Harris, T., Streets, J., Carpenter, J., 2021. *Low Tunnels for Beginners* (Gardening 101). West Virginia Extension. https://extension.wvu.edu/lawn-gardening-pests/gardening/gardening-101/low-tunnels-for-beginners.

Heller, M.C., Mazor, M.H., Keoleian, G.A., 2020. Plastics in the US: toward a material flow characterization of production, markets and end of life. Environ. Res. Lett. 15 (9), 094034. https://doi.org/10.1088/1748-9326/ab9e1e.

Hellevang, K., 2020. Proper Spring Grain Drying and Storage Critical. North Dakota State University Extension. https://www.ag.ndsu.edu/news/newsreleases/2020/march-23-2020/proper-spring-grain-drying-and-storage-critical.

Hendrickson, T.P., Bose, B., Vora, N., Huntington, T., Nordahl, S.L., Helms, B.A., Scown, C.D., 2024. Paths to circularity for plastics in the United States. One Earth 7 (3), 520–531. https://doi.org/10.1016/j.oneear.2024.02.005.

Hernandez-Charpak, Y.D., Mozrall, A.M., Williams, N.J., Trabold, T.A., Diaz, C.A., 2024. Biochar as a sustainable alternative to carbon black in agricultural mulch films. Env., Res. 246, 117916. https://doi.org/10.1016/j.envres.2023.117916.

Hofmann, T., Ghoshal, S., Tufenkji, N., Adamowski, J.F., Bayen, S., Chen, Q., Demokritou, P., Flury, M., Hüffer, T., Ivleva, N.P., Ji, R., Leask, R.L., Maric, M., Mitrano, D.M., Sander, M., Pahl, S., Rillig, M.C., Walker, T.R., White, J.C., Wilkinson, K.J., 2023. Plastics can be used more sustainably in agriculture. Commun. Earth Environ. 4 (1), 332. https://doi.org/10.1038/s43247-023-00982-4.

Horodytska, O., Valdés, F.J., Fullana, A., 2018. Plastic flexible films waste management – a state of art review. Waste Manag. 77, 413–425. https://doi.org/10.1016/j.wasman.2018.04.023.

Huang, D., Wang, X., Yin, L., Chen, S., Tao, J., Zhou, W., Chen, H., Zhang, G., Xiao, R., 2022. Research progress of microplastics in soil-plant system: ecological effects and potential risks. Sci. Total Environ. 812, 151487. https://doi.org/10.1016/j.scitotenv.2021.151487.

Huang, Z., Zhang, Y., Zhang, C., Yuan, F., Gao, H., Li, Q., 2024. Lignin-based composite film and its application for agricultural mulching. Polymers 16 (17), 2488. https://doi.org/10.3390/polym16172488.

Janke, R.R., Altamimi, M.E., Khan, M., 2017. The use of high tunnels to produce fruit and vegetable crops in North America. Agric. Sci. 08 (07), 692–715. https://doi.org/10.4236/as.2017.87052.

Javaid, M., Haleem, A., Khan, I.H., Suman, R., 2023. Understanding the potential applications of artificial intelligence in agriculture sector. Adv. Agrochem. 2 (1), 15–30. https://doi.org/10.1016/j.aac.2022.10.001.

Jin, T., Tang, J., Lyu, H., Wang, L., Gillmore, A.B., Schaeffer, S.M., 2022. Activities of microplastics (MPs) in agricultural soil: a review of MPs pollution from the perspective of agricultural ecosystems. J. Agric. Food Chem. 70 (14), 4182–4201. https://doi.org/10.1021/acs.jafc.1c07849.

Jones, A., 2021. High Quality Baling Twine. Jones Twine Net Wrap. https://www.jonestwine.com/baling-twine/.

Jones, G., 2018. Recovering agricultural plastics: obstacles and opportunities. Waste Advant. Mag. https://wasteadvantagemag.com/recovering-agricultural-plastics-obstacles-and-opportunities/.

Kallsen, C.E., Douhan, G., Jetter, K., Stewart, D., Sumner, D.A., 2021. Sample Costs to Establish an Orange Orchard and Produce. University of California Agriculture and Natural Resources Cooperative Extension.

Kan, M., Wang, C., Zhu, B., Chen, W., Liu, Y., Ren, Y., Xu, M., 2023. Seven decades of plastic flows and stocks in the United States and pathways toward zero plastic pollution by 2050. J. Ind. Ecol. 27 (6), 1538–1552. https://doi.org/10.1111/jiec.13427.

Kim, T.-H., Lee, J.-Y., 2022. Are particulate pollutants emitted by open-burning of agricultural plastic waste (Greenhouse LDPE Film) harmful? J. People Plants Environ. 25 (6), 585–594. https://doi.org/10.11628/ksppe.2022.25.6.585.

King, C.D., Stephens, C.G., Lynch, J.P., Jordan, S.N., 2023. Farmers' attitudes towards agricultural plastics – Management and disposal, awareness and perceptions of the environmental impacts. Sci. Total Environ. 864, 160955. https://doi.org/10.1016/j.scitotenv.2022.160955.

Knott, C., Lee, C., Green, J.D., Grove, J., Haramoto, E., Legleiter, T., McGrath, Reyes, J., Ritchey, E., Salmeron, M., Venard, C., Wendroth, O., Zhang, X., Bradley, C., Wise, K., Villanueva, R., Bessin, R., Johnson, D., Halich, G., McNeill, S., 2023. A Comprehensive Guide to Soybean Management. https://publications.ca.uky.edu/sites/publications.ca.uky.edu/files/ID249.pdf.

Korol, J., Hejna, A., Wypiór, K., Mijalski, K., Chmielnicka, E., 2021. Wastes from agricultural silage film recycling line as a potential polymer materials. Polymers 13 (9), 1383. https://doi.org/10.3390/polym13091383.

Kratsch, H.A., Schrader, J.A., McCabe, K.G., Srinivasan, G., Grewell, D., Graves, W.R., 2015. Performance and biodegradation in soil of novel horticulture containers made from bioplastics and biocomposites. HortTechnology 25 (1), 119–131. https://doi.org/10.21273/HORTTECH.25.1.119.

Lahoz, A., 2023. Main Types of Plastics by Use and Recycling Tolerance. RepetCo Innovations. https://www.repetco.com/main-types-of-plastics-by-use-and-recycling-tolerance/.

Lamont Jr., W., 2017. 3—Plastic mulches for the production of vegetable crops. In: Orzolek, M. (Ed.), A Guide to the Manufacture, Performance, and Potential of Plastics in Agriculture, 1st ed. Elsevier, pp. 45–60. https://doi.org/10.1016/B978-0-08-102170-5.00003-8.

Lamont Jr., W., Harper, J., Jarrett, A., Orzolek, M., Crassweller, R., Demchak, K., Greaser, G., 2023. Irrigation For Fruit and Vegetable Production. PennState Extension. https://extension.psu.edu/irrigation-for-fruit-and-vegetable-production.

Lark, T.J., Schelly, I.H., Gibbs, H.K., 2021. Accuracy, bias, and improvements in mapping crops and cropland across the United States using the USDA cropland data layer. Remote Sens. 13 (5), 968. https://doi.org/10.3390/rs13050968.

Lase, I.S., Tonini, D., Caro, D., Albizzati, P.F., Cristóbal, J., Roosen, M., Kusenberg, M., Ragaert, K., Van Geem, K.M., Dewulf, J., De Meester, S., 2023. How much can chemical recycling contribute to plastic waste recycling in Europe? An assessment using material flow analysis modeling. Resour. Conserv. Recycl. 192, 106916. https://doi.org/10.1016/j.resconrec.2023.106916.

Laur, S., Da Silva, A.L.B.R., Díaz-Pérez, J.C., Coolong, T., 2021. Impact of shade and fogging on high tunnel production and mineral content of organically grown lettuce, basil, and arugula in Georgia. Agriculture 11 (7), 625. https://doi.org/10.3390/agriculture11070625.

Lawrence, M., 2017. 10—disposal of plastics. In: Orzolek, M. (Ed.), A Guide to the Manufacture, Performance, and Potential of Plastics in Agriculture, 1st ed. Elsevier, pp. 61–77. https://doi.org/10.1016/B978-0-08-102170-5.00003-8.

Leal Filho, W., Saari, U., Fedoruk, M., Iital, A., Moora, H., Klöga, M., Voronova, V., 2019. An overview of the problems posed by plastic products and the role of extended producer responsibility in Europe. J. Clean. Prod. 214, 550–558. https://doi.org/10.1016/j.jclepro.2018.12.256.

LeMoine, B., Eralinna, L., Trovati, G., Casallo, I.M., Amate, J.J., Zlatar, K., Butlewski, K., Ojanpera, M., Picuno, P., 2021. *Reducing the Plastic Footprint of Agriculture* (No. Minipaper B; EIP-AGRI Focus Group). EIP-AGRI Agriculture & Innovation. https://ec.europa.eu/eip/agriculture/sites/default/files/eip-agri_fg_plastic_footprint_minipaper_b_final.pdf.

Levitan, L., Barros, A., 2003. *Recycling Agricultural Plastics in New York State* (Environmental Risk Analysis Program. Cornell University, pp. 1–30. http://www.cfe.cornell.edu/erap/C&ER/PlasticsDisposal/AgPlasticsRecycling/.

Lewis, K., 2018. A New Industrial Revolution for Plastics. USDA Biopreferred Program. https://www.usda.gov/about-usda/news/blog/new-industrial-revolution-plastics.

Li, L., Luo, Y., Li, R., Zhou, Q., Peijnenburg, W., Yin, N., Yang, J., Tu, C., Zang, Y., 2020. Effective uptake of submicrometre plastics by crop plants via a crack-entry mode. Nat. Sustain. 3 (11), 929–937.

Liang, W., Zhao, Y., Xiao, D., Cheng, J., Zhao, J., 2020. A biodegradable water-triggered chitosan/hydroxypropyl methylcellulose pesticide mulch film for sustained control of phytophthora sojae in soybean (Glycine max L. Merr.). J. Clean. Prod. 245, 118943. https://doi.org/10.1016/j.jclepro.2019.118943.

Liu, Y., Lai, J., Ma, S., Feng, Q., Yang, G., Zhao, Z., Yang, J., Zhou, C., 2023. Supply chain plastic footprint analysis. Circ. Econ. 2, 100037.

Loftness, 2022. Grain bagging: a flexible storage option for bumper crops. Agric. Artic. https://www.loftness.com/grain-bagging-a-flexible-storage-option-for-bumper-crops/.

Madrid, B., Wortman, S., Hayes, D.G., DeBruyn, J.M., Miles, C., Flury, M., Marsh, T.L., Galinato, S.P., Englund, K., Agehara, S., DeVetter, L.W., 2022. End-of-life management options for agricultural mulch films in the United States—a review. Front. Sustain. Food Syst. 6, 921496. https://doi.org/10.3389/fsufs.2022.921496.

Magdoff, F., van Es, H., 1993. *Building Soils for Better Crops: Ecological Management for Healthy Soils* (No. 4th edition; Handbook Series Book, 10. Sustainable Agriculture Research and Education, p. 371. http://journals.lww.com/00010694-199311000-00014.

Malarkey, K., Babbitt, C.W., 2025. The Plastic Footprint of the U.S. Agricultural System. figshare. Dataset. https://doi.org/10.6084/m9.figshare.28377275.v1.
Mamun, A.A., Prasetya, T.A.E., Dewi, I.R., Ahmad, M., 2023. Microplastics in human food chains: food becoming a threat to health safety. Sci. Total Environ. 858, 159834. https://doi.org/10.1016/j.scitotenv.2022.159834.
Mansfield, B., Werner, M., Berndt, C., Shattuck, A., Galt, R., Williams, B., Argüelles, L., Barri, F.R., Ishii, M., Kunin, J., Lapegna, P., Romero, A., Caicedo, A., Abhigya, Castro-Vargas, M.S., Marquez, E., Ojeda, D., Ramirez, F., Tittor, A., 2024. A new critical social science research agenda on pesticides. Agric Hum. Values 41 (2), 395–412. https://doi.org/10.1007/s10460-023-10492-w.
Maraveas, C., 2020. Environmental sustainability of plastic in agriculture. Agriculture 10 (8), 310. https://doi.org/10.3390/agriculture10080310.
Martin, W., 2022. Pine Creek Farm & Feed [Personal communication].
Marvinney, E., Kendall, A., 2021. A scalable and spatiotemporally resolved agricultural life cycle assessment of California almonds. Int. J. Life Cycle Assess. 26 (6), 1123–1145. https://doi.org/10.1007/s11367-021-01891-4.
Michael, A., 2017. 8—Horticulture plastics. In: Orzolek, M. (Ed.), A Guide to the Manufacture, Performance, and Potential of Plastics in Agriculture, 1st ed. Elsevier, pp. 129–143. https://doi.org/10.1016/B978-0-08-102170-5.00003-8.
Moore, M., 2018. From seed bag to bulk container. Farm Prog. https://www.farmprogress.com/seed/seed-bag-bulk-container.
Mottet, A., De Haan, C., Falcucci, A., Tempio, G., Opio, C., Gerber, P., 2017. Livestock: on our plates or eating at our table? A new analysis of the feed/food debate. Glob. Food Sec. 14, 1–8. https://doi.org/10.1016/j.gfs.2017.01.001.
Mpanga, I.K., Idowu, O.J., 2021. A decade of irrigation water use trends in Southwestern USA: the role of irrigation technology, best management practices, and outreach education programs. Agric. Water Manag. 243, 106438. https://doi.org/10.1016/j.agwat.2020.106438.
Munch, D., 2023. Grain Storage Capacity Can Buffer Impact of Transportation Disruptions. American Farm Bureau Federation. https://www.fb.org/market-intel/grain-storage-capacity-can-buffer-impact-of-transportation-disruptions.
Muñoz, K., Thiele-Bruhn, S., Kenngott, K.G.J., Meyer, M., Diehl, D., Steinmetz, Z., Schaumann, G.E., 2022. Effects of Plastic versus Straw Mulching Systems on Soil Microbial Community Structure and Enzymes in Strawberry Cultivation. Soil Systems 6 (1), 21. https://doi.org/10.3390/soilsystems6010021.
Nath, S., 2024. A vision of precision agriculture: balance between agricultural sustainability and environmental stewardship. Agron. J. 116 (3), 1126–1143. https://doi.org/10.1002/agj2.21405.
Netafim, 2023. Heavywall Driplines. Netafim USA. https://www.netafimusa.com/agriculture/products/product-offering/heavywall-driplines/aries/.
Panke-Buisse, K. (2022). *Dairy Forage Research Center* [Personal communication].
O'Connor, J., Skeaff, S., Bremer, P., Lucci, G., Mirosa, M., 2023. A critical review of on-farm food loss and waste: Future research and policy recommendations. Renewable Agriculture and Food Systems 38, e24. https://doi.org/10.1017/S1742170523000169.
Pazienza, P., De Lucia, C., 2020. For a new plastics economy in agriculture: policy reflections on the EU strategy from a local perspective. J. Clean. Prod. 253, 119844. https://doi.org/10.1016/j.jclepro.2019.119844.
Peck, D. (2022). *Beekeeping* [Personal communication].
Pérez-Blanco, C.D., Hrast-Essenfelder, A., Perry, C., 2020. Irrigation Technology and Water Conservation: A Review of the Theory and Evidence. Review of Environmental Economics and Policy 14 (2), 216–239. https://doi.org/10.1093/reep/reaa004.
Prata, J.C., Da Costa, J.P., Lopes, I., Andrady, A.L., Duarte, A.C., Rocha-Santos, T., 2021. A one health perspective of the impacts of microplastics on animal, human and environmental health. Sci. Total Environ. 777, 146094. https://doi.org/10.1016/j.scitotenv.2021.146094.
Putman, B., Rotz, C.A., Thoma, G., 2023. A comprehensive environmental assessment of beef production and consumption in the United States. J. Clean. Prod. 402, 136766. https://doi.org/10.1016/j.jclepro.2023.136766.
Qi, Y., Beriot, N., Gort, G., Huerta Lwanga, E., Gooren, H., Yang, X., Geissen, V., 2020. Impact of plastic mulch film debris on soil physicochemical and hydrological properties. Environ. Pollut. 266, 9. https://doi.org/10.1016/j.envpol.2020.115097.
Ramsay, C., 2023. Nonrefillable containers (Plastic). Pestic. Environ. Steward. https://pesticidestewardship.org/handling-pesticide-containers/nonrefillable-containers-plastic/.
Reed, D.W., Lacey, J.A., Thompson, V.S., 2018. *Separation and Processing of Plastic Films* (No. INL/EXT–18-45484-Rev000, 1468644; p. INL/EXT–18-45484-Rev000, 1468644). Idaho National Laboratory. https://doi.org/10.2172/1468644.
Ritchie, H.. *FAQs on plastics*. Our World in Data. https://ourworldindata.org/faq-on-plastics.
Rogers, D.H., Lamm, F.R., Aguilar, J., 2018. Subsurface Drip Irrigation (SDI) in Kansas: an Overview. Kansas State University Cooperative Extension.
Rotz, C.A., Asem-Hiablie, S., Place, S., Thoma, G., 2019. Environmental footprints of beef cattle production in the United States. Agric. Syst. 169, 1–13. https://doi.org/10.1016/j.agsy.2018.11.005.
Roy, 2024. Animal feed bags: everything you need to know [XIFA Group]. Woven Polypropylene Bags Manufacturer. https://xifagroup.com/blog/animal-feed-bag/understanding-animal-feed-bag/.
Salama, K., Geyer, M., 2023. Plastic mulch films in agriculture: their use, environmental problems, recycling and alternatives. Environments 10 (10), 179. https://doi.org/10.3390/environments10100179.
Samuelson, M.B., Reid, E.V., Drijber, R., Jeske, E., Blanco-Canqui, H., Mamo, M., Kadoma, I., Wortman, S.E., 2022. Effects of compost, cover crops, and local conditions on degradation of two agricultural mulches in soil. Renewable Agriculture and Food Systems 37 (2), 128–141. https://doi.org/10.1017/S1742170521000405.
Sands, R.D., Meade, B., Seale Jr, J., Robinson, S., Seeger, R., 2023. Scenarios of Global Food Consumption: Implications for Agriculture. U.S. Department of Agriculture, Economic Research Service, pp. 1–58. ERR-323.
Sarpong, K.A., Adesina, F.A., DeVetter, L.W., Zhang, K., DeWhitt, K., Englund, K.R., Miles, C., 2024. Recycling agricultural plastic mulch: limitations and opportunities in the United States. Circ. Agric. Syst. 4 (1). https://doi.org/10.48130/cas-0024-0003.
Saxe, C., 2016. *Managing Forage in Bunker Silos* (No. Volume 3, Number 6; Focus on Forage). Wisconsin Team Forage. https://fyi.extension.wisc.edu/forage/managing-forage-in-bunker-silos/.
Scarascia-Mugnozza, G., Sica, C., Russo, G., 2011. Plastics materials in European agriculture: actual use and perspectives. J. Agric. Eng. 42 (3), 15–28.
Schade, A., Melzer, M., Zimmermann, S., Schwarz, T., Stoewe, K., Kuhn, H., 2024. Plastic waste recycling-A chemical recycling perspective. ACS Sustain. Chem. Eng. 12 (33), 12270–12288. https://doi.org/10.1021/acssuschemeng.4c02551.
Schrader, J.A. (2013). *Report on the annual consumption of plastics for specialty-crop containers in the United States*. https://doi.org/10.13140/RG.2.2.29992.39689/1.
Schrader, W.L., 2000. Plasticulture in California Vegetable Production. University of California, Agriculture and Natural Resources. https://doi.org/10.3733/ucanr.8016.
Seier, M., Archodoulaki, V.M., Koch, T., 2024. The morphology and properties of recycled plastics made from multi-layered packages and the consequences for the circular economy. Resour. Conserv. Recycl. 202, 107388.
Senese, A., Pecci, M., Ambrosini, R., Diolaiuti, G.A., 2023. MOUNTAINPLAST: a new Italian plastic footprint with a focus on mountain activities. Sustainability 15 (8), 7017. https://doi.org/10.3390/su15087017.
Shaffer, J., 2022. *Netwrap* vs. *Twine: How to Choose for Your Operation*. Makin' Hay, Vermeer. https://makinhay.com/netwrap-vs-twine/.
Sharma, S., Sharma, V., Chatterjee, S., 2023. Contribution of plastic and microplastic to global climate change and their conjoining impacts on the environment—A review. Sci. Total Environ. 875, 162627. https://doi.org/10.1016/j.scitotenv.2023.162627.
Shcherbatyuk, N., Wortman, S., McFadden, D., Weiss, B., Weyers, S., Ahmad, W., Bajwa, D., Galinato, S., Formiga, A., Gramig, G., DeVetter, L., 2024. Alternative and emerging mulch technologies for organic and sustainable agriculture in the United States: a review. HortScience 59 (10), 1524–1533. https://doi.org/10.21273/HORTSCI18029-24.
Shinners, K.J., Huenink, B.M., Muck, R.E., Albrecht, K.A., 2009. Storage characteristics of large round Alfalfa bales: dry hay. Trans. ASABE 52 (2), 409–418. https://doi.org/10.13031/2013.26825.
Sintim, H.Y., Shahzad, K., Bary, A.I., Collins, D.P., Myhre, E.A., Flury, M., 2022. Differential gas exchange and soil microclimate dynamics under biodegradable plastic, polyethylene, and paper mulches. Ital. J. Agron. 17 (3), 1979. https://doi.org/10.4081/ija.2022.1979.
Smith, A., 2022. *Grain bags* vs. *Grain bins*. FarmProgress. https://www.farmprogress.com/wheat/grain-bags-vs-grain-bins.
Soulliere-Chieppo, M., 2020. Plastic Pots and the Green Industry: Production, Use, Disposal, and Environmental Impact. Association of Professional Landscape Designers, p. 19.
Spangler, K., Burchfield, E.K., Schumacher, B., 2020. Past and Current Dynamics of U.S. Agricultural Land Use and Policy. Frontiers in Sustainable Food Systems 4, 98. https://doi.org/10.3389/fsufs.2020.00098.
Srivastav, A.L., Patel, N., Rani, L., Kumar, P., Dutt, I., Maddodi, B.S., Chaudhary, V.K., 2023. Sustainable options for fertilizer management in agriculture to prevent water contamination: a review. Environ. Dev. Sustain. 26 (4), 8303–8327. https://doi.org/10.1007/s10668-023-03117-z.
Sui, R., Fisher, D.K., Reddy, K.N., 2015. Yield response to variable rate irrigation in corn. J. Agric. Sci. 7 (11), p11. https://doi.org/10.5539/jas.v7n11p11.
Sumberg, J., Giller, K.E., 2022. What is 'conventional' agriculture? Glob. Food Sec. 32, 100617. https://doi.org/10.1016/j.gfs.2022.100617.
Tan, Q., Yang, L., Wei, F., Chen, Y., Li, J., 2023. Comparative life cycle assessment of polyethylene agricultural mulching film and alternative options including different end-of-life routes. Renew. Sustain. Energy Rev. 178, 113239. https://doi.org/10.1016/j.rser.2023.113239.
Tariq, M., Iqbal, B., Khan, I., Khan, A.R., Jho, E.H., Salam, A., Zhou, H., Zhao, X., Li, G., Du, D., 2024. Microplastic contamination in the agricultural soil—Mitigation strategies, heavy metals contamination, and impact on human health: a review. Plant Cell Rep. 43 (3), 65. https://doi.org/10.1007/s00299-024-03162-6.
Tew, J., 2022. Honey Bee husbandry in plastic hives. Bee Cult. https://www.beeculture.com/honey-bee-husbandry-in-plastic-hives/.
Thomas, M.M., 2021. From pails to pipelines: the origins and early adoption of plastic tubing in the maple syrup industry. Vt. Hist. Soc. 89 (1), 52–78.
Tian, L., Jinjin, C., Ji, R., Ma, Y., Yu, X., 2022. Microplastics in agricultural soils: sources, effects, and their fate. Curr. Opin. Environ. Sci. Health 25, 100311. https://doi.org/10.1016/j.coesh.2021.100311.
Tudi, M., Daniel Ruan, H., Wang, L., Lyu, J., Sadler, R., Connell, D., Chu, C., Phung, D.T., 2021. Agriculture development, pesticide application and its impact on the environment. Int. J. Env. Res. Public Health 18 (3), 1112. https://doi.org/10.3390/ijerph18031112.
Ullah, R., Tsui, M.T., Chen, H., Chow, A., Williams, C., Ligaba-Osena, A., 2021. Microplastics interaction with terrestrial plants and their impacts on agriculture. J. Env., Qual. 50 (5), 1024–1041. https://doi.org/10.1002/jeq2.20264.
US EPA. (2024). *The U.S. Recycling System* [Overviews and Factsheets]. https://www.epa.gov/circulareconomy/us-recycling-system.

USDA AMS, 2024. USDA definition of a specialty crop. United States Department of Agriculture Agricultural Marketing Service. https://www.ams.usda.gov/services/grants/scbgp/specialty-crop.

USDA NASS, 2020. *2019 Census of Horticultural Specialties* (Special Studies No. AC-17-SS-3; 2017 Census of Agriculture, p. 604). USDA National Agricultural Statistics Service. https://www.nass.usda.gov/Publications/AgCensus/2017/Online_Resources/Census_of_Horticulture_Specialties/HORTIC.pdf.

USDA NASS, 2024. *2022 Census of Agriculture* (Geographic Area Series No. AC-22-A-51; p. 757). USDA National Agricultural Statistics Service. https://www.nass.usda.gov/Publications/AgCensus/2022/Full_Report/Volume_1,_Chapter_1_US/usv1.pdf.

USGR, 2019. *About Greenhouse Coverings*. U.S. Global Resources. https://www.usgr.com/greenhouse-coverings/about_greenhouse_coverings/.

USGS, 2018. *Irrigation: Drip or Microirrigation* [Water Science School]. U.S. Geological Survey. https://www.usgs.gov/special-topics/water-science-school/science/irrigation-drip-or-microirrigation.

van den Oever, S.P., Haselmann, A., Schreiner, M., Fuerst-Waltl, B., Zebeli, Q., Mayer, H.K., Knaus, W., 2021. Hay versus silage: does hay feeding positively affect milk composition? Int. Dairy J. 118, 105024. https://doi.org/10.1016/j.idairyj.2021.105024.

Vashisth, T., Kadyampakeni, D.M., Morgan, K.T., Zekri, M., Schumann, A.W., Guzmán, S., Alferez, F., Obreza, T.A., 2023. 2023–2024 Florida citrus production guide: irrigation management of citrus trees: CPG ch. 14, CG093/CPG12, rev. 5/2023. EDIS 7. https://doi.org/10.32473/edis-cg093-2023.

Villagrán, E., Romero-Perdomo, F., Numa-Vergel, S., Galindo-Pacheco, J.R., Salinas-Velandia, D.A., 2023. Life Cycle Assessment in Protected Agriculture: Where Are We Now, and Where Should We Go Next? Horticulturae 10 (1), 15. https://doi.org/10.3390/horticulturae10010015.

Vox, G., Loisi, R.V., Blanco, I., Mugnozza, G.S., Schettini, E., 2016. Mapping of agriculture plastic waste. Agric. Agric. Sci. Proc. 8, 583–591. https://doi.org/10.1016/j.aaspro.2016.02.080.

Wang, F., Wang, Q., Adams, C.A., Sun, Y., Zhang, S., 2022. Effects of microplastics on soil properties: current knowledge and future perspectives. J. Hazard. Mater. 424 (127531), 1–21. https://doi.org/10.1016/j.jhazmat.2021.127531.

Wang, Z., Culumber, C., Bali, K., 2024. Chapter 12—Application of chemical materials. In: Ayars, J., Zaccaria, D., Bali, K. (Eds.), Microirrigation for Crop Production. Elsevier Science, pp. 359–392. https://doi.org/10.1016/B978-0-323-99719-5.00014-9.

Wells, T., 2021. 2-in-1 films on agriculture: a sustainable option [Agriplastics Community]. Agriplast/ Commun.: Agric. Plast. Ind. News Trends. https://agriplasticscommunity.com/sustainable-agriculture-films/.

Willden, S.A., Pritts, M.P., Loeb, G.M., 2022. The effect of plastic low tunnels on natural enemies and pollinators in New York strawberry. Crop Prot. 151, 105820. https://doi.org/10.1016/j.cropro.2021.105820.

Winiarska, E., Jutel, M., Zemelka-Wiacek, M., 2024. The potential impact of nano- and microplastics on human health: understanding human health risks. Env. Res. 251, 118535. https://doi.org/10.1016/j.envres.2024.118535.

Yang, Y., Tilman, D., Jin, Z., Smith, P., Barrett, C.B., Zhu, Y.-G., Burney, J., D'Odorico, P., Fantke, P., Fargione, J., Finlay, J.C., Rulli, M.C., Sloat, L., Jan van Groenigen, K., West, P.C., Ziska, L., Michalak, A.M., 2024. Climate change exacerbates the environmental impacts of agriculture. Science 385 (6713), eadn3747. https://doi.org/10.1126/science.adn3747.

Yates, J., Deeney, M., Rolker, H.B., White, H., Kalamatianou, S., Kadiyala, S., 2021. A systematic scoping review of environmental, food security and health impacts of food system plastics. Nature Food 2 (2), 80–87. https://doi.org/10.1038/s43016-021-00221-z.

Yu, H., Zhang, Y., Tan, W., Zhang, Z., 2022. Microplastics as an emerging environmental pollutant in agricultural soils: effects on ecosystems and Human health. Front. Environ. Sci. 10, 855292. https://doi.org/10.3389/fenvs.2022.855292.

Zeng, R., Ren, W., 2022. The spatiotemporal trajectory of US agricultural irrigation withdrawal during 1981–2015. Environ. Res. Lett. 17 (10), 104027. https://doi.org/10.1088/1748-9326/ac91e2.

Zhang, L., Wei, H., Zhang, K., Li, Z., Li, F.-M., Zhang, F., 2024. Plastic film mulching increases crop yields and reduces global warming potential under future climate change. Agric. Meteorol. 349, 109963. https://doi.org/10.1016/j.agrformet.2024.109963.

Zhang, S., Li, Y., Chen, X., Jiang, X., Li, J., Yang, L., Yin, X., Zhang, X., 2022. Occurrence and distribution of microplastics in organic fertilizers in China. Sci. Total Environ. 844, 157061. https://doi.org/10.1016/j.scitotenv.2022.157061.

Zhou, J., Jia, R., Brown, R.W., Yang, Y., Zeng, Z., Jones, D.L., Zang, H., 2023. The long-term uncertainty of biodegradable mulch film residues and associated microplastics pollution on plant-soil health. J. Hazard. Mater. 442, 130055. https://doi.org/10.1016/j.jhazmat.2022.130055.