The impacts of polycrystalline solar panels on highly productive lands and the environment.

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Abstract.
The types of contaminants in a heavy loam at Brookside (Canterbury, New Zealand) replicated the materials found in solar panels placed above ground. These heavy metals had accumulated in the root zone of plants because of soil type and soil compaction. The impacts of increasing levels of metal contaminants changed the NPK of soils, changed the pH of soils, reduced total organic carbon, reduced colonies of soil microorganisms, reduced earthworm populations, changed the composition of plant communities, increased bulk density of soils, changed the macro-porosity of soils, increased run-off of stormwater, increased uptake of heavy metals by plants, and resulted in aluminium toxicosis in a lamb grazing contaminated ryegrass.

Leached heavy metals (mainly aluminium, iron, manganese, and lead) killed clovers under panels and suppressed clover growth 2-6 m from panels. However, nitrates leached from solar panels increased ryegrass growth between panels. Actively growing ryegrass accumulated heavy metal leachates with a bio-concentration factor (BCF) that appeared greater than those of earthen metals. The hard compacted soil will increase run-off of contaminants in the floodwaters that flow onto surrounding land, into surrounding streams, and into Lake Ellesmere.

The implications of these findings for other types of solar panels situated elsewhere are self-evident. The soil type where a solar farm is established will determine the impacts of utility scale solar panels on highly productive lands, and the risks that heavy metals and PFAS leached from panels present to the food-webs of terrestrial animals and aquatic ecosystems.

Introduction.

Many people believe the drawbacks of converting agricultural land to ‘utility scale solar power’ (USSP) facilities are circumvented by combining farming and solar energy generation: a practice now referred to as agrivoltaics. Unfortunately, to date there have been no long-term studies on the cost-benefits of this practice, the impacts on the health of animals grazing under panels, or the risks to the environment associated with the practice. This research was undertaken as a pilot study that evaluated the effects on soils of placing polycrystalline solar panels on a silty clay loam soil at Brookside (Canterbury, NZ) for 9.5 years, the effects of leachates from those panels on soil organisms, the effects on a ryegrass and clover pasture growing under and around solar panels, and the impacts of panels on the health of livestock grazing contaminated pasture.

Solar technologies contain a class of materials known as “forever chemicals”. These include heavy metals and per- and poly-fluoroalkyls (PFAS) that do not degrade in soils or water. The materials have a propensity to bioaccumulate in living organisms (plants and animals) because they have a long half-life in tissue. When ingested in chronic or sub-chronic doses the heavy metals and PFAS become very hazardous materials, and so it is important that the contaminants from solar panels, batteries, inverters, and transformers do not persist in the biosphere of air, soils, or water as outlined in the RMA (1991).

In New Zealand the Resource Management Act (RMA) was passed into law in 1991 to specifically prevent human activities and the development of amenities impacting natural assets like soils, air, and water. More specifically within this Act are provisions that prevent contaminants from industry affecting not only natural assets, but the flora, fauna, and health of organisms living within different ecosystems.

Because New Zealand is reliant on primary production for trade (81.4% of exports still come off the land), the New Zealand government introduced the National Policy Statement on Highly Productive Land (NPS-HPL) under section 52(2) of the Resource Management Act during 2022. Theoretically this should protect good farmland for agriculture and horticulture, but increasingly that intent is compromised by use of the green belt around towns for housing development, and use of productive land for utility-scale solar photovoltaic (USSP) facilities. This lack of due diligence by councils at protecting productive lands ultimately results in lost export earnings and New Zealand running bigger and bigger current account deficits each year.

The National Policy Statement for Freshwater Management (NPS-FM) was introduced *under section 52(2) of the Resource Management Act* in 2020 in the hope of preventing further desecration of rivers and lakes as happened during 2000-2020 following poor local government administration of the RMA. The NPS-FM contains specific directions on water management to prevent contaminants from land and commerce entering both surface-water and groundwater, and the procedures necessary to monitor water quality where contaminants may be an issue. Existing eutrophication of most lowland rivers and all lowland lakes in the Selwyn District has happened because of poor council management of natural assets. This has the potential to be exacerbated by added heavy metals and per-and poly-fluoroalkyl substances (PFAS) from solar farms.

Selwyn District Council and Environment Canterbury are signatories along with Ngai Tahu to a co-governance agreement for Te Waihora. That co-governance agreement specifically refers to the protection of kai (food from the lake for the 'kaitiakitanga' or guardians of the lake) and improvements to water quality. That agreement enshrines the principles outlined in Ngai Tahu's 'Mahaanui Iwi Management Plan 2013' and the 'Ngai Tahu Freshwater Policy Statement'. In deference to local treaty partnerships between Maori and the Council, a solar farm is being constructed on the banks of a waterway from which watercress is harvested, and a waterway that flows into Lake Ellesmere where *tuna*, *karekau* and waterfowl are harvested by Maori.

Despite the clear directions within RMA legislation and Local Government Act 2002, councils continue to make major change to the environment by exempting both the public and Crown Research Institutes from their decision-making through "limited notifications" of "discretionary activities" to a few neighbours that have less than 6 weeks to respond to a resource consent application. In this study the impacts of solar panels on soils gazetted as LUC2 and LUC3 lands at Brookside (i.e., "highly productive lands") were assessed by taking soil samples from under solar panels and comparing them with 'control' soils some 40-60m away. In addition to the effect of contaminants on soils, the levels of contaminants in vegetation and in livestock eating that vegetation were also measured. The implications of establishing ground-mounted solar panels on soil compaction and soil macro-porosity are measured, the implications of increased run-off of floodwaters are discussed, the effects of contaminants on soil organisms are discussed, the effects on terrestrial vertebrates that consume contaminated vegetation are evaluated, and results from this study are compared with published international research.

Methods

1. Panels

A small array of solar panels was established on the property of Michael Dalley at Brookside during 2014 by Campbell McMath of KEA-X Ltd. These were arranged on 12 rows of tables that were each fitted with between 8—40 polycrystalline solar panels per table (type = Kyocera KD215GH-2PU panel) on a land area of 0.6ha. The panels were formed with iron pyrites (FeS_2) in the semi-conductor layer below the outer anti-reflective coatings (Lu *et al*. 2021). The core of panels containing the photovoltaic solar cells (with Cd, Pb, As, Cr, Zn, Ni in components) were surrounded by a polymer encapsulant so these substances only begin to show in soils after panels have been in the field 10 years or more. During normal weathering the outer layers containing Si_3N_4, Na_3N, B_2O_3, Al_2O_3, SiO_2, Fe_2O_3, MnO_2, Li_2O, Ag, and Ti are initially leached, followed by FeS_2, Al, Ag, In, Cu, Pb, and Sn from the semi-conductor layer. After 9.5 years exposed to the weather the panels superficially appeared to be in good condition, but there were overt signs that leachates from panels were affecting plant growth. Some vegetation beneath the panels was stunted, the leaves of some grasses were bronzed, and clovers were not growing in the vicinity of panels.

2. Contaminants in Soil

Soils were independently sampled from beneath panels by a soil technician from Ravensdown Ltd. using a soil probe that took cores to a depth of 15cm during November 2023 and early April 2024. During collection of samples 6 'test' core samples were taken from under panels and compared to 6 'control' soil samples taken approximately 40 metres distant from panels. Other than contaminants from panels, the test and control soils were originally very much the same. The probes of soil were placed in a chilli bin and maintained at low temperature while being transported to Analytical Research Laboratories (ARL), Napier, Hamilton. A further 15 soil probes were taken from each of 'test' and 'control' soils in late April 2024 and sent to Hill laboratories. At the laboratory soils were maintained at <10^0C prior to analysis. During analysis all soils were air dried at 38 ^{0}C and ground to pass through a 2mm screen. The 'test' and 'control' soils were then separately blended into two homogenous samples. The list of established analytical methodologies used on soil samples are available from ARL and Hill Laboratories for anyone wanting a detailed description of laboratory methodologies.
Differences between "test" and "control" soils were measured as:

- changed concentrations of heavy metals,
- changed concentrations of trace elements,
- differences in NPK (nitrogen, phosphorous, and potassium),
- changes in nitrate-nitrogen and mineral-N,
- changes in total organic carbon and total nitrogen, and
- differences in soil pH.

The means and standard deviations for measured concentrations (mg/kg) of macro-nutrients, trace elements, and added heavy metals from 3 separate measures of 'test' and 'control' soils were then calculated.

3) Changes in microorganisms in soil

Soil probes (*n*=10) were taken from each of 'test' (contaminated) soils and 'control' soils (50-60m from panels). In addition, the root systems of 2 clover plants were recovered from near solar panels (viz. 'test' plants) and the root systems of 2 clover plants from soils 50-60m away from panels ('control' plants). Each of these samples was placed in an individually labelled plastic bag and couriered to 'Soil Foodweb NZ' for counts of microorganisms (bacteria, fungi, protozoa) *per* gram of soil (μg/g or cfu/g) or counts of mycorrhizae on clover roots (% of roots colonized).

4) Changes in earthworm abundance

Plugs of soil (n=10) to a depth of 15cm were dug up from under solar panels during summer and weighed on an electronic balance before being manually crushed, and where practicable screened on a soil sieve to remove earthworms from soils. The count of worms was recorded alongside the soil weight to estimate worms per kilogram of 'test' soil.

The process was repeated in 'control' soils 30-60m distant from solar panels. The 10 counts of earthworms per kilogram of soil in 'test' and 10 counts in 'control' soils were then compared by an unpaired t-test.

5) Soil compaction

The density of air-dried samples of soil for 'test' and 'control' soils was measured as grams per millilitre of soils by ARL laboratories. Although this measure is only an indicator of possible differences in soil bulk densities, it is a useful indicator of changes to soil density.

i) Bulk density

Bulk density of 'test' soils (under panels) and 'control' soils (40-80m from panels) was measured with a standard 100mm diameter stainless-steel ring that was 75mm deep. Grass was scraped from the surface of soils before the ring was pressed in to neatly fill the volume of the ring. A flat edge on a builder's trowel was used to neatly cut off soil extending above and below the Bulk Density ring, so the soil collected neatly fitted into a stainless-steel cylinder 75mm tall and just under 100mm in diameter. This soil was placed in a labelled plastic bag before another cylinder of soil was recovered from the hole at a depth of 75-150mm. Ten random sites were sampled in this way from under solar panels and compared with 10 random sites from nearby 'control' soils. Soil samples (n=40) were oven dried at 104-115^{0}C to a constant dry weight. The dry weight of soil was divided by 566ml (the volume of the stainless-steel ring) to give a measure of bulk density (gm/ml or tonnes/m^3). The two soil strata for 'control' and 'test' soils were compared separately by unpaired t-test to establish if surface and sub-surface layers could be pooled. The two strata of soils (the top surface layer at 0-75mm and bottom soils at 75-150mm) were then separately compared as 'test' soils (under solar panels) and 'control' soils (40-80m from panels) by unpaired t-test.

ii) Macro-porosity

Macro-porosity is a measure of the proportion of large pores in the soil that both provide air supply to the roots and allow passage of moisture through soils. It is measured in two ways. The first is the percentage of pores in soil measured at a tension of -5 kpa to comply with existing council records as shown in the New Zealand database of soils. The 2nd is measured at a tension of -10 kpa to encapsulate recent changes to measures of macro-porosity that better define air-filled spaces in soil.

Replicated measures of this parameter were made for 'test' soils near solar panels at depths of 0-75mm and at depths of 75-150mm, and similarly macro-porosity was measured in 'control' soils 40-60m from panels at the two soil depths.

Macro-porosity was measured by Landcare Research (Hamilton).

6) Pasture composition

An examination of the site showed distinct differences in the pasture composition on 'test' soils under and adjacent to solar panels compared to pasture on nearby 'control' soils. The entire pasture was a mix of 'Nui' ryegrass and 'Huia' white clover established before the solar farm was constructed during 2014. The two species in pasture are at opposite ends of the spectrum for susceptibility to heavy metals; Nui ryegrass will bioaccumulate heavy metals at 'normal' pH (Gray & McLaren 2005), but heavy metals in soils will kill clovers (Sotiriou *et al.* 2023). For this reason, white clover was used as an indicator species for changes to soil composition that may affect plant growth.

A circular hoop with an inner circumference of 3.54m and diameter of 1.13m was used to record the number of clover plants per square metre of pasture. Transects were randomly located through the site using 120m of twine strung between posts at opposite ends of the solar enclosure. Along the transect a splash of red paint had been applied to twine at 4m-intervals. At each 4m point the distance from the centre of the vegetation hoop placed on the ground to the nearest solar panel was measured with a fibre tape. In this way pasture was searched semi-randomly for clover plants in relation to the distance from solar panels. The number of clover plants in the hoop was counted.

The abundance of clover plants in pasture was then correlated with the distance from the source of leachates by regression analysis. Data was tested by ANOVA and multiple-range tests to ascertain clover abundance in relation to distance from panels.

7*) Contaminants in ryegrass*

A 'test' sample of early-summer ryegrass with developing seedheads was taken from under panels and levels of macronutrients, trace elements, and ancillary heavy metals in that grass were compared by Hill laboratories (Hamilton) with 'control' ryegrass harvested >40-m from panels. The measures of contaminants in 'test' and 'control' grass were replicated again during early autumn.

8) Haematology, histopathology and toxicology of a lamb

An 8-month-old lamb that had grazed pasture under and around panels for 5 months had blood taken in EDTA and serum tubes 2 weeks before it was euthanized, and haematology was undertaken at Awanui Veterinary Laboratories (Christchurch).

The lamb was euthanized 2 weeks after haematology and tissue samples taken from the liver, kidney, pulmonary tissue, muscle, and brain for histopathology and placed in containers containing 10% formalin before being sent to Awanui Veterinary (Christchurch) where they were sectioned and examined under a microscope. Tissue samples were also taken and chilled in a refrigerator before being sent to Hill laboratories (Hamilton) for measurement of metal residues (Al, Fe, Mn, Cu, Pb) in tissues.

Results

Soils

Plant nutrients found in soils fall into three classes as:

- macronutrients: nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), sulphur (S), carb on (C) magnesium (Mg), hydrogen (H), oxygen (O): or,
- micronutrients or trace minerals: iron (Fe), boron (B), chlorine (Cl), manganese (Mn), zinc (Zn), copper (Cu), molybdenum (Mo), Nickel (Ni), selenium (Se): or,

- ancillary heavy metals: sodium (Na), lead (Pb), aluminium (Al), cadmium (Cd), silver (Ag), mercury (Hg), arsenic (As) chromium (Cr), lithium (Li), strontium (Sr), titanium (Ti), indium (In), tin (Sn), etc.

The mean concentrations of bioavailable macronutrients in soils near solar panels are shown below (Table 1). The variance in measured parameters across 3 sampling periods was influenced by sampling intensity, and presumably because different panels are not degrading at a uniform rate which resulted in a slight ‘patchiness’ of added contaminants to soils. None-the-less over the 3 replicates of soil analysis there was a consistent increase in nitrate-nitrogen and a significant decline in bioavailable potassium and phosphorous because these substances were being occluded by high Fe and high Al.

Table 1. The mean percentage increase or decrease of bioavailable macro-nutrients (± standard deviation) during 3 analysis of soils under solar panels, compared to nearby ‘control’ soils.

	Nitrate-N mg/kg	**Mineral-N** mg/kg	**Extract-S** mg/kg	**Olsen-P** mg/L	**Potassium** kg/ha	**Calcium** kg/ha	**Magnesium** kg/ha	**Sodium** kg/ha
Solar panel	21.0 ±0.9	30.6 ±5.7	5.7 ±1.5	34.7 ±2.1	12.3 ±0.6	15.3 ±1.2	67.7 ±6.4	9.0 ±1.7
‘Control’	15.0 ±4.8	20.7 ±0.7	5.0 ±1.7	50.3 ±13.4	25 ±7	16.3 ±2.5	65.3 ±8.5	6.7 ±1.1
Minimum	>15	>25	**15-20 -L**	25-40	>11	5-10	>8	>6
Change %	**+ 40%**	**+ 48%**	**+14%**	**-31%**	**-51%**	**n.c.**	**n.c.**	**+34%**

n.c.=no measurable change

In general, an elevation of macronutrients is tolerated by most plants, but when ‘trace’ elements and ancillary heavy metals exceed a threshold determined by soil pH, soil structure, and soil moisture they become toxic to plants. Unfortunately, most of the trace elements and all the ancillary heavy metals listed below are in different types of solar technologies, so leachates not only affect soils, but they also eventually affect plant growth.

The mean change in ‘trace elements’ leached into soils from solar panels over 9.5 years is shown in Table 2. The largest amounts of added trace elements were Fe (an average 623 m/k had accumulated from panels), Mn (an added 55 m/k had accumulated in soil), and Cu was increasing.

Table 2. The percentage increase in bioavailable trace elements added to soils under solar panels during a 9-year period.

	Fe	**Cu**	**Co**	**Mn**	**Zn**	**Ni**	**B**
S. Panels	1821 ±230	4.6 ±0.8	1.6 ±0.1	272.3 ±9.6	93.3 ±29.2	10.3 ±0.9	1.5 ±0.6
‘Control’	1198 ±54	3.1 ±0.9	1.2 ±0.4	217 ±26.4	87.6 ±27.3	9.5 ±0.3	1.3 ±0.5
UK MAL soils		63		**80 -H**	200		
	Added 623m/k	**1.5**		**added 55.3**	**5.7**		
Change (%)	**+ 51.9%**	**+ 47%**	**n.c.**	**+ 25%**	**6.5%**	**n.c**	**+15%**

The increase in ancillary heavy metals from solar panels added to soils is shown in Table 3. The most significant increase in ancillary heavy metals added to soils was aluminium (on average 800 mg/kg of additional aluminium had accumulated in soils below panels) and lead (Pb) was on the increase.

Table 3. The percentage increase in heavy metals leached onto soils by solar panels.

	Pb	Al	As	Cd	Cr	Hg
S. Panels	19.6 ±0.5	16,250 ±353	5.23 ±0.15	0.21 ±0.01	19.9 ±2.0	<0.12
'Control'	16.9 ±0.6	15,450 ±303	4.61 ±0.64	0.17 ±0.005	18.2 ±0.8	<0.12
Added HM by solar panels	**2.7** mg/kg	**800 mg/kg**	0.62 mg/kg	0.04 mg/kg	1.7 mg/kg	n.c.
Change (%)	+15%	+5%	+13%	+21%	+9%	n.c.

All the above leachates (from Tables 1, 2, 3) change soils in their own way and influence pH, soil density, total carbon, the ability of soils to bind cations (CEC), and they reduce organic matter (Table 4). Because these soils had only been exposed to solar panels for 9.5 years, it is unknown where these parameters will be in 45 years' time (viz. the duration of the consent for the solar farm).

Table 4. Change in soil parameters (± standard deviation) under panels compared to 'control' soils

	soil pH	Dry wgt to volume	C/N ratio	Total C	Total N	CEC cation exc. capacity	Organic matter
		gm/ml	w/w	% w/w	% w/w	me/100g	% w/w
'Test'	6.2 ±0.26	1.01	9.1 ±0.17	4.0 ±0.33	0.47±0.04	21.5 ±2.1	6.9 ±0.7
'Control'	6.6 ±0.15	0.86	10.5 ±1.0	4.6 ±0.19	0.42±0.05	23.5 ±0.7	7.8 ±0.3
Optimal	>6	<0.9	>10	>3	>0.2	>15	>7
Change (%)	-7%	+17%	-13%	-12%	+11.9	-8.5%	-11%

Although this is only a small site (0.6 ha), there was variance in measured parameters under panels (as shown by standard deviations) across the 3 repeated analysis of soils. This is in part is because panels are not degrading at a uniform rate. In this study there was no discernible breakage or visible cracks in any of the panels, but leakage happened through the development of "micro-cracks".

The important indicators from above that had changed between 'test' soils under panels and 'control' soils were soil density (increased by 17%), increased nitrogen, declines in bioavailable potassium and soluble phosphorous/phosphate, big increases in accumulated iron, aluminium, manganese, and modest increases in materials that were just beginning to be released from the core of solar panels (e.g., Pb, Cu).

Contaminants in ryegrass

Ryegrass was actively growing because of added nitrides leached from solar panels, and this vegetative growth had higher nitrogen than 'control' grasses (Table 5). Bioavailable potassium (K) and phosphates (P) were reduced in soil because of occlusion of these substances by iron and aluminium, and this similarly reduced phosphates and potassium in the ryegrass plant (Table 5).

Table 5. **Macro-nutrients measured in ryegrass under solar panels as a percentage of the plant (standard deviations in parenthesis).**

Unit	N nitrogen	P phosphorous	K potassium	Ca Calcium	S or SO_4^-	Mg Magnesium
Test	1.7 ±0.3	0.2 ±0.04	1.35 ±0.2	0.4 ±0.02	0.2 ±0.01	0.16 ±0.02
Control	1.3 ±0.14	0.28 ±0.01	1.55 ±0.07	0.41 ±0.0	0.21 ±0.06	0.155 ±0.02
Change (%)	**+ 30%**	**- 28%**	**- 13%**	**n.c**	**n.c.**	**n.c**

The increase in trace elements in ryegrass is shown in Table 6. The biggest increases of trace elements in grasses were iron (Fe) and manganese (Mn) that had been leached from the semi-conductor layer of solar panels. The added boron has come from the borosilicate glass used on panels to prevent the reflection of sunlight back into the atmosphere.

Table 6. **The percentage increase in trace elements in ryegrass plants under solar panels.**

Unit	Fe	Na	Cu	Mn	Zn	B
Test (mg/kg)	91 ±9.8	0.139 %	7.5 ±0.7	92 ±9.9	23.5 ±4.9	6.5 ±0.7
Control (m/k)	60 ±7.0	0.109%	5 ±0.0	57 ±7.8	24.0 ±5.6	5.5 ±0.7
FAO/WHO permissible level for plants	425.5	n.s.	73.3	44.6 **(above MAL)**	99.4	13
Change (%)	**+52%**	**+27%**	**+50%**	**+60%**	**n.c.**	**+18%**

The increase in heavy metals in ryegrass is shown in Table 7. The largest increases were aluminium and lead (Pb).

Table 7. The percentage increase in ancillary heavy metals in ryegrass near solar panels.

Unit	Al Aluminium	Pb Lead	Cd* Cadmium	As* Arsenic	Cr* Chromium
Test (mg/kg)	49.5 ±6.6	6.5 ±0.7	<0.004	<0.10	<0.2
Control (mg/kg)	22.0 ±5.6	4.5 ±0.7	<0.004	<0.10	<0.2
FAO/WHO permissible level for plants		0.3 **(above MAL)**	0.2	0.5	1.3
Change %	**+ 125%**	**+ 44%**	**n.c.**	**n.c.**	**n.c.**

- the limit of detection on tests was not sensitive enough to monitor change.

Aluminium has increased in soil by only 5% but has increased in ryegrass by 125%. Manganese has increased in soils by 25% but increased 60% in plants. Lead (Pb) has increased in soils by 15% but increased in ryegrass by 44%. These results suggest aluminium, manganese, and lead leached from panels are more labile than the natural forms of these substances, and so they exceed published bioconcentration factors (BCF) for these metals.

Changes in microorganisms in soil

Once trace elements and ancillary heavy metals reach a critical threshold in soils, the concentration becomes toxic enough to kill 50% of soil microorganisms (referred to as the EC_{50}). The overall results show a substantial decline of microorganisms in soil with an increase in heavy metals (Table 8). The fungal microorganisms in soils were generally low because permanent pasture had not had significant organic matter added for several years. Mycorrhizae on clover roots were reduced by 59%. Total bacteria in 'control' soils were 'normal' and were less affected by contaminants than fungi. Soil amoeba and ciliates (i.e., protozoa) were decimated by added heavy metals.

Table 8. Measured microorganisms in 'test' soils below solar panels and 'control' soils in an adjoining paddock. Measured microorganism concentrations in 'test' soils that will significantly affect soil metabolism are in 'bold'.

Type of microorganism	'Normal' range	'Test' soils	'Control' soils	Decline (%)
Fungi				
Total fungi (µg/g)	>300	**140.4**	297.5	-52.8%
Active fungi (µg/g)	>30	**4.0**	8.3	-52.0%
Mycorrhizal fungi (% clover roots colonized)	50 -70	**22**	54	-59.3%
Bacteria				
Total bacteria (µg/g)	>300	377.8	453.6	-16.7%
Active bacteria (µg/g)	>30	**11.8**	13.7	-14.0%
Protozoa				
Amoeba (cfu/g)	>10,000	**175**	1901	-90.2%
Ciliates (cfu/g)	<7,000	**579**	8084	-92.8%
Flagellates (cfu/g)	>10,000	579411	647103	-10.5%

Changes in earthworm abundance
Earthworms in soils below panels were generally of a small size and were low in abundance. Because the soils under solar panels during summer were compacted with many hard clods it took some time to break it down into small particulates of a size that could not harbour an earthworm. To do this these soils were spread onto a breadboard and then systematically crushed. On average, around 1.8 kg of soil down to a depth of 15cm was systematically searched until the observer was confident all worms were found in the soil sample. Results showed worms were not uniformly distributed throughout either 'test' or 'control' soils. More importantly there were significant differences ($t=4.1$, $P<0.01$) in the numbers of worms in 'test' compared to 'control' soils. Earthworm numbers were down on average by 64% in 'test' soils containing contaminants compared to the 'control' soils.

Table 9. Numbers of worms in 'test' soils under panels, and 'control' soils.

Plot	Worms per kg of 'test' soils	Worms per kg of 'control' soils
1	1.0	3.8
2	1.4	2.2
3	1.4	3.5
4	1.2	1.9
5	0.6	5.7
6	0.0	3.2
7	1.2	3.2
8	1.6	1.7
9	1.5	5.3
10	1.8	1.3
Mean ±std. dev.	1.2 ±0.5	3.2 ±1.5

Pasture composition.
If all contaminants were dropped onto soils from a common source and dispersed by physical forces, then amounts at a set distance from that source would follow an 'inverse square law'. Conversely, the diminishing effects of contaminants on clover should be measured as the square of the distance from the source of contamination. Therefore, as expected, regression analysis showed clover abundance in pasture in relation to distance from panels fitted a power function ($r^2=0.96$) almost perfectly, because growth factors for clover plants were directly associated with the diminished effects of soil contaminants as vegetation plots were placed further from solar panels (Fig. 1).

Although we never had the time or resources to harvest and measure the biomass of ryegrass, the trend was the opposite of that seen for clover. The nitrates coming off panels promoted ryegrass growth close to panels, and the biomass of ryegrass declined the further from panels vegetation plots were located. This effect was misinterpreted by an agronomist inspecting solar panels nearby as a changed "micro-climate" between panels that he believed promoted vegetative growth. It is in fact simply a result of added nitrogen and nitrates to soil.

Although the paddock where panels were located was reasonably flat, there were small humps, slight hollows; so, predictably contaminants were not spread uniformly. Despite the variance in data created by these subtle effects, the differences between the 'distance classes' shown in figure 1 were highly significant ($F_{4,126}$=16.3, P<0.01) with a Duncan's multiple range test showing significant differences (P<0.05) between treatment groups.

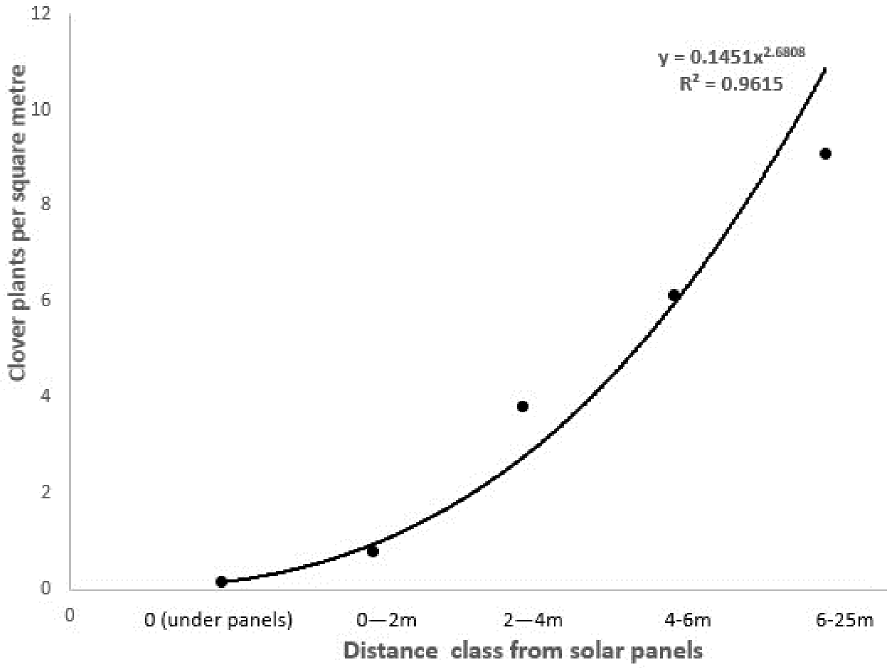


Figure 1. **Trends in the abundance of clovers in pasture in relation to the proximity of plants to contaminants leached from solar panels.**

Soil compaction

The soils at Brookside were described by a soil scientist from Landcare Research as a "mottled argillic pallic soil" with the top 3-inches a silt loam, and the soils below grading into a silty clay loam.

The results from Landcare Research on bulk density and macro-porosity were as follows.

i) Bulk density

The bulk density of silt loams at the soil surface (0 – 75mm deep) had increased under solar panels (t=3.30, P<0.01), but were still only 'slightly compacted' at 1.13 t/m^3. However, the sub-surface soils (75 – 150mm deep) that grade into a silty clay loam were substantially more compacted with bulk density significantly increased (t=4.85, P<0.001) from 1.1 t/m^3 ('control' soils) to 1.35 t/m^3 ('test' soils). At 1.35 t/m^3 these soils were listed as 'very compacted' under SINDI (i.e., Soil INDIcator classification system; Fig. 2) because of the solar panels placed above them.

In comparison the bulk densities of 'control soils were no different at the soil surface (0-75mm) and below the surface (75-150mm), with an overall mean of 1.1 t/m^3.

ii) Macro-porosity

At a tension of -5kpa the porosity of the 'control' silt loam (10.1% v/v) in 'test' topsoil (0-75mm deep) was reduced to 9.7% v/v under solar panels. However, the change to the silty-clay loam layer of soil was more significant with solar panels reducing macro-porosity from 10.1% v/v to just 3.3% v/v in soils that were 75-150mm deep. These tests were undertaken with a tension of -5kpa to provide results consistent with the National Soils Database of New Zealand.

The air-filled porosity of 'control' soils exposed to -10 kpa of tension was 12.2% v/v for topsoil (0-75mm deep) and 12.1% v/v for bottom soils (75-150 mm deep). So, prior to putting solar panels on soils, the top 6-inches (0-150mm) of soil was well aerated. However, under solar panels the pores available for aeration of plant roots and water storage were substantially reduced. Although the top 0-75mm of silt loam under panels was still aerated with a measured macro-porosity of 11.4% v/v the bottom 75-150mm had compacted with air-filled macro-porosity of soil just 4.6% v/v at a tension of
-10kpa.

To interpret these results, we have included graphs below for bulk density (Fig. 2) and macro-porosity (Fig. 3) supplied by Landcare Research that form part of the SINDI soil classification system. We can see for this soil type that placing solar panels on the soil for 10 years has plummeted bulk density into a red zone (1.35 t/m^3) where the efficacy of 'highly productive lands' is reduced to around 50% of its environmental & productive capacity. If we look at macro-porosity, then on the NZ database the score for percent of aerated pores in soil have been reduced from 100% of productive and environmental capacity to around 50% of productive capacity.

Under the provisions of the NPS-HPL, reducing the productive capacity of land to 50% of what it once was is not protecting these LUC2 and LUC3 lands as highly productive soils. Moreover, the effects on land under section 104D of the RMA are not "minor". What is of more concern is that a consent has been issued for 45 years for this solar farm, so we can only presume by 2070 what was once "highly productive land" will have assumed an even more compacted texture.

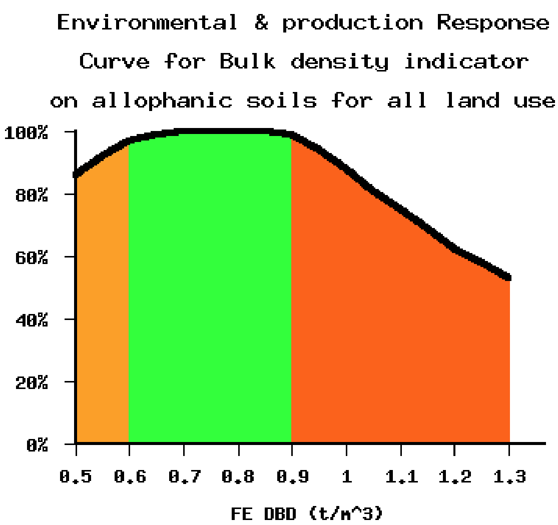


Fig 2. Efficacy of soils in relation to bulk density

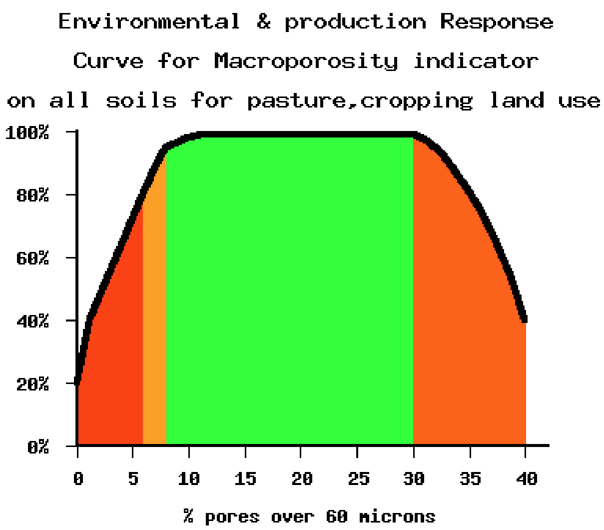


Fig. 3 Efficacy of soils in relation to macro-porosity

Haematology, Toxicology and Histopathology of a lamb

i) Symptoms and signs.

The lamb was often observed lying down and periodically showed signs of lameness. It was observed with diarrhoea 3 weeks before it was euthanized.

During necropsy two small cysts (<2mm in diameter) were found on the surface of the kidney, but nothing unusual was seen within the kidney as it was sectioned. The liver when sectioned leaked small amounts of a translucent fluid; and the lungs were slightly firmer and slightly paler than is normal. There was slight inflammation observed in the stomach and around intestines, and during post-mortem the lamb had diarrhoea. It is possible that the inflammation and diarrhoea may have arisen from elevated levels of heavy metals (Fe, Al, Mn) impacting microbiota in the GI tract over a 5-month period.

ii) Haematology

The bloods (Table 10) showed that RBC, WBC, MCH, and haemoglobin were on average lower in the 'test' lamb than for 'control' lambs. However, it should be noted all these parameters still fell within the lower end of a 'normal' range. The low RBC and haemoglobin are indicative of low Fe in bone, while low WBC and very low monocytes are indicative of bone marrow disorders. A low MCH (mean corpuscular haemoglobin) is often an indicator of iron deficiency in bone (Polizopoulou 2010). Furthermore, where protein is high and iron is deficient (viz. as in transferrin disorders), then albumin is often lower than average (Cacoub *et al*. 1996). The haematocrit to packed cell volume ratio (HCT/PCV) was slightly below average, but not low enough to suggest anaemia. Creatinine was well below the 'normal' range, indicating poor muscle mass, and/or impaired kidney function. The high globulin and high fibrinogen (both outside 'normal') are most likely a sign of the inflammation seen in and around the GI tract during necropsy. The lower-than-average urea-N and high blood protein are sometimes a reflection of liver maladies.

In summary, the results of haematology were lower than expected for some parameters and higher than average for others but only a few measurements were outside the 'normal' range; the results suggested a lamb in poor condition that was combating an infection and/or inflammation.

Table 10. The reported haematological parameters for a 'test' lamb grazing under solar panels and equivalent measures for 'control' lambs. The parameters outside 'normal' are in bold.

Parameter	'Test'	'Control'	Parameter	'Test'	'Control'
RBC (10^{12}/L)	10.0	11.8	Chloride (mmol/L)	110	114
Haemoglobin (g/L)	95	121	Albumin (g/L)	26	37
MCH (pg)	9	10.8	**Globulin (g/L) -H**	60	30
WBC (x10^9/L)	5.4	8.4	**Total protein (g/L) - H**	86	66
Lymphocytes (x10^9/L)	2.8	4.9	**Phosphorous (mmol/L)L**	**1.6**	2.2
Monocytes (x10^9/L)	0.1	2.2	**Creatinine (mmol/L)-L**	45	105
Eosinophils (x10^9/L)	0.2	0.06	AST (IU/L)	86	107
Basophils (x10^9/L)	0.1	0.02	Urea N (mmol/L)	4.4	7.6
Neutrophils (x10^9/L)	2.2	2.7	**Magnesium (mmol/L) L**	**0.96**	2.6
Fibrinogen (g/L) – H	5	2.6	HCT/PCV ratio	0.29	0.35

Things of note were:
a) other research has shown the addition of Fe and Al to the diet of lambs (ingesting 0.15% phosphates in grass) had the effect of lowering serum phosphorous to 1.5 mmol/L (Rosa *et al.* 1982, Valdivia *et al*. 1982); the same as during this study. Although these serum phosphorous levels (1.6 mmol/L in this study) are not outside a 'normal' range, they were much lower than the average 2.2 mmol/L reported for 'control' lambs of this age (Sharifi *et al*. 2005).

b) The addition of 760 ppm Fe and Al to the diet of lambs significantly lowered serum magnesium in lambs (Rosa *et al*. 1982, Valdivia *et al*. 1982); the same as during this study. Because lambs have virtually no readily metabolizable reserves of magnesium they are reliant on a constant dietary intake to maintain serum levels >>1 mmol/L (Allen 1984); however, the presence of Al and Fe in the diet had reduced serum Mg levels in the ram lamb during this study to only 0.96 nmol/L.

iii) Toxicology

Aluminium levels were above normal in the liver and kidney (suggesting Al was being actively excreted); and Al was slightly elevated in meat.

Copper was lower than average in all tissues, but especially in the brain. Because the diet of sheep was high in Fe and Al, this had reduced Cu absorption in the small intestine (de Sousa *et al*. 2012, Suttle *et al*. 2019). The amounts of lead (Pb) in tissues were also influenced by elevated Fe in the diet.

Table 11. Measured concentrations (mg/kg) of Fe, Al, Cu, Pb and Mn in a 'test' ram lamb grazed under solar panels for 5 months, compared with the values cited for 'control' animals grazing pasture.

Heavy Metal	**Liver**		**Kidney**		**Muscle / Meat**		**Brain**		**Lung**	
	Test	Lit.	Test	Lit.	Test	Lit.	Test	Lit.	Test	Lit.
Fe	55	46[a]	**47 L**	66[a]	15.4	16[a]	10.8	11[a]	73	64[b]
Al	**1.1 H**	0.08[d]	**3.4 H**	2.3[c]	**0.6 H**	0.4[c]	0.2	n/r	0.4	n/r
Cu	**52 L**	114[a]	3.4	4[a]	**0.76 L**	0.94[a]	**1.1 L**	3.0[a]	**2.1 L**	3.1[b]
Pb	0.02	0.08[d]	0.03	0.1[d]	0.004	0.06[d]	0.004	n/r	0.004	n/r
Mn	3.0	3.3[a]	0.74	0.84[a]	0.061	0.071[a]	0.26	0.31[a]	0.14	0.01[b]

a = Beef and Lamb NZ
b = Kendal *et al*. 2020 in 'nutrient optimiser'
c = Valdivia *et al*. 1982
d= average of several studies where no added contaminants in grass
n/r=not reliably reported

Things of note were:

a) Previous research has shown elevated Fe in the diet lowers serum copper, and this was not mitigated by feeding lambs supplements containing high copper (de Sousa *et al*. 2012, Prabowo *et al*. 1988). In this study copper was elevated in ryegrass because of the leachates from solar panels but Cu was consistently low in all tissues.
b) Aluminium may result in overload of Fe in the liver (Igbokwe *et al*. 2019), with much of this washed out in the spleen of lambs (Rosa *et al*. 1982). In this study low levels of Fe were found in the kidney suggesting low serum Fe, and little Fe was being excreted *via* the kidney.
c) Raised Fe and Al in the diet of lambs lowers manganese in tissues (Rosa *et al.* 1982), and in this study manganese was lower than results reported for tissue by Beef and Lamb NZ. The irony of this scenario is manganese was high in the diet, but utilisation was impeded by high Fe and Al in the diet.

iv) Histopathology

Despite symptoms, and results from haematology and toxicology (i.e., deficits of copper, magnesium, phosphorous, and added aluminium), there were no substantial changes to tissue during histopathology. The few observations of note were:
a) Pulmonary tissue: The parenchyma of one section of lung was consolidated and showed a thickened and hyperplastic bronchial epithelium, with thickening of some septa between bronchioles.
b) Liver: some regions of the liver were vacuolated with small areas of necrosis.
c) Kidney: occasional cortical tubules contain eosinophilic protein within the lumen.

In most tissues there was an increase in neutrophilic granulocytes and lymphocytes, which is consistent with other studies where elevated levels of aluminium have regularly occurred in the diet (Zaman *et al.* 1993).

Discussion

In this study the effect of leached heavy metals significantly reduced soil microorganisms (protozoa and fungi) and invertebrate populations (e.g., earthworms) below a level necessary to maintain a healthy soil, the heavy metals reduced soil mycorrhizae on clover roots, the heavy metals (viz. Fe and Al) changed the NPK of soils, and panels leached nitrates that enhanced ryegrass growth. The solar panels significantly increased soil compaction and reduced soil macro-porosity; effects that will increase run-off of stormwater and reduce plant growth. Aluminium, iron, and manganese leachates were at high concentrations in soils close to the panels, and those metals as well as lead and copper were taken into ryegrass at concentrations that exceed the maximum allowable limits (MAL) for vegetation. The results from toxicology on a lamb grazing pasture under solar panels showed aluminium and iron had jointly impacted animal welfare.

Leachates

The effects of leachates from solar panels on vegetation was apparent as a series of parallel lines of bronzed and stunted vegetation where heavy metals had been deposited on soils and green strips where nitrates leached from antireflective coatings promoted ryegrass growth (photo 1). Although these panels were sited on soils sown in Nui ryegrass and Huia white clover, clover plants were rarely seen growing within 2-m of the panels.

Leachates happen because micro-cracks develop on the surface of solar panels as they expand and contract in sunlight, when panels flex slightly in high winds, or when solar panels are impacted by hailstones (Komatsu *et al*. 2018, Dong *et al*. 2018, Bdour *et al.* 2020). These micro-cracks were not visible to the naked eye during a thorough examination of the glass surface on panels. The microscopic cracks progressively release heavy metals and polyfluoroalkyl substances (PFAS) from within the structural layers of a solar panel as it degrades. Because these materials are leached from microscopic cracks they exist at a molecular level and in some cases as very fine nanoparticles of soluble metallic salts. This appears to make them more labile than other metals, and more readily absorbed by plant roots. In a study of metal uptake by mint, capsicum, and cabbage plants it was noted that a 10% increase in leached lead into soil from perovskite panels increased the lead in plants by 100% (Li *et al*. 2020). A study of the impacts of metal nanoparticles from solar panels on soil microorganisms showed toxicity was enhanced because of small particle size and the particulate shape of leachates; with solar panel contaminants appearing more toxic than equivalent earthen metals during standard HSNO tests (Wang *et al*. 2020). Similarly, the measured aquatic toxicity of lead from perovskite panels was elevated compared to historical data for this substance (Kwak *et al.* 2021). In *this study*, a 5% increase in aluminium in soil resulted in a 125% increase in aluminium in plants; a 25% increase of manganese in soils resulted in a 60% increase in plants, and a 15% increase of added lead (Pb) to soils resulted in a 44% increase in plants. Several other studies have observed the same effects, but a controlled comparison has yet to be made by probit analysis of dose-related uptake of solar panel leachates with those of standard earthen metals.

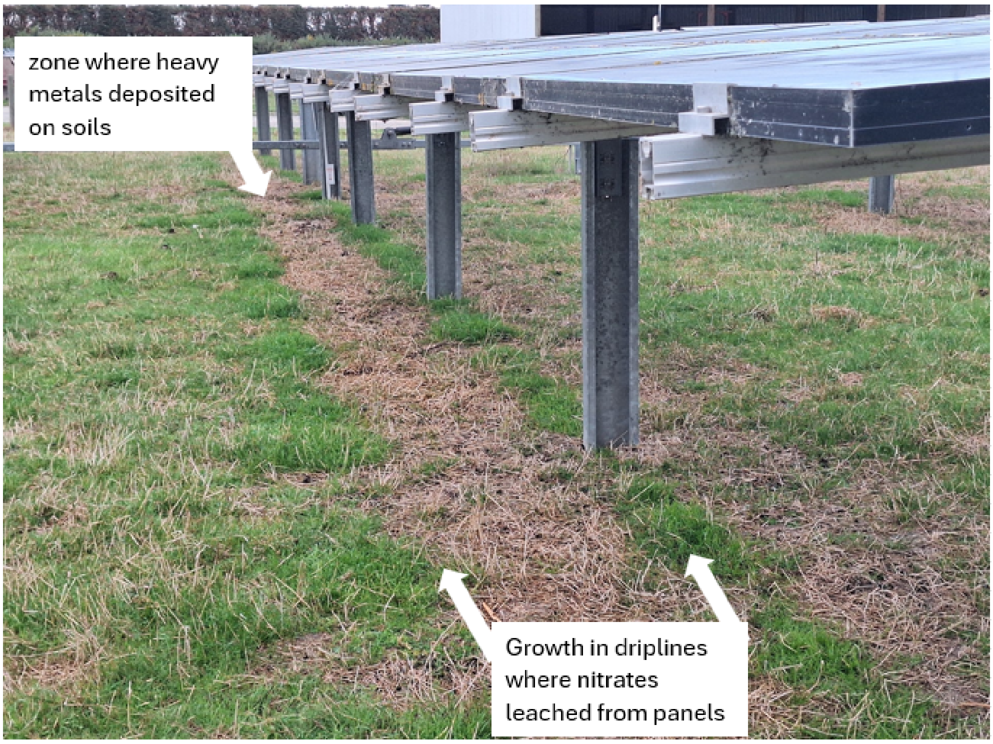


Photo 1 taken at Brookside during autumn growth 2024. The areas under the panels are affected by leachates from solar panels.

A multitude of international studies have measured leachates from solar panels using different testing procedures, all of which demonstrate heavy metals (viz. especially aluminium and lead) are deposited onto soils (e.g., Lu *et al*. 2022). For polycrystalline panels historical leaching studies have shown Al, Fe, Cu, Pb, Si, Mn, N, Ni, Zn, As, Ag, Cd, Cr and PFAS may be released from panels (Panthi *et al.* 2021, Sharma *et al*. 2021, Nain *et al.* 2023, Nain *et al*. 2020). The use of monocrystalline panels in deference to polycrystalline panels at the Brookside solar farm as proposed by Mr. McMath is unlikely to mitigate the release of contaminants, because laboratory studies (Fig. 4) have shown monocrystalline panels leach more aluminium (81 *vs* 49 mg/L), more lead (5.7 *vs* 3.8 mg/L), and more nickel (5.0 vs 3.0 mg/L) than polycrystalline panels (Panthi *et al*. 2021).

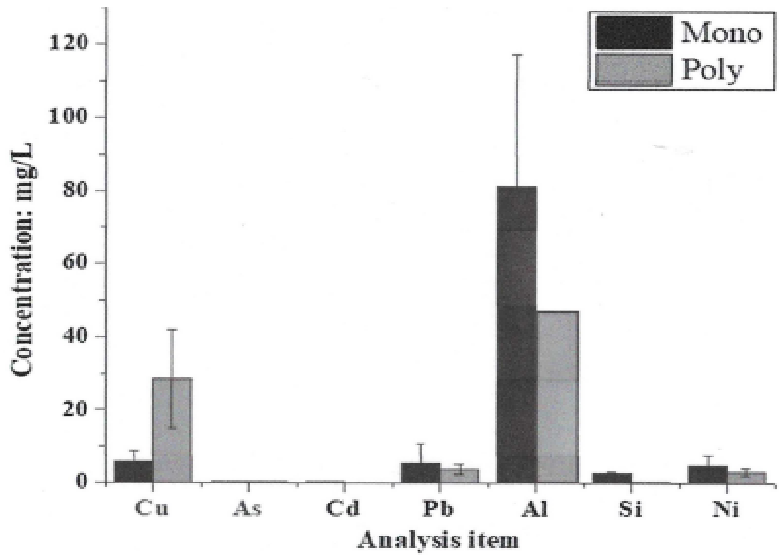


Figure 4. Comparison of measured leachates from monocrystalline solar panels with those of polycrystalline panels during laboratory studies (Panthi *et al.* 2021)

The site in total was only 0.6 of a hectare, so by normal testing procedures for soils it was grossly over-sampled, yet there remained these slight differences in measured parameters for soil pH, total carbon, total nitrogen, and bioavailable sulphur over 3 repeated measures of soils. Some of this is normal sampling error, but it is also likely panels are not degrading at a uniform rate creating a "patchiness" in soil quality. The results for metal leachates from panels were irrefutable and consistently demonstrated that significant amounts of iron (average=623 mg/kg), aluminium (average=800 mg/kg), and manganese (average=55 mg/kg) had been added to soils from the outer layer of panels. After 9.5 years lead (Pb) and copper (Cu) are beginning to be released from the core layers of solar panels, and from this core there were also traces of Ni, Zn, Cd, As, and Cr starting to show in soil tests. As panels degrade within a normal decay curve into the future, these metals from the core will increasingly show in soil tests. The results are consistent with those previously reported in international journals for this type of solar panel (Sharma *et al*. 2021, Panthi *et al*. 2021), with the latter stages of breakdown characterized by a high release of Pb (9.7 mg/L) in the toxicity characteristic leaching procedure (TCLP) test (Sharma *et al*. 2021).

Sodium nitride and silicon nitride leached from antireflective coatings increase nitrates and bioavailable nitrogen in soils, and this promotes ryegrass growth and uptake of contaminants by the plant. Following the development of micro-cracks, the semi-conductor pyrite (FeS_2) was released from outer layers of panels and deposited on soils where it was degraded in a reaction with oxygen and water ($FeS_2 + 3.75O_2 + 3.5H_2O \rightarrow Fe(OH)_3 + 4H^+ + 2SO_4^{2-}$) to add significant amounts of iron (623 mg/kg) to soils. As the panels further degrade, they will leach silver, magnesium, manganese, boron, zinc, cobalt, copper, arsenic, cadmium, lead, and aluminium. The latter 5 of these substances are especially toxic in an aquatic environment (Aziz *et al.* 2023).

Soils

In their meta-analysis of the impacts of solar panels on soils Dvořáčková *et al*. (2024) stated that they "*encountered problems related to the heterogeneity of the environment countless times*". One of the main sources of that heterogeneity is the type of soil at a solar farm. Different types of soil either accumulate leachates or rapidly move heavy metals and PFAS deep underground out of harm's way. For example, the mobility of carbon (from fires) through topsoil and subsoil (Fig. 5) has previously been measured for sandy soils (where carbon moved through soils rapidly) and loams (where added leachates remained suspended in the root zones of plants for an extended period). In the case of compacted loams at Brookside any contaminant from solar technologies is likely to remain near the soil surface or be taken up by plants and enter the food web of terrestrial vertebrates.

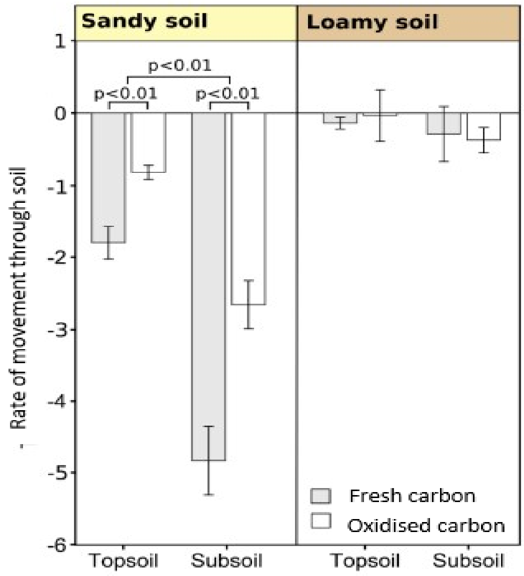


Figure 5. **The rates of migration of pyro-carbon leachates through sandy soils and loams (*from* Schiedung *et al.* 2020).**

In a further experiment, the effects of added iron and aluminium into loams was shown to further reduce the permeability of soils to both water and heavy metals (Fig. 6).

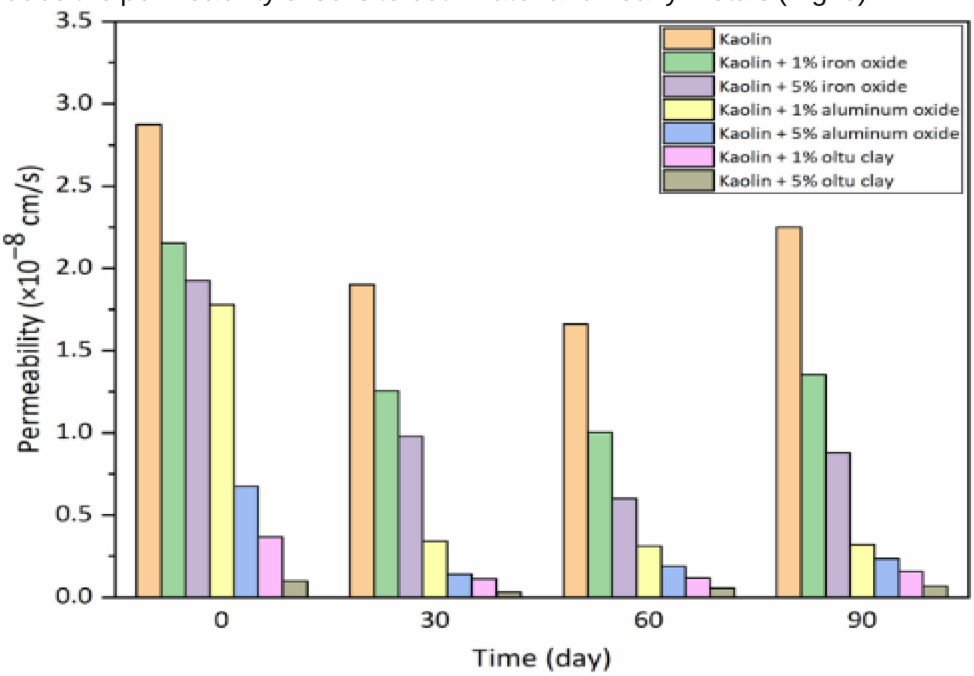


Figure 6. **The permeability of kaolin soils is progressively reduced with the compounded effects of added iron, added aluminium, and added clay into topsoil** (*from* Özçoban *et al*. 2022)**.**

These two factors outlined in Figures 5 and 6 above demonstrate i) the very low movement of leachates through loams compared to sandy soils, and ii) permeability of soils is slowed when

Al and Fe are added to soil. These factors allow the accumulation of heavy metals and/or PFAS leachates in topsoil on highly productive lands. This suggests the choice of site for a solar farm is critical.

At a study site on Long Island (New York) where a solar farm was eventually established (Fig. 7), it was shown the measured concentrations of aluminium, calcium, and magnesium in soil were influenced by pH, the depth at which soils were sampled, and most importantly by soil type (Mancuso *et al*. 2010). Aluminium concentration was lowest in well-drained Deerfield (De) glacial soils (<2,000 mg/kg for aluminium) but were 5x higher in Riverhead (Rd) loam (9,000 to 14,000 mg/kg for aluminium) and up to 10x higher in slow-permeability Plymouth (Pl) loams (16,600−20,200 mg/kg). In the Mancuso study the Deerfield (De), Pine Barrens sands (Ps), and Sudbury (Su) soils were all moderately free-draining and suited to a solar farm, but the Riverhead loam and Plymouth loams are likely to accumulate heavy metals and increase risks to soil organisms and terrestrial vertebrates. This suggests soil type and soil permeability are key parameters in determining the concentrations of heavy metals that accumulate in soils at a solar farm, and the risks that the leachates from solar panels present to the health of animals, people, and ecosystems.

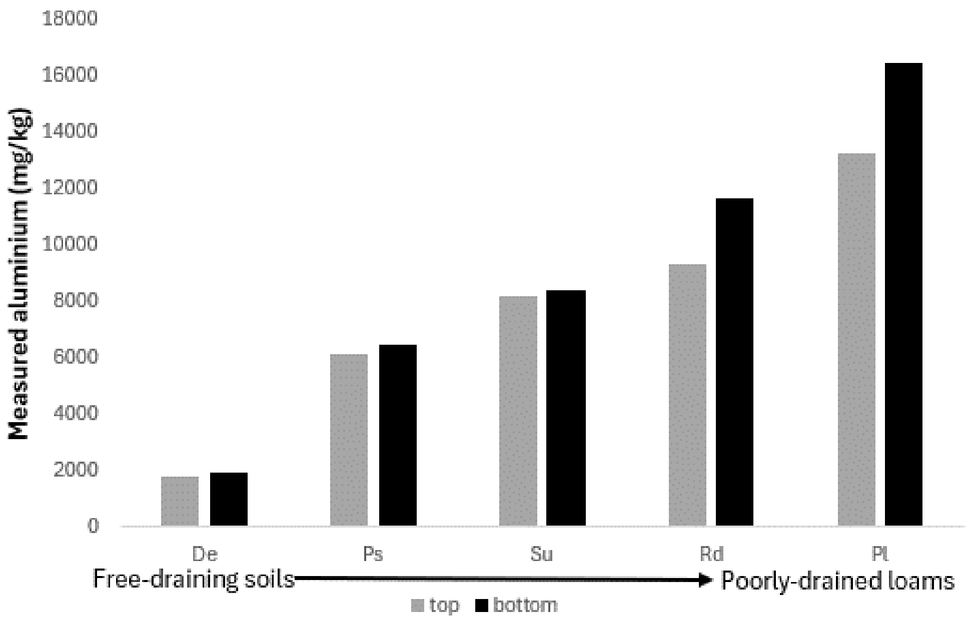


Figure 7. **Measured concentrations of aluminium in acid soils (pH=4.5−5.0) at the site of the Long Island solar farm (USA). There were differences in Al concentrations in the top 0−6 inches of soil compared to a bottom strata of soil 6-16 inches below the surface, but the biggest differences in aluminium concentrations related to soil type and whether those soils were free-draining or heavy loams with slow permeability (***adapted from* **Mancuso** ***et al*****. 2010).**

During ***this study*** a map of soil permeability published by Landcare Research (Fig. 8) showed Brookside soils had the "slowest permeability" of any soils in Canterbury, and correspondingly the heavy loams had readily accumulated heavy metals.

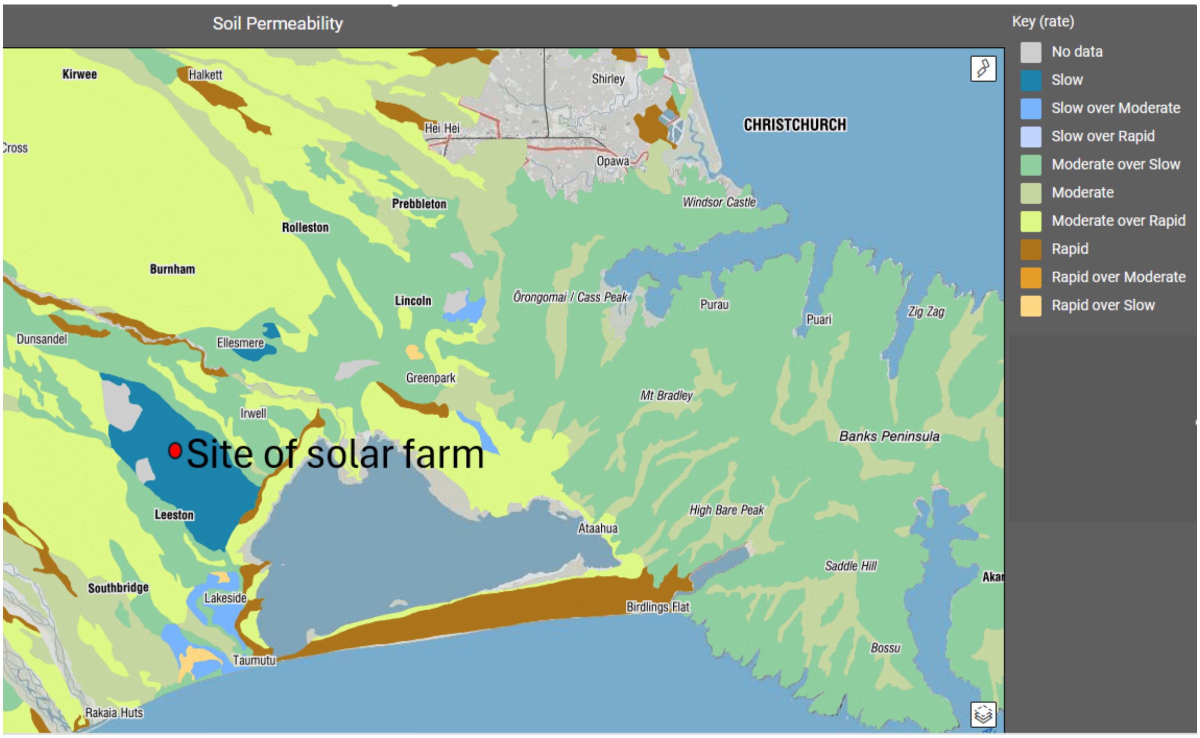


Figure 8. **Soil permeability map for soils at and around the solar farm. This map suggests that if the solar farm was located 5km north, 8km west, or 7km south then many of the problems associated with soil type could have been circumvented.**

GIS (global information systems) have been developed that weigh the risks, costs, and benefits of siting a solar farm on agricultural land as opposed to degraded soils. In addition, there have been numerous papers written on where solar farms are best placed. These include a) the sites of old landfills (USEPA 2021), b) sites where soils are degraded and not suited to agriculture, and c) where there are light permeable soils (alluvial soils, sandy soils, deserts) that facilitate the movement of leachates out of topsoil. Meta-analysis of over 40 science papers written on the siting of utility scale solar photovoltaic facilities (Fig. 9) stated that "*lands that are protected, lands that are cultivated and productive, and lands alongside watercourses are sites considered to have the highest restriction factors against solar development described in the literature"* (Garni *et al.* 2018). The 4th highest factor that precludes siting a solar farm at any location are residents living alongside the site. The site chosen for the solar farm at Brookside has all 4 factors (land protected by the NPS-HPL, it is a heavy agricultural loam, streams exist alongside solar panels where contaminants trigger the NPS-FM, and the area has a high number of residents) and so it is really unsuited as a site for a solar farm.

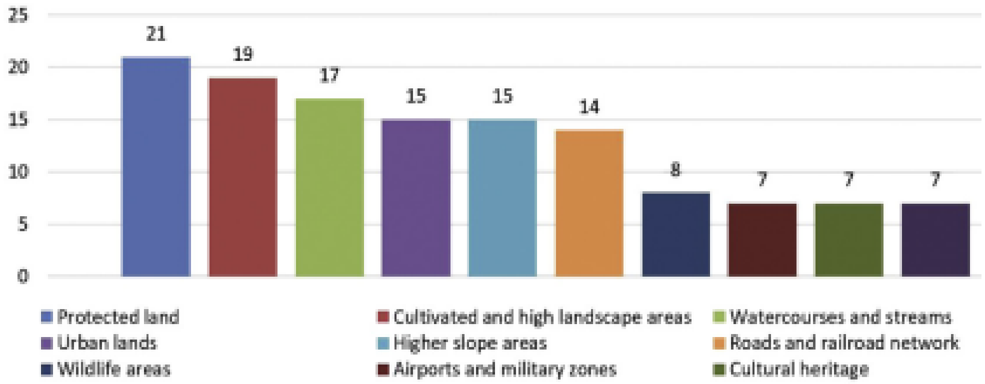


Figure 9. The worst factors that prevent the use of a site for a solar farm (from Garni *et al.* 2018).

Many studies measure leachates in soils after solar panels have been in place for 1-2 years, or measure stock performance under panels that have been *in situ* for only 1-5 years (e.g., Andrew *et al*. 2021) that completely disregard the fact that the weathering of panels follows a decay curve, and that heavy metals accumulate in agricultural soils through time. If we model the results from this and other studies on agricultural soils, we find there is an exponential growth of the risks over time (Fig. 10).

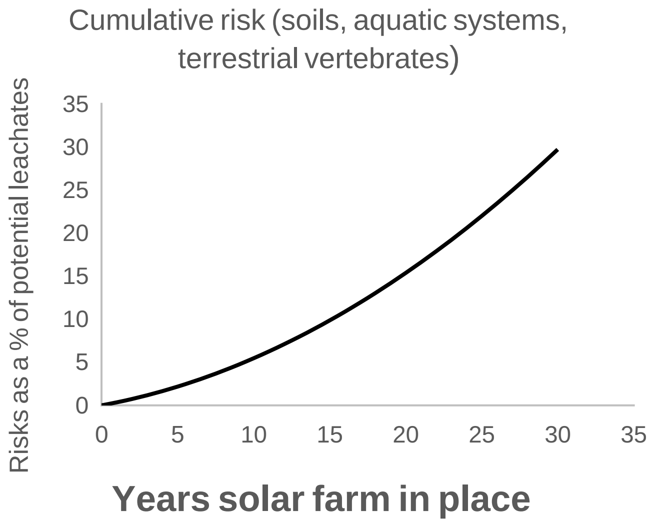


Figure 10. A predictive model of the cumulative risks that solar farms present to the environment (soils, water, vegetation, ecosystems) with the passage of time.

Soil organisms

i) *Earthworms*

Historical research has shown that increased concentrations of aluminium impact both reproduction and the size of earthworms. For example, with active aluminium at 500ppm (i.e., 500 mg/kg) the number of cocoons was reduced by 75% and the number of surviving young worms reduced by 48% compared to control soils containing no aluminium; at 1000ppm of aluminium the numbers of cocoons were reduced by 95% and surviving young worms reduced by 98.3%; and at 1500ppm aluminium there were no young worms produced by adults (Annapoorani 2014). Similar results were published by Gestel (1992), who also showed earthworm reproduction was influenced by soil acidity (which makes aluminium more labile in soils). With solar panels leaching aluminium onto soils, then long-term declines in earthworm populations at a solar farm are to be expected. In addition, Cu, Cr, Pb, Zn, As, Cr and Cd are known to affect earthworm mortality in a dose-dependent manner which further impact the abundance of soil invertebrates. All heavy metals (especially aluminium) reduce the size of worms (Yadav *et al*. 2023).

In *this study* the earthworm population was 64% lower under solar panels than in 'control' soils. The mean concentration of aluminium in 'control' soils was already high (viz. at 15,500 ppm aluminium earthworm populations were already suppressed, and worms were of a small size), but the addition of labile aluminium off solar panels to soils had lowered the population further. It is assumed existing earthworm populations are currently maintained by cocoons in the surface-layers of silt-loam soil where aluminium concentrations are lowest. However, at the time of the study soils were very dry and no cocoons were found during a systematic search of soils.

Because earthworms bioaccumulate heavy metals (Latifi *et al.* 2020, Yadav *et al.* 2023), they present a toxic hazard to passerines (e.g., blackbird, thrush) that feed on invertebrates. In artificially contaminated soils over several weeks it was shown worms could accumulate 2-2,500 mg/kg of lead (Pb), 85-500 mg/kg of cadmium (Cd), 100-500 mg/kg of nickel (Ni), 20-250 mg/kg of copper (Cu), and around 100mg/kg of zinc (Zn), which either alone or in combination (there is a synergy between many HMs that enhance toxicity) may be lethal to birds in chronic or sub-chronic doses (Yadav *et al.* 2023).

ii) Soil microorganisms

Previous research has shown soil microorganisms are impacted by ground-mounted solar panels. In a study of 3 solar farms on agricultural loams it was found the microbial biomass under panels was on average halved after solar panels had been in place for 5-9 years, and that the CO_2 effluxes from basal respiration within soils was reduced by just over 50% (Lambert *et al*. 2021). Moscatelli *et al*. (2022) found a similar decline in microbial activity in soils near panels as opposed to the 'gaps' at the solar farm where there were no solar panels.

During *this study* soil microorganisms were impacted by accumulated heavy metals from solar panels. Although we did not have the resources to identify the types of microorganisms, heavy metal contaminants had reduced total fungi by 53%, soil mycorrhizae (nitrogen-fixing fungi on clover roots) by 59%, soil amoeba was reduced by 91%, soil ciliates by 93%, and overall bacteria by 17%. So, in this study soil fungi and protozoa were more affected by solar panel leachates than soil bacteria.

The metals at highest concentrations in soil were iron, aluminium and manganese. When aluminium is labile in soils this impacts rhizobium in soil (e.g., mycorrhizae on clover roots) as well as other types of soil fungi (Niu *et al*. 2020). As aluminium-sensitive fungi in soils are reduced, this then increases aluminium-tolerant fungi (*Penicillium, Cladosporium, and Talaromyces*) that changes the bioavailability of plant nutrients such as carbon, nitrogen, and organic matter (Shi *et al.* 2020). The other primary soil contaminant at Brookside was Fe^{2+} that also causes significant changes to soil microorganisms. The aerobic *Pseudomonas, Sphingomonas, Nictobacter, Escheria* and *Acidovorax* are significantly inhibited by Fe^{2+} which reduces the amount of oxygen in soil; this then increases anaerobic and chemoautotrophic bacteria like *Alicylobacillus, Desulfosporosinus*, and *Nitrosovibrio* that increase CO_2 in soils, that increase the release of methane, and that change sulphates to sulphides (Zhang *et al.* 2022). Anaerobic soil bacteria may turn nitrites and ammonia into diatomic nitrogen (N_2) that is released back into the atmosphere (Strous *et al.* 2004); suggesting denitrifying bacteria may eventually reduce bioavailable nitrogen for plants. Other types of heavy metal leached onto soils also impact communities of microbes in soil (Jarosławiecka *et al.* 2022).

Soil compaction

In a summary of impacts of solar farms on agricultural land in Wales, ADAS (2022) state *"the key impact of solar PV sites on farmland and soil are caused by compaction leading to soil structural damage. These effects lead to reduced permeability to water and air, as well as increased surface run-off and erosion. The reversibility of soil compaction may take many years, and in some cases, compaction may be permanent".* In a further study, Lambert (2021) demonstrated that "*solar panels changed soil aggregate stability and increased aggregation that degraded the physical quality of soil*"; and over the 3 solar sites on loamy soils the average bulk density increased from 1.11 t/m^3 on 'control soils' to 1.32 t/m^3 on 'test' soils under solar panels. Choi (2020) found that 7 years after solar panels were established "*soils contained a greater fraction of coarse particles with this heterogeneity of soil aggregation contributing to uneven moisture distribution*". Moscatelli (2022) showed that "*seven years of soil coverage by solar panels had modified soil fertility with significant reductions of water holding capacity and soil temperature, while electrical conductivity (EC) of soil had changed, pH was increased, total organic carbon was reduced by 61% and total nitrogen reduced 50%".* Other studies on agricultural loams also reference soil compaction under solar panels.

i) Bulk density

In ***this study***, the solar farm had been in place for 9.5 years on Brookside soils. Compaction in the silt loams at the soil surface (0-75mm deep) had increased bulk density to 1.12 t/m^3, while just below the surface (75-150mm deep) bulk density was further increased from 1.1 t/m^3 to 1.35 t/m^3 (i.e., soils had become '**very compacted'** as categorized by the SINDI classification of soils). Inevitably this level of compaction will progressively get worse throughout the 45-year period that was consented for the Brookside solar farm.

ii) Macro-porosity

Macro-porosity is a measure of the proportion of large pores in the soil and is currently defined for the National Soils Database of New Zealand as the proportion of soil drained at pressure levels of -5 kPa on the water desorption curve (equivalent to a 6-micron pore size). Macro-porosity evaluations undertaken by Landcare Research at -5kpa showed the pores draining soils had declined from an average 10.1 to 9.7 (% v/v) in the top 0-75mm of silt loam soil (i.e., only a slight change after solar panels were established) but had declined from 9.9 to 3.3 (% v/v) in the silty clay loam at 75-150mm below the surface (i.e., soils had become poorly drained and poorly aerated and had the lowest classification for macro-porosity of '**very poor'** on the SINDI classification of soils).

Air filled macro-porosity at -10kpa showed this parameter had declined from 12.1% to 4.6% (% v/v) in soils 75-150mm deep and so macro-porosity was classified as '**very poor'** by SINDI. These results suggest root growth of plants near solar panels will be severely affected at depths >75mm, with reduced oxygen diffusion to roots, and poor drainage in wet weather.

We can only speculate on where levels of soil compaction will be 35-years into the future on these heavy loam soils, but inevitably it will be considerably worse than after just the 9.5 years under solar panels, and possibly as described by ADAS (2022) the effects of soil compaction may be "permanent and irreversible". The travesty is that this was once highly productive irrigated land that returned >$10,000/ha to the New Zealand economy that may ultimately finish as a compacted wasteland with negligible returns from agriculture or pastoral farming.

Stormwater

In recent years, solar farms have been shown to increase runoff of stormwater and the peak times of floods (e.g., Nair *et al.* 2022). At locations where solar panels had only been in place for a short time, Cook *et al.* (2013) reported that solar panels increased storm run-off by 7% and peak discharge by 73% compared to 'control' areas without solar panels. Baiamonte *et al.* (2023) states "*solar panels increase the peak discharge of stormwater about 11 times compared to a reference hillslope without solar panels*". Once again, these studies were undertaken on agricultural loams where slow-moderate permeability of soils existed; so unsurprisingly solar panels created issues with stormwater discharge.

In ***this study*** locals and "council experts" at a hearing on the solar farm agreed that Brookside soils frequently resulted in surface water running off farmland after just 13mm of rain. Unsurprisingly, this happens because soils have been gazetted by Landcare Research as having "slow permeability". As soils become very compacted by solar panels, the effects of increased stormwater discharge are exacerbated (photo 2). This suggests stormwater contaminated with heavy metals and PFAS will increasingly flow into the streams that surround a solar farm and down to Lake Ellesmere.

Photo 2. **Stormwater at Brookside is unable to be absorbed into the 'very compacted' ground under solar panels, and instead this contaminated water flows into surrounding streams and down to Lake Ellesmere.**

In a comparison of the hazards of water-borne materials leached from solar panels with the deadly poison sodium monofluoroacetate (1080), we note the EC_{50} of 1080 to trout is 54 mg/litre whereas heavy metal leachates from solar panels are much more toxic with EC_{50} values of 1.5 mg/L for aluminium, 1.3 mg/L for lead, 8.5mg/L for silver, 4.7 mg/L for manganese, 0.05 mg/L for cadmium, and 0.5 mg/L for copper; with a natural synergy between some of these substances (e.g., Tao *et al.* 1999) that further increases risk. The irony of this scenario is that existing regulations prohibit the application of 1080 within 100-m of a stream, yet at Brookside solar panels with hazards to aquatic ecosystems that are an order of magnitude higher than 1080 are being placed on the stream bank immediately adjacent to surface waters that flow into Te Waihora.

Of further concern at Brookside are the implications of contaminated stormwater flowing along existing flood channels onto adjoining farmland. Photographs were supplied of waters flowing along floodwater channels onto adjoining properties (*see* photo 3). Once the solar farm is established these floodwaters will contain suspended or dissolved contaminants that will affect neighbouring farmers. Under section 15 of the RMA 1991 this type of contamination of adjoining land is a prohibited activity.

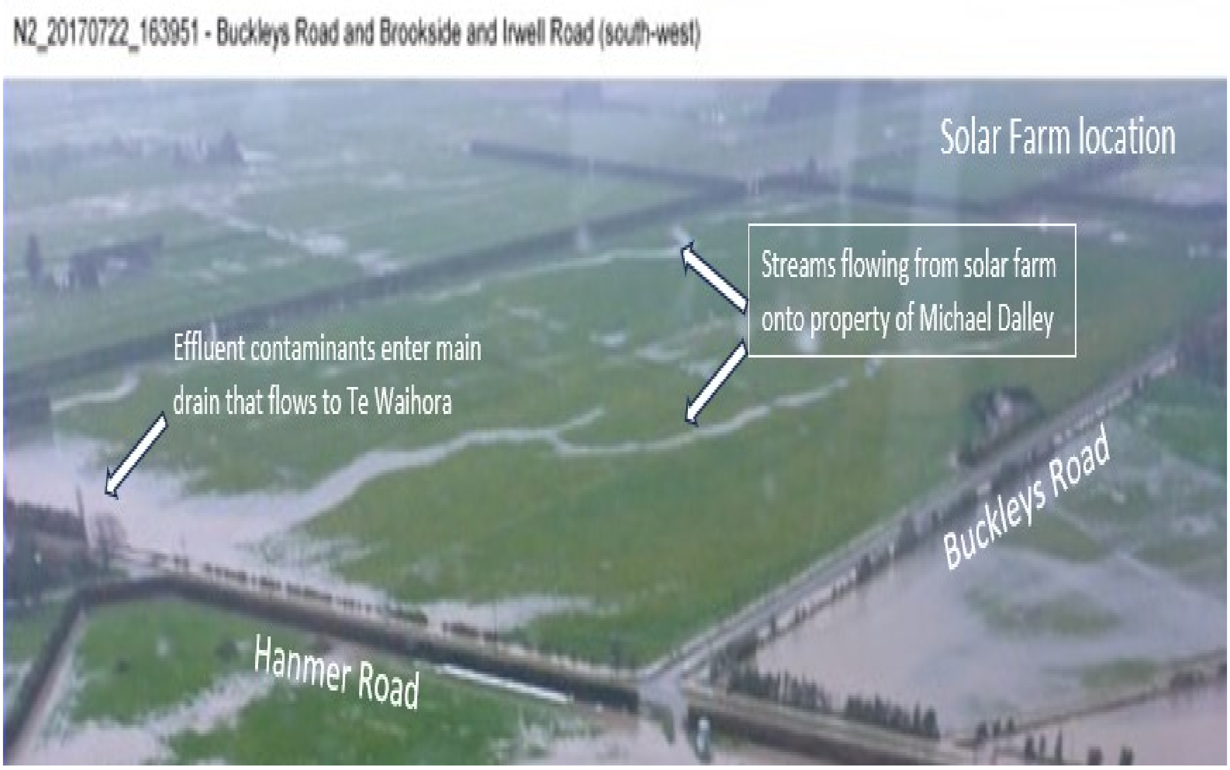


Photo 3. **Run-off of floodwaters that will contain heavy metal and PFAS contaminants if a solar farm is located at Brookside.**

Vegetation

In an alluvial or free-draining sandy soil, the leachates from panels rapidly disappear from the root zone of plants and migrate deep underground where they remained buried. In a heavy loam where there is “slow permeability”, then solar panel leachates remain near the soil surface and in the root zone of plants. This effect is exacerbated by increased bulk density and reduced macro-porosity of soils under panels (*above*), which means most leachates progressively accumulate in the root zone of plants. These heavy metals in topsoil are absorbed by roots and bioaccumulate in plant tissue, fruits, and the seeds of plants. The ryegrass in *this study* contained high levels of aluminium, iron, and manganese as well as modest levels of copper and lead that all exceeded maximum allowable daily limits (MAL) for vegetation. The ryegrass contained low phosphorous (P) and low potassium (K), but high nitrogen (N) which reflected the measured NPK of soils under panels. These heavy metals and grasses with depleted P were eaten by sheep grazing pasture under solar panels.

The high bioconcentration factor (BCF) of solar panel leachates in plants should be discussed, albeit briefly because this requires further research. In this study total aluminium in soils was measured in the laboratory using replicate samples of ‘test’ or ‘control’ soils; with the difference being the two indicating the amounts of aluminium released from panels. The aluminium in soils exists in many forms. It is an amphoteric substance that dissolves and disproportionately affects soils and plants at low (i.e., pH <5.5) or high pH (>7). However, it is not only pH that affects absorption by plants. Aluminium exists in many forms, with some Al encapsulated in aluminosilicates, some encapsulated in an oxygen tetrahedron, some encapsulated in an oxygen octahedron, and some as non-labile aluminium salts. The subtle changes in pH during this study will make little difference to its availability in soils. However, changes as it is hydrolysed markedly affect rates at which is either adsorbed onto roots or absorbed into the root as one of the hydroxides:

$Al^{3+} + 3H_2O \rightarrow Al(OH)_3 + 3H^+$

$Al^{3+} + H_2O \rightleftarrows Al(OH)^{2+} + H^+$

$Al(OH)^{2+} + H_2O \rightleftarrows Al(OH)_2{}^+ + H^+$

$Al(OH)_2{}^+ + H_2O \rightleftarrows Al(OH)_3 + H^+$

$Al(OH)_3 + H_2O \rightleftarrows Al(OH)_4{}^- + H^+$

In this study most natural aluminium was probably absorbed in the form of $Al(OH)_2{}^+$. The nanoparticles and aluminium molecules from ‘micro-cracks’ are in a form more likely to be absorbed than earthen metals. For other types of solar panel, the levels of leached aluminium in soils may be higher than those reported in this study. We can see from Table 12 that sheep eating grass are consuming 10x the permitted level of aluminium.

Iron also occurs in many forms. It exists as ferrous iron (Fe^{2+}), the insoluble ferric states (Fe^{3+}) geothite (-FeOOH), magnetite (Fe_3O_4), maghemite (Fe_2O_3), ferrihydrite (Fe2O3 x n H2O), pyrites ($Fe^{2+}S$), but is mainly absorbed by plants as Fe^{2+}. Therefore, only a percentage is bioavailable, and this bioavailability appears higher for leachates from solar panels than earthen iron.

Other materials (e.g., Cu, Pb, etc) have similar differences in properties. Added to these factors is the issue of materials off a solar panel have come through “micro-cracks” and are at a molecular level or occur as soluble nanoparticles.

Pastoral farming.

In this study soil contaminants (especially Fe and Al) occluded bioavailable phosphorous and potassium in soils, and more than halved soil organisms and soil microorganisms. There was a 59% decline in mycorrhizae on the roots of clover. On pastures where concentrations of labile Al exceed as little as 3.3ppm in topsoil it starts to impede the growth of legumes, with white clover more susceptible to aluminium than other legumes (Moreton & Moir 2018). These factors (high labile aluminium, low mycorrhizae, low potassium, low phosphates, high soil compaction) all combined to severely restrict the growth of clovers close to panels. Negligible numbers of clover plants were located within 2-m of solar panels.

Nui ryegrass readily grew in contaminated soils when supplemented with nitrates off solar panels. Other varieties of ryegrass (e.g., Expo) are less tolerant of heavy metal contaminants (Parra-Almuna *et al.* 2018) The ryegrass eaten by a 35kg lamb contained heavy metals that in some cases exceeded the MAL for vegetation provided by WHO (Table 12). For example, the lamb in this study was consuming 10x the permitted levels of aluminium.

Table 12. Estimated daily intake of heavy metals by a 35kg lamb grazing 2.4 kg of grass each day from under solar panels.

Contaminant	Daily MAL mg/kg - WHO	Daily intake by sheep m/k	Impacts on sheep	**Impacts on health if sheep grazed long enough**
Silica (Si)	not stated	unknown	**Yes**	When inhaled causes silicosis of lung, coughing.
Iron (Fe)	10	5.5	**Yes**	High Fe affects homeostasis of P, Mg, Cu.
Boron (B)	0.2*	0.4	unlikely	Unlikely, doesn't bioaccumulate (HL=1 day)
Aluminium (Al)	2 m/k/week 0.3 m/k/day	3.0	**yes**	Neurological effects, possible necrosis of pulmonary, hepatic, renal tissue. Long HL
Lead (Pb)	0.025m/k/week	0.4	**yes**	Neurological effects; possible necrosis of renal and hepatic tissue. Bioaccumulates; long HL in tissue.
Arsenic (As)	0.001 in $H_2$0 0.001 in food	<0.1	unlikely	At this stage contaminants in ryegrass were too low to impose a significant risk.
Cadmium (Cd)	0.003 in $H_2$0 0.1 in food	<0.01	unlikely	Leached cadmium is increasing in soil but is not yet an issue. long HL in tissue.
Manganese	Adults=2.3 Infant=0.6	5.5	**yes**	Neurological affects resembling Parkinson's disease; cardiotoxicity, and hepatotoxicity.
Zinc	1	1.4	unlikely	Insufficient in plants at this stage; although long HL in tissue.
Copper	0.15	0.45	**possibly**	Impacts GI microflora, immune system, cytotoxicity. Long HL in tissue
Chromium III	1	<0.1	unlikely	The LOD for the test used on plants is too high to quantify risk. Long HL in tissue, bioaccumulates.
Chromium IV	0.0007			

Note: The maximum allowable limits (MAL) for boron have not been established, but the USEPA (2004) recommends dosage should not exceed 0.2 mg/ kg bw/day.

Horticultural & vegetable plants

If a person was eating 200g of greens with the measured lead levels in ryegrass during *this study*, they would already be eating 2x the stated MAL for Pb in vegetables. In a study reported by Su *et al*. (2019) an average person eating three 100g portions of brassicas each week that were grown in soils containing solar panel leachates, would consume at least twice the permitted level of aluminium (Fig. 11). Aluminium has been linked to growing levels of neurocognitive disorders and low efficacy of vaccines, suggesting that 'agrivoltaics' on heavy agricultural loams like those at Brookside is likely to add to health risks.

A multitude of international studies have shown that fruit, berries, vegetables, and herbs grown in contaminated soils at solar farms exceed the MAL for heavy metals.

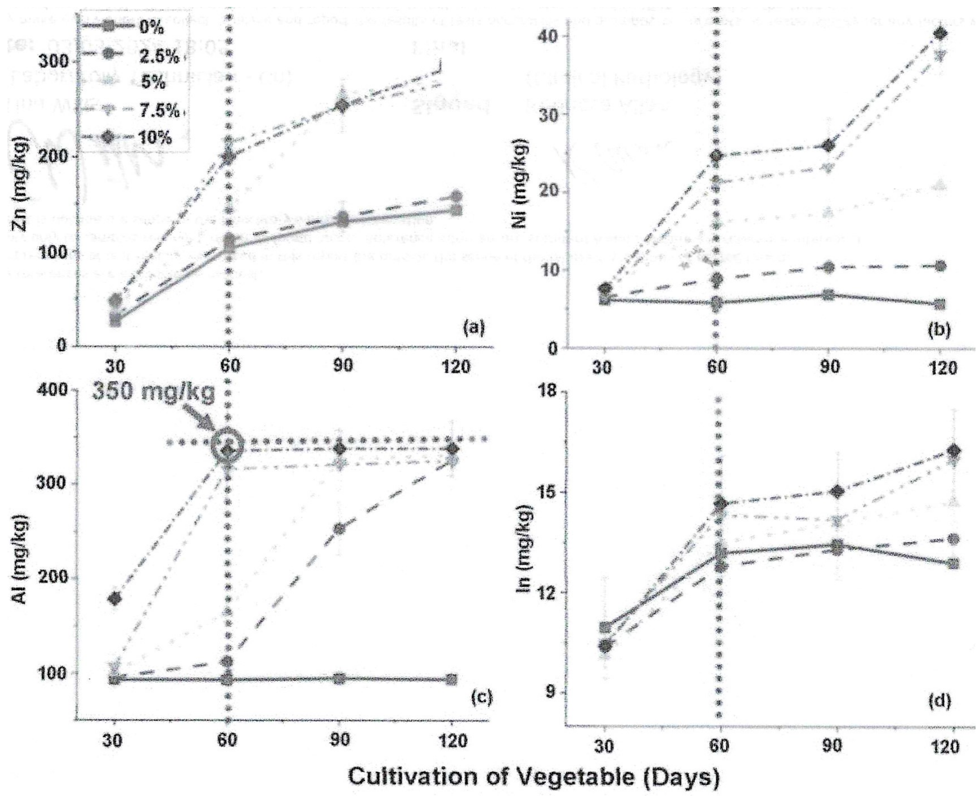


Figure 11. Uptake of zinc, nickel, aluminium, and indium in the leaves of brassica plants grown in soils containing 0%, 2.5%, 5%, and 10% of the heavy metals from solar panels (Su *et al.* 2019).

A heavy metal leachate regularly associated with all types of solar panels is lead (Pb). The listed maximum permissible intake by WHO is only 0.025 mg/kg/week. Therefore, a 60kg person has a permissible intake of 1.5mg of Pb per week. In this study solar panels are just starting to leak Pb, but a person eating leafy plants grown in soils would currently accumulate sufficient lead to affect their health. In a study in China, lead from perovskite panels was bioconcentrated in the leaves of mint plants at levels 1.7x the concentration found in soils (Fig. 12); but what was of more concern was that the roots accumulated lead at 19x the concentration found in soils (Vikash *et al.* 2020). There are 2 issues arising from the Vikash (2020) research; the 1st is that roots accumulate inordinately more heavy metals than stems and leaves, and the 2nd is that the bioconcentration factor (BCF) of solar panel leachates seems very high compared to earthen metals. The results of this and other research reported elsewhere suggest contaminants in root crops for human consumption (e.g., carrots, parsnips, potatoes) or root crops for livestock (e.g., fodder beet, swedes) may potentially pose more of a risk to mammalian health than the leaves and fruits of plants.

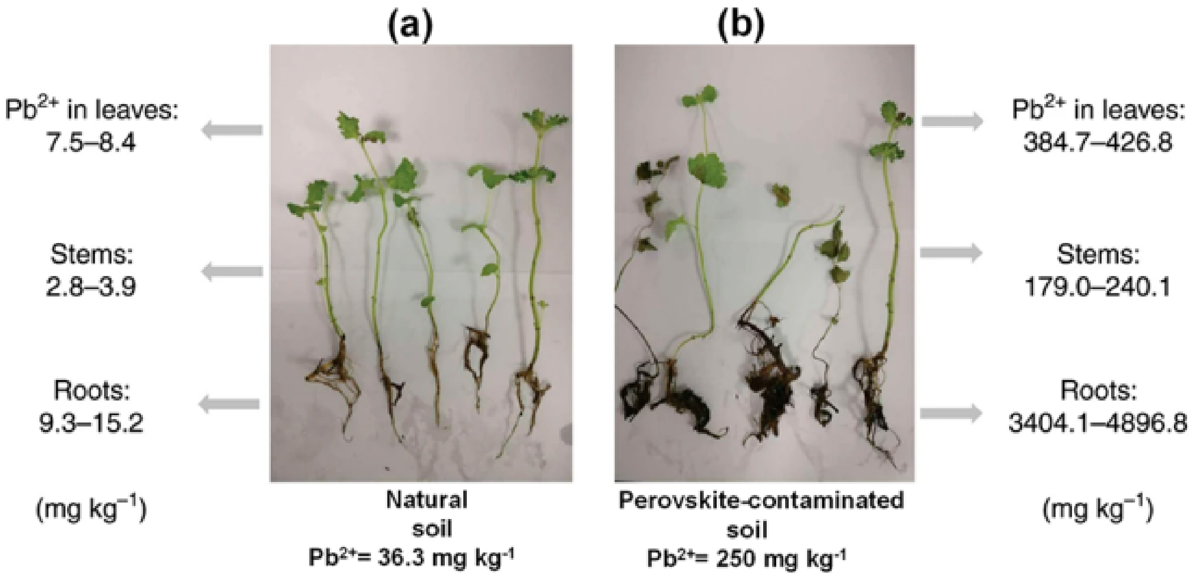


Figure 12. **In natural soils containing Pb (a) plants accumulated lead at around 0.2x of the soil Pb concentration; but (b) leachates from solar panels were measured at 1.7x soil concentrations in leaves and 19x the soil Pb concentration in roots through bioaccumulation of labile Pb into plants** (Vikash *et al.* 2020).

Agricultural crops

Moderate levels of metal contaminants in Polish soils resulted in high levels of heavy metal contaminants in grain (Table 13). When this grain was fed to pigs on a cereal-based diet then moderate amounts of heavy metals were found in pork, liver and kidney (Chałabis-Mazurek *et al.* 2021) that exceed maximum allowable limits (MAL) for the European Union.

Table 13. Contaminated soils in Poland grew grain that bioaccumulated heavy metals (mg/kg), which when fed to pigs resulted in elevated heavy metals in meat, liver, and kidneys.

Type of heavy metal in soil / food	MAL in meat (EU)	Contaminants in soils[1]	Contaminants in cereal used to feed pigs	Heavy metals in pig meat	Heavy metals in pig liver	Heavy metals in pig kidney	Wild boar livers contain high contaminants[2]
Cadmium	0.05	0.03 – 1.0	0.125	0.005	0.043	0.05	0.483
Lead	0.1	0.1 -40	0.147	0.09	0.756	0.60	0.195
Copper	0.5	0.01 – 50	27.3	13.7	30.5	35.8	
Zinc	0.3	5 – 150	179	128	230	116	63
Iron	0.5	50 – 3,000	207	81	486	185	
Manganese	n/a	0.02 - 0.5	94	1.2	11.3	6.2	
PFAS	0.7	n/a		1.4			117

[1] Tomczyk *et al*. 2023. [2] Kasprzyk *et al*. 2020

These results suggest agrivoltaics on agricultural soils with “slow permeability” will affect the composition of plant communities, will affect plant growth, and may result in hazardous heavy metal and polyfluoroalkyl substances entering the food web. Before agrivoltaics becomes widespread the MPI and the MFE must regulate the types of soil used for agrivoltaics and monitor the accumulation of heavy metals and PFAS within soils and any surface waters adjoining a solar farm.

Haematology, Toxicology, and Histopathology of a lamb

Aluminium toxicosis in ruminants is notoriously difficult to diagnose, with Al-content of urine the best method identified for cows affected by high aluminium in hay and silage (Eppe *et al*. 2023). In this study, haematology and histopathology by a reputable agency (Awanui Veterinary Ltd.) provided data that could not identify any significant effects from aluminium and iron ingested in sub-chronic doses over 5 months. This was of no surprise as previous clinical studies have encountered similar problems. The aluminium in the diet of the lamb inhibits the homeostasis of critical minerals like P, Fe, F, Cu and in sub-chronic doses lowers Mg and Ca, in blood serum (Allen 1984, Rosa *et al.* 1982). In *this study* sub-chronic doses of aluminium in small, divided doses over 5 months had a similar effect with measured levels of P, Mg, Fe, and Cu low in serum and some tissues of the 'test' lamb grazed under solar panels.

Before discussing the results from toxicology and histopathology for the lamb, it is important to understand the overall toxicokinetic of aluminium (Al) and iron (Fe) in animals. The Al ion has no physiological role in animal metabolism (Exley & House 2011) but can act as a metallic toxicant to humans and animals (Becaria *et al*. 2002) when there is high body burden of the metal following long periods of natural or unnatural exposure (Exley 2013). The effects of high aluminium in the diet have been well-researched and show a varying percentage of what is ingested is absorbed in the small intestine depending on diet, and whether the animal is a ruminant (e.g., sheep, cattle) or is monogastric (e.g., humans, horses, pigs). The difference arises because aluminium reacts with phosphates and/or phosphorous in the stomach (especially herbivores) to form an aluminium-phosphate complex that is poorly absorbed by the small intestine, whereas monogastric animals generally have lower levels of stomach phosphorous and more readily absorb aluminium in the intestines. This in effect is the 1st stage of aluminium toxicosis, because in ruminants high Al may cause deficiencies of absorbed phosphorous that reduces growth, causes soft bones and bone fractures, and lowers animal fertility (Agriculture Victoria 2023, Allen 1984). In *this study* aluminium in the diet was high and phosphorous in plants was low; so, the lamb most likely absorbed a significant amount of the Al from ryegrass; the remainder would be excreted in faeces. In the 2nd stage of aluminium toxicosis the absorbed aluminium then affects iron homeostasis (Ward *et al.* 2001, Igbokwe *et al*. 2019). The Al that is absorbed is a cation of similar size and shape to Fe and so readily becomes bound to the transferrin protein in blood (viz. transferrin is the vehicle that transports iron around the body). Having bonded to transferrin Al is then distributed to bones (60%), pulmonary tissue (25%), muscle (10%), liver (3%), and the brain (<1%) (Rahimzadeh *et al*. 2022, Igbokwe *et al*. 2019). In the 3rd stage of aluminium toxicosis aluminium reduces synthesis of red blood cells (viz. the aluminium displaces some iron, calcium, and phosphorous in bone) and this may result in anaemia (low RBC, low haemoglobin, and sub-clinical ketosis in livestock; Eppe 2023) as well as lowered WBC count (viz. WBC are made in bone marrow). In the 4th stage of aluminium toxicosis, aluminium is excreted *via* the kidney, which may result in chronic kidney disease (de Oliviera *et al*. 2021). In the 5th stage of aluminium toxicosis, aluminium overload in the blood affects Fe, Cu, Mg, Al, and Mn deposition in critical regions of the brain, that may eventually result in the onset of Alzheimer's disease and other neurodegenerative disorders (Tyczyńska *et al*. 2024). Other materials lowered in blood serum by Al include fluorine (F), phosphorous (P), and it also affects calcium (Ca) homeostasis (Allen 1984) The 6th stage of aluminium toxicosis arises because its presence on transferrin causes inadequate distribution of iron (Fe) to muscle (this causes fatigue and low muscle strength), and results in inadequate

Fe in pulmonary tissue that predisposes mammals to COPD, asthma, and cystic fibrosis as impacts on health (Neves *et al*. 2019, Neidlein *et al.* 2021).

Manganese is an essential trace element for basal metabolism, but in excess is a substance that causes neurological disorders like Parkinson's disease.

Because aluminium leached from solar panels accumulates in agricultural loams of slow permeability and these contaminants are labile (i.e., readily absorbed by plants), this casts doubt on whether produce (grain, fruits, berries, herbs, grass and meat) harvested from some soil types during "agrivoltaics" is safe for human consumption. The toxicokinetic of Al outlined above suggest it takes some time for aluminium to build up in the body and change basal physiology, and so young animals (e.g., lambs) accumulate lesser amounts of aluminium than older livestock (ewes) (e.g., Menzies *et al.* 2003).

During *this study* a lamb was selected for toxicology and histopathology because this class of animal was most likely to be grazed under solar panels on LUC2 and LUC3 soils on a "finishing farm" at Brookside. The Ward farm at Brookside has no run-off for sheep and lambs, so livestock will be permanently fenced under solar panels. Therefore, aluminium ingested will bioaccumulate in blood and tissues. Aluminium bound to transferrin in blood is transported throughout the lamb's body with elevated Al levels measured in the kidney and liver (indicating a percentage was being excreted), moderate amounts of Al were measured in pulmonary tissue and muscle, and a small repository of aluminium was measured in the brain (this fits with the published literature from *above*). The amounts in all tissues will increase with the passage of time because aluminium has a long half-life in mammals (e.g., half-life in brain is 7 years).

Most iron in mammals (approximately 65%) is contained within the haemoglobin (which is synthesised in bone). Therefore, as with other animals exposed to aluminium the red blood cell counts of the 'test' lamb were lower than for those grazing uncontaminated grass (RBC=10.0^{12} *versus* an average of 11.8^{12}/L), haemoglobin was lower (95 *versus* an average 121g/L for lambs grazing uncontaminated grass), and the white blood cells synthesised in bone marrow were lower (5.4x 10^{9} *versus* 8.4x10^{9}). These haematological measures are lowered, but as the literature indicates they are typically not outside the 'normal' range. The irony of the above scenario is that leached Fe from solar panels gave the lamb a diet that was high in iron (viz. grass contained 91 mg/kg of Fe), but it was not able to utilize Fe because the pathway for iron haematosis was partially blocked. Quite simply, elevated levels of aluminium in the diet impede normal physiological processes. Furthermore, the transferrin in blood was not able to transport the high levels of iron in the lamb's diet to the tissues that needed it most (e.g., bones and muscle). This may explain the observed fatigue and lameness. Iron, Cu, P, and Mg were low in the brain (which along with other elements contributes to neurodegenerative disorders). These changes associated with Al ingestion that cause low Cu, Fe, Mg, and P in the brain have previously been shown to affect behaviour and cognition of lambs (Asin *et al*. 2020). It is quite probable the health of this 'test' lamb would have deteriorated further following longer exposure to leachates.

Another effect of high Fe and Al in the diet, is low uptake of copper. In a study on 56 sheep, it was found that high Fe levels in the diet caused low copper levels, and this occurred even when Cu was administered as a supplement (de Sousa *et al*. 2012). Copper absorption in the small intestine of sheep is reliant on Cu^{2+} being absorbed across the apical membrane of enterocytes as Cu^{2+} *via* DMT1 (using a common pathway with iron) or being reduced from Cu^{2+} to Cu^{+} (by endogenous biological reductases and dietary components such as vitamin C in a common pathway with Fe^{2+}), and then transported through the cardiovascular system bound to serum albumin (Lee *et al.* 2024). Iron and aluminium in the diet impede these processes. Absorption of lead (Pb) in the small intestine happens in a similar way and has been shown to be around 10-15% lower in ruminants than in monogastric animals. Therefore, the high Fe and Al in the diet of the lamb are the reasons for low Cu and Pb in the liver during this study, when both Cu and Pb were elevated in ryegrass.

The lamb had low iron levels as shown by lowered haemoglobin and RBC counts; and had low copper in the brain along with low Mg and P in blood serum. These factors contribute to neurological disorders as well as physical maladies. When agrivoltaics is undertaken on the wrong type of soils like those at Brookside, these maladies invoke issues affecting 'animal welfare'.

There has been a plethora of studies undertaken that assess the growth and performance of livestock under solar panels. <u>All these studies have been undertaken where panels that have been in place <5 years</u> (i.e., materials leached from panels have not had time to accumulate in soils) and/or have been undertaken on soils with good permeability (i.e., where heavy metals and PFAS substances move rapidly out of the root zone of plants). The same is true for ongoing research assessing the growth of horticultural and agricultural crops under solar panels. When contaminant levels are high, berry crops grown in soil resulted in blackberries containing up to 29x the permitted level of Pb (Vlad *et al*. 2019), and rosehips grown on very contaminated soils were shown to bioaccumulate 8,242 mg/kg of aluminium (Al), 11.3 mg/kg of nickel (Ni) and 3.34 mg/kg of lead (Pb); contaminant levels all well above WHO guidelines (Zeiner *et al.* 2018).

If soils are to be used for agrivoltaics where pastoral farming is undertaken, where the cultivation of agricultural crops is planned, or where horticultural crops are grown, then those soils must be free-draining and not able to accumulate leachates from solar panels.

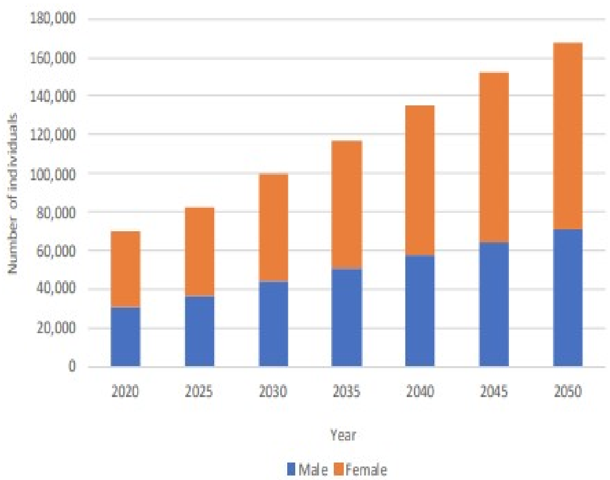
Health Effects

Just as the health of the lamb has been impacted by consuming vegetation growing under solar panels, so too will the health of people by consuming contaminated fruit, berries, foliar plants (brassicas, lettuce), and especially root crops grown in soils containing leachates. It is now well established that changes in heavy metals (especially P, Al, Mn, Cd, Cu, Mg, Fe, Pb, Ca) are implicated in the rise of Alzheimer's disease and other related brain disorders (e.g., Bakulski *et al*. 2020). The agrivoltaics proposed at Brookside and other sites with poorly drained agricultural soils result in the accumulation of Al, Mn, Pb, Cd, Cu and other ancillary heavy metals in soils and plants. These metals were shown in this and other studies to alter P, Mg, Cu, Fe, Mn, Ca, F in the brain that appear to cause a malaise of neurodegenerative disorders (Fig. 13). Just like humans, lambs ingesting chronic doses of aluminium also experience changes in behaviour and cognition (Asin *et al*. 2020). Another important consideration of agrivoltaics is the effect of aluminium on lowered efficacy of vaccines.

Most heavy metals (including excess Fe) are cancer-inducing agents (Tchounwou *et al*. 2012). Increased exposure to carcinogens through contamination of soils, and then uptake into plants may in future be a contributory factor to the rising rates of cancer (Fig. 14).

A range of other maladies that affect public health arise from consumption of polyfluoroalkyl substances. Polyfluoroalkyl substances (PFAS) in recent years have been identified as serious catalysts to health problems in Asia (e.g., Parvez *et al*. 2021).

In China where solar technologies have been deployed in ‘agrivoltaics’ for 25 years, there are now serious health issues amongst pregnant women and their infants at contaminated sites because e-waste accumulates in the placenta of the foetus (viz. average for contaminated sites=30mg/kg compared to <5mg/kg at non-contaminated sites), and results in babies born with low AGPAR1 scores (Parvez *et al*. 2021). These children grow up with serious health issues and neuropsychiatric disorders. Of course, no-one can be sure of the sources of all these contaminants, but the problems began just before the new millennium with the emergence of solar technologies and agrivoltaics in Asia, and by 2022 China was spending around $28 billion annually attempting to clean-up contaminated land.



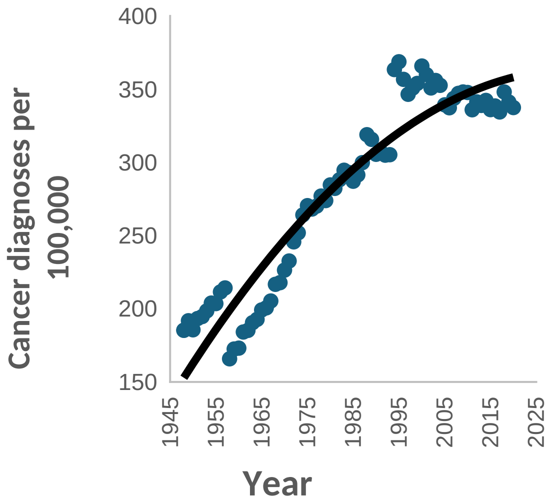


Figure 13. Predicted rise in dementia in NZ. Fig. 14. Increased rates of diagnosed cancer in NZ

The primary leachates during ongoing research on solar technologies remain as aluminium and lead, that each come with their own health hazards. The impacts of other heavy metals (Cu, Zn, Ni, As, Cd, etc) and PFAS become more important during the 2nd half of the life of a solar panel (typically around 15-30 years).

Environmental risks
Solar farms require large land areas (c. 1.5 - 3ha per Mw of electricity; Onga *et al.* 2013) to generate electricity. There are a multitude of different materials used in solar technologies to manufacture solar panels, within the framing for tables, within inverters, within transformers, within cabling, within circuit boards, and within batteries. The main ones detected as important leachates during ongoing research are shown in table 14 in comparison with brodifacoum (as a toxic rodenticide). We can immediately see from this table that most materials used to make solar technologies are very hazardous when released into the environment. In the model ‘Risks=Hazards x Exposure’, if “hazards” are high, then “exposure” must be low.

Table 14. The half-lives, health, and environmental risks of materials used in solar technologies by HSNO classification.

Chemical	Metal half-life Liver (d)	Aquatic toxicity 9.1	Soil toxicity 9.2	Terrest. Vert. 9.3	Oral toxic 6.1	Mutagen 6.6	Carcinogen 6.7	Reproductive toxicity 6.8	Target Organs 6.9
Brodifacoum	114.6	9.1D	n/t		6.1E				6.9B
Aluminium	150 in liver; 7years brain	9.1A	9.2B		6.1E				6.9B
Lead	36 blood 130 liver 2 years brain	9.1A 9.1B	9.2B	9.3A	6.1C	6.6B	6.7B	6.8A	6.9A
Silica		9.1B		9.3C					6.9A
Cadmium	4 -19 yrs	9.1B			6.1C		6.7A	6.8B	6.9A
copper	21 d 435 d brain	9.1A	9.2D	9.3B	6.1B	6.6A			6.9B
Nickel	35 d	9.1B		9.3B	6.1C		6.7A		
Boron	1.5 d	9.1B	9.2D	9.3C	6.1E			6.8B	6.9A
Zinc	245 d	9.1A		9.3C	6.1D				6.9B
Silver	50d	9.1A	9.2B	9.3A	6.1C			6.8B	6.9A
Arsenic	10 hrs	9.1A	9.2B	9.3B	6.1C		6.7A		6.9A
Chromium	9 d	9.1A	9.2B	9.3B	6.1A	6.6A	6.7A	6.8A	6.9A
Selenium	150d	9.1C	9.2C		6.6B	6.6B			6.9B
Lithium	1-2d	9.1D	9.2D		6.1D				
Strontium	50.5 d	9.1C	9.2D		6.1D				
Titanium	12.7 d	9.1B			6.1E		6.7B	6.8B	
PFAS	5.5 – 8.5 yrs	9.1A 9.1B	9.2C	9.3B	6.1C			6.8A	6.9B

A multitude of studies have demonstrated leachates are invariably found under solar panels (e.g., Lu *et al*. 2022). The risks associated with toxic substances are updated every 2 years within the ATSDR (Agency for Toxic Substances and Disease Registry) for impacts on human health (i.e., hazard x exposure). Within this ATSDR the ranking of solar panel leachates are high: arsenic is ranked hazard No. 1, then No. 2 (lead), No. 3 (mercury), No. 7 (cadmium), No. 17 (chromium), No.57 (nickel), No. 74 (zinc), No. 104 (thorium), No. 120 (copper), and No. 127 (strontium). Just below this on the list are manganese, fluoranthene, selenium, a range of per- and poly-fluoroalkyls, aluminium and silver. Essentially, at solar farms many substances that present a significant risk to human health and the health of ecosystems are washed off solar technologies into the environment.

A quick perusal of the table 14 above shows all components of solar technologies present serious risks to aquatic ecosystems (HSNO classifications are mainly 9.1A or 9.1B), and most are toxic to soil organisms (HSNO classifications are mainly 9.2B). Also of note are oral toxicities, and effects on target organs. The oral toxicities are not acute (i.e., hazard class 6.1A or 6.1B where a material ingested as a single dose may be lethal within 24-48 hours) but have classifications that range from 6.1C to 6.1E (i.e., they only become toxic when consumed in small, divided amounts as a chronic or sub-chronic poison). The potent rat poison (brodifacoum) is listed in the same way (6.1E), but it will readily kill all rats when it is ingested as a chronic poison over 3 days. Just like brodifacoum in the rat poison, what makes these materials toxic is they have a long half-life and readily bind to tissue where blood is filtered (viz. the liver, kidney, placenta, cardiopulmonary system, and brain), and they bioaccumulate over many months until they have serious effects on target organs (HSNO classifications are mainly 6.9A and 6.9B). Birds, rodents, cats, and aquatic organisms around solar farms may eventually find themselves feeding on contaminated vegetation, contaminated berries, contaminated seeds, contaminated earthworms, or contaminated rodents that affect breeding or debilitate their health (HSNO=9.3A or 9.3B). We also get tertiary poisoning because raptors (owls, hawks, falcons) feed on sub-lethally poisoned mice, rats, and small birds, and these raptors then bioaccumulate toxic levels of heavy metal and PFAS compounds. Offshore, there are serious concerns about the impacts of heavy metals and PFAS substances on birds (Richard *et al*. 2021), and in particular kestrels, owls, hawks, and falcon (e.g., Scheuhammer 1987, Monclus *et al*. 2020). For this reason, heavy metals and PFAS have a HSNO classification of 9.3A or 9.3B for terrestrial vertebrates.

In aquatic environments a similar phenomenon is observed with aquatic plants (e.g., plankton, algae, watercress) bioaccumulating heavy metals and PFAS, which are fed on by invertebrates, that are then eaten by small fish, that are then eaten by large fish (Ali *et al.* 2019). At each trophic level the metals and PFAS bioaccumulate until they eventually become lethal. For humans feeding on contaminated fish this creates increased risks of cancer, liver disease, nephritis, and neurological disorders (Panda *et al*. 2023). In the USA and China freshwater fish are now so contaminated with PFAS and heavy metals that many authorities recommend people not consume them (e.g., Barbo *et al.* 2022, Ai *et al.* 2022).

At Brookside the run-off of flood waters containing contaminants are likely to impact streams and Lake Ellesmere over the 45-year period of the consent for the solar farm. Leachates from solar panels, leachates from batteries, and leachates from other ancillary equipment not only change soils, but the composition of plant communities growing on those contaminated soils. If widescale use was made of the panels currently located at Buckleys Road, then at the very least in the long-term the iron and aluminium released from panels would further exacerbate compaction of topsoil (Mazurana *et al*. 2017, ADAS 2023), result in the development of an iron pan above subsoil (Cunningham *et al.* 2001), the heavy metals deposited on soils would collectively impact the abundance of soil microorganisms (Zhang *et al.* 2023, Jarosławiecka *et al.* 2022), and panels would change the composition of plant communities. The outcomes of this after 9.5 years are already apparent with the loss of clovers growing in and around solar panels at Buckleys Road.

Unbelievably, proponents of solar farms have become indoctrinated with a belief that this is all "clean and green", because that is a message that has been repeated to them over-and-over again.

It is poignant to state here that solar farms have been banned on agricultural land in Italy and Cyprus from May 2024, and are in the throes of being banned on productive lands in the Netherlands.

Clearly, in New Zealand there is a complete lack of oversight about where and how solar farms should be sited, suggesting that this activity needs to be better researched, and better regulated.

The economics of USSP solar power
China has a policy to invest in electricity wherever possible (*see* Asher 2020) because this provides leverage for foreign direct investment by the 'Chinese Communist Party' (CCP) in other ventures. For example, in Mozambique the CCP funded 3 high dams on the Zambezi for household electricity; then with the obligations imposed on locals they took control of tens of thousands of hectares of very fertile land along the Zambezi, each year they take a mountain of food resources from what is regarded as the "fruitbowl of Africa", they have control of "blood timber" that is illegally harvested from indigenous forests by militant groups of Muslims, as well as approvals to take tonnes of mineral resources that they require for industries in China. Unsurprisingly, most of the utility scale solar farms being established throughout New Zealand are funded by Chinese investors. So, just as foreign investment in banks has created huge deficits (Fig. 15), and drained the New Zealand economy of $6-8 billion annually or $58.5 billion over the 12 years preceding 2024, so foreign investment in USSP electricity may eventually drain New Zealand of around $2-3 billion annually with proceeds mainly going to China.

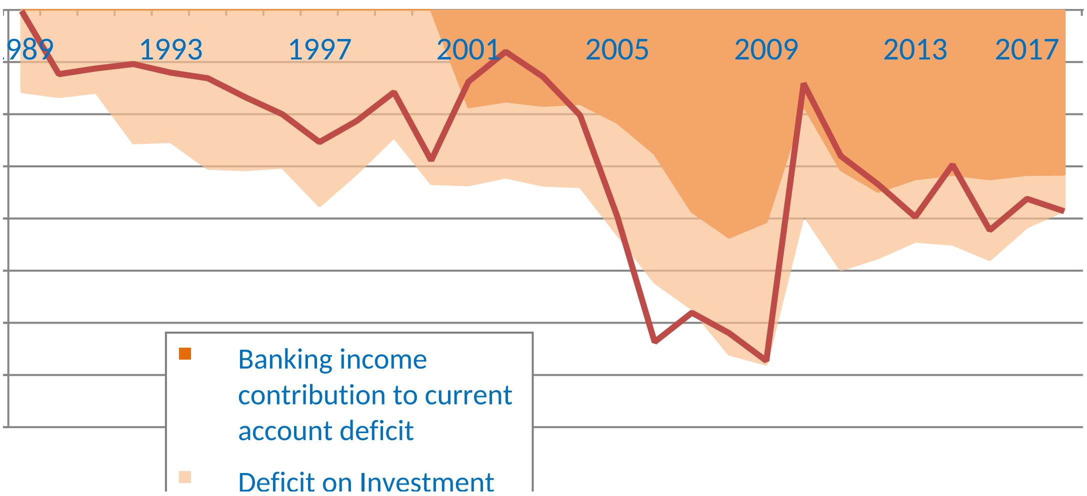


Figure 15. **Banking deficits as a percentage of the current account deficit following privatisation and asset sales.**

As a party that opposed a planned solar farm at Brookside, I sat down and did the calculations; it was estimated that this one solar farm would siphon around $1.2 billion out of the pockets of power consumers into offshore bank accounts during the life of the solar farm (45 years) at 30c per unit. Of course it could be considerably more once China has leveraged the spot-price for electricity to optimize returns on investment. It's yet another of those schemes that will not only take billions out of the New Zealand economy, but further put the nation into a situation where the arm of 'Kiwis' forced up their backs until they sublimate to China's whims. Does this all sound a little cynical? They have taken control of around $25 billion of assets already (farms, forestry, several dozen vineyards, wineries, milk processing factories, fruit processing, meat processing factories, tourist hotels, water bottling, etc). Diplomacy requires public servants and politicians say nothing in case meat, butter, milk powder, fruit, and horticultural produce sits on a wharf in China and is not paid for. With John Key and Jacinda Adern at the helm the China got whatever it asked for with no questions asked, and no complaints were voiced. The construction of solar farms is likely to give a Chinese investor a return of 15% on investment at todays prices for grid electricity, but with power predicted to be 45c a unit by 2030, then their return on investment will climb to 21% *per annum* in 6-years time.

There is a very good report published by Saul Griffith (2024) on use of rooftop solar energy compared to USSP power from the grid. He modelled what could be achieved in New Zealand with government subsidies for rooftop electricity compared to grid electricity. Because the cost of installing rooftop power has dropped from 50c per watt (2014) to just 20c per watt (2022) with batteries included (Fig. 16), it makes sense for the government to subsidize the installation of solar panels on homes. This has been done in Australia where around 37% of all new homes now have rooftop electricity. If a similar policy was introduced in New Zealand, this would result in considerable savings. He estimates the costs of rooftop solar in the long-term at 10c per kw/hr (viz. for household lighting, appliances, and energy used to charge an electric vehicle) compared to electricity out of the grid from USSP facilities at 50c per unit by 2040. The national savings if this was widely accepted would amount to around $10.7 billion annually or around $95 billion in total by 2040 (Fig. 17). Not included in these costings are likely payments for international sourced carbon credits of around $1 billion *per annum* currently and anywhere between $12-23 billion by 2030 for carbon emmissions (i.e., New Zealand has committed to this under the Paris Agreement to reduce net greenhouse gas emissions in 2030 to 50 per cent below gross emission levels in 2005, if we don't then we must pay for carbon credits). To me rooftop electricity is a no-brainer that should be implemented immediately.

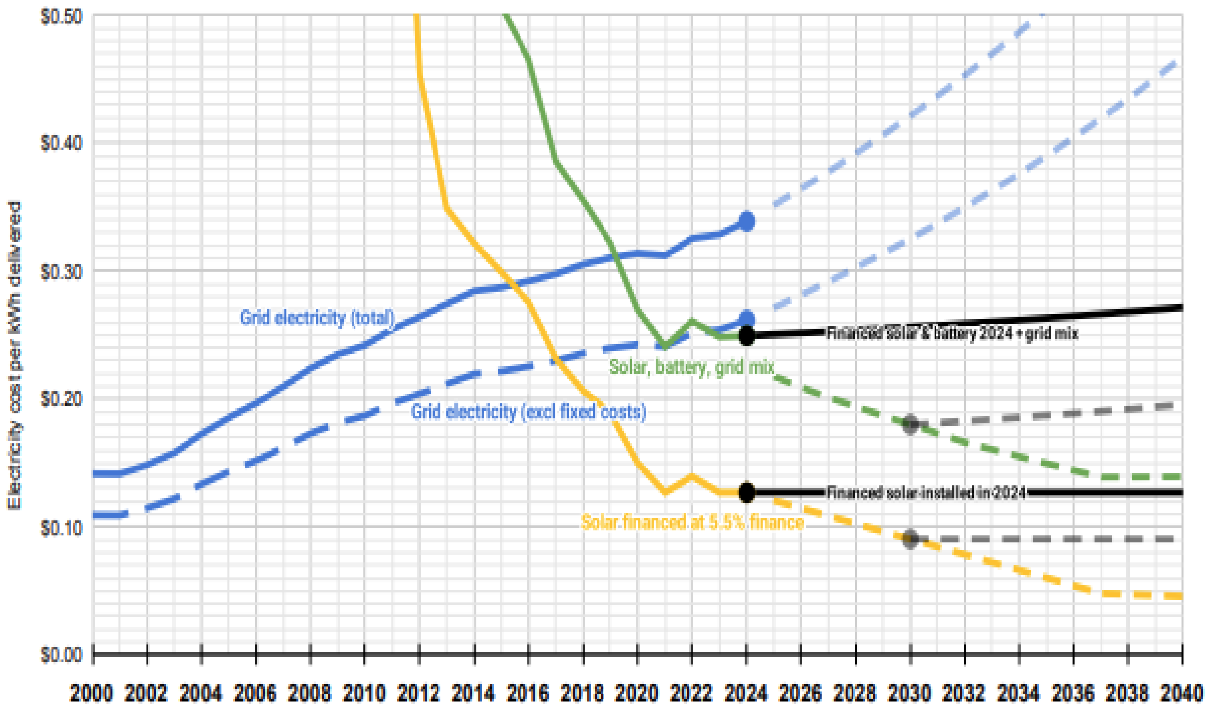


Figure 16. **Projected costs of electricity put into the grid by USSP solar farms (blue lines) and the costs of electricity from rooftop solar panels (yellow lines).**

The national savings from a government subsidised rooftop scheme are shown below (Fig. 17).

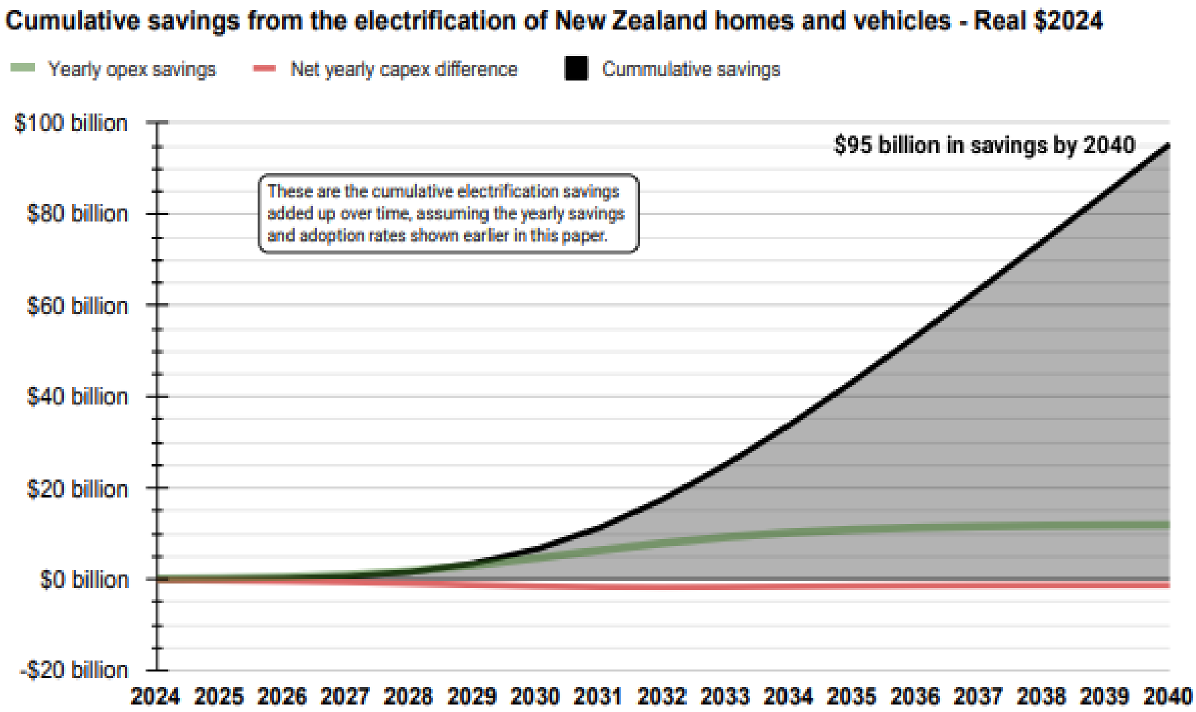


Figure 17. **Cumulative savings arising from the installation of rooftop solar panels (Gilbert et al. 2024).**

If we take the protocol for installing roof-top solar energy in Australia and then compare it to the grid electricity from the consented solar farm at Brookside (as an example), then the differences in costs to the householder and nation are shown below. There are some high up-front costs for rooftop solar, but long-term the dividends are huge.

Table 51. Comparison of the cost-efficiency of roof-top solar and solar farm energy for 11,000 homes over a 45-year period.

	Rooftop solar		USSP solar farm energy from the grid	
	Govt cost	Household cost for 11,000 homes	National cost	Household cost (45 yrs)
Government subsidy @ $15,000 per home for 11,000 houses (interest free)	$165 million		0	
Opportunity cost of lost interest at 4% over 10 years	$66 million			
Repayment of loan over 10 years	-$165 mill	$165 million		
Balance of 27k installation cost still owed by households		$110 million		
Cost of maintaining rooftop solar electricity over 45yrs		$71.5 million	Orion= $15 million for line + substation upgrades	
Total + admin over 45 years for electricity (11,000 homes)	$80 mill	$346.5 mill $31,500/house	$1.2 billion added to C/A deficit as exported capital by foreign investors	$1,525 million for 11,000 homes
Cost of electricity (6,000 units for house + 1000 units for car each day)		10c per unit		44c per unit average
Cost of lost farm revenue ($12,000/ha) as export earnings			$1.32 mill/annum $59.4 mill - 45 yr	
Annual costs (mean) for a house		$700		$3,080 for 2024
Electricity costs (45 years)		$31,500		$138,600
Energy cost car (petrol=$3,200/yr) over 45 years with 1 car per household		$0 (incl above)	Carbn=1,237,500 t $74 million for carbon credits	$144,000
Total costs	$80 million	**$31,500/house**	**$1.35 billion**	**$282,600/ house**

Note: 1 litre petrol produces 2.3 kg CO_2, so a car produces 2.5 tonne carbon/yr or 112.5 tonne over 45 years

Not only are USSP facilities an order of magnitude less cost-effective than rooftop solar, but the many undesirable facets of renewable energy from solar farms cast a long shadow over their use as a form of electricity production in New Zealand. In China where solar power has been extensively used for some time, heavy metals and polyfluoroalkylyls (PFAS) that comprise the bulk of the ‘forever chemicals’ leached from solar technologies have increasingly entered surface and ground water, contaminated soils and plants growing in those soils, as well as meat and milk from farm animals with deleterious effects on the health of humans (Parvez *et al.* 2022) and wider ecosystems.

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