

Residual Contamination Risks from Solar PV Farms in Agricultural Soil

Executive Findings

Evidence Strength: Overall, there is **weak to moderate evidence** that utility-scale solar installations leave residual chemical contaminants in soil that could significantly enter food crops. Under **normal operations** with intact crystalline-silicon (c-Si) panels, studies find no significant increases in lead (Pb) or cadmium (Cd) in nearby soils ¹ ². Most measured metal concentrations under operating solar arrays remain below regulatory concern levels ². *However*, measurable changes in certain trace elements (e.g. selenium, lithium, nickel) have been observed beneath panels ³ ⁴. Under **abnormal events** like large-scale panel breakage, wildfire, or improper disposal, there is a plausible risk of localized contamination – especially from thin-film modules containing Cd or other toxic elements – but field evidence so far indicates **few if any cases** where post-event soil contaminant levels exceeded health or crop safety thresholds ⁵ ⁶. In short, **normal solar farm operation has not been shown to harm crop yields or safety**, and even in worst-case accidents the available evidence points to minimal lasting soil contamination if debris is promptly cleaned up.

Limits and Differentiation: Crystalline-silicon PV (the majority of installations) contain small amounts of Pb (solder) and other metals, but these are encapsulated and largely immobile during use ⁶. Thin-film modules (CdTe, CIGS, a-Si) contain more inherently toxic elements (Cd, Se, etc.), yet cadmium telluride in panels is a chemically stable compound that is ~100× less toxic than free cadmium and remains >99.9% encapsulated even in extreme fire conditions ⁷. Thus under normal conditions, both c-Si and thin-film modules pose *little immediate contamination risk*. The key distinction is that **thin-film panels, if shattered or burned, have higher potential to release hazardous metals (cadmium, selenium, etc.)** than c-Si panels do. Similarly, abnormal events (hailstorms, fires, tornadoes scattering debris, or improper decommissioning practices) present higher risk of soil contamination than routine operations. Even then, documented cases (hail damage in Texas, etc.) have not found substantial soil contaminant uptake by crops or groundwater pollution ⁵. The evidence to date suggests that with proper management – including debris removal, site cleanup, and monitoring – former solar sites can be returned to agriculture **without significant impact on crop yield or food safety**. Nonetheless, continued monitoring and research are warranted, especially for thin-film installations and under extreme damage scenarios.

Contaminants, Pathways, and Persistence After Solar Farm Removal

After decommissioning a solar farm (i.e. removal of panels, racks, and equipment), the **most plausible residual contaminants** in soil are trace metals associated with PV module materials and balance-of-system

components, along with any chemicals from operational spills or firefighting. Key contaminants and their pathways include:

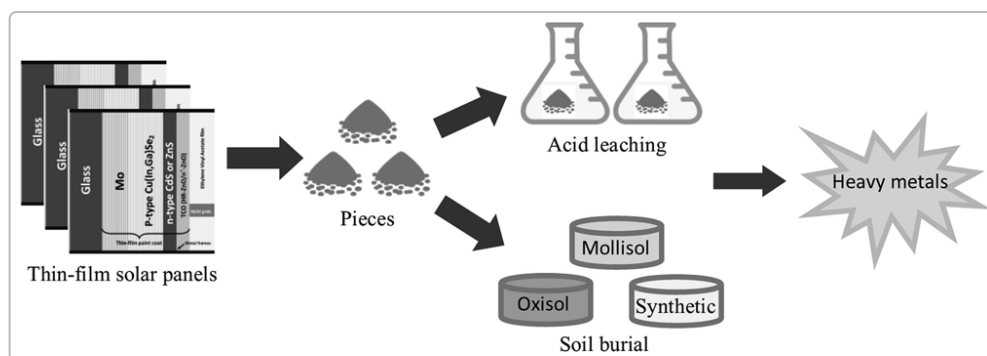
- **Lead (Pb):** Used in solder (panel cell interconnects, junction boxes) and historically present in some galvanizing or cable insulation. Pb can enter soil if panel fragments with solder are left behind or if lead-containing components corrode over decades. Pathway: weathering and corrosion of solder or leaded coatings, particularly in acidic soil or if water infiltrates cracked panels ⁸. Lead strongly binds to soil particles and tends to remain in topsoil near the source.
- **Cadmium (Cd):** Present in **CdTe thin-film** module semiconductor layers and as a minor impurity in some c-Si panel components (e.g. trace Cd in solder or pigments). Cd can be released if CdTe panels are broken, burned, or improperly discarded. Pathways: glass breakage that exposes CdTe to weather (allowing leaching of Cd compounds), or ash deposition after a fire. Research shows intact CdTe panels leach negligible Cd, but physical damage can create leaching pathways ⁹ ¹⁰. Cadmium can persist in soil as adsorbed ions or precipitated compounds; it does not readily biodegrade.
- **Selenium (Se):** Found in **CIGS (Cu-In-Ga-Se) thin-film** modules and sometimes used as a dopant or coating. Selenium can leach from broken CIS/CIGS panels or possibly from weathering of certain module coatings ¹¹ ¹². Selenium can exist in soluble forms in alkaline soils, making it somewhat mobile. Notably, one field study detected ~0.3 µg/g (~0.3 mg/kg) higher Se in soil near CIS panels compared to background ¹³, and another found Se nearly doubled under c-Si arrays (source hypothesized to be construction materials) ³.
- **Antimony (Sb) and Tin (Sn):** Antimony is used as a fining agent in solar glass (Sb₂O₃) and may be present in cell solder (as Sb-Sn alloys). Tin is in solder (Sn-Pb or Sn-Ag-Cu). If panel glass shards remain, Sb can slowly leach; one long-term PV site showed moderate antimony buildup in soil attributable to panel materials ¹⁴. Both Sb and Sn typically form low-solubility oxides; they tend to sorb to soils, so they persist but with limited mobility or bioavailability.
- **Indium (In) and Gallium (Ga):** These “*technology-critical elements*” are in CIGS thin-films (and indium tin oxide coatings). Indium and Ga were found at elevated but *moderate* levels in soils near an older PV farm in Poland, likely from panel material degradation over time ¹⁵. These metals can enter soil via tiny flakes of semiconductor material or electrode coatings from broken panels. They persist in topsoil (Indium as oxides/hydroxides). Limited data exist on their soil mobility.
- **Chromium (Cr), Nickel (Ni), Zinc (Zn), Copper (Cu):** Common in **balance-of-system hardware** – e.g. galvanized steel (Zn), stainless steel bolts (Cr, Ni), copper wiring and grounding rods. Weathering of galvanized racks can deposit zinc (and minor Pb) into soils over decades; steel hardware can release Cr/Ni if coatings degrade. A U.S. study found Ni and Zn concentrations slightly *lower* under panels than outside (possibly because dust deposition elsewhere) ¹⁶, but another study noted Zn and Cu enrichments correlated with adding panel scraps to soil ¹⁷ ¹⁸. Typically, Zn and Cu from galvanization and wiring are not expected to exceed natural background by much, except possibly right at metal contact points (e.g. around pole mounts). They persist as metal oxides or carbonates in soil, and are micronutrients at low levels but toxic to plants at high concentrations.

- **Arsenic (As):** Not usually in modern panels except trace in some alloys, but some early thin-films (e.g. GaAs cells) or certain diode materials contain arsenic. As is also a common impurity in galvanized coatings and solder. While not a primary concern for most PV farms, any arsenic present could leach from corroding metal or burned components. The Heliyon 2024 study included As in its monitoring suite ¹⁹, but did not highlight any concerning increases (meaning As remained near background).
- **Silver (Ag):** Used in c-Si cell metallization (silver paste) and contacts. Total silver content per panel is small, and elemental Ag is not highly soluble. Minimal research exists on Ag release from panels. If released (e.g. from burned silver paste), Ag would likely precipitate as silver chloride or bind to organic matter, with low bioavailability.
- **Polymer microdebris:** PV modules contain polymer encapsulants (EVA or polyolefin) and backsheets (often PET or PVF fluoropolymer). Over decades, backsheets can chalk or crack, shedding flakes. Cable insulation and plastic zip-ties can also leave fragments. These **microplastics** persist in soil. They do *not* constitute chemical contamination per se, but research shows that very small micro/nanoplastic particles can be taken up by plant roots in lab settings ²⁰. In an agricultural context, there is *currently no evidence* that panel-derived microplastic fragments significantly enter plant tissues or affect crop safety. Nonetheless, these physical residues remain in soil unless physically removed, and are an **emerging concern** for soil health (they could alter soil structure or carry other pollutants).
- **Herbicide residues:** Many solar farms use herbicides for vegetation management (e.g. glyphosate or pre-emergent herbicides). Most commonly used herbicides (glyphosate, 2,4-D, etc.) degrade within weeks to months in soil and are unlikely to persist post-decommissioning at harmful levels. However, if long-residual herbicides (e.g. soil sterilants or certain persistent broadleaf herbicides) were used improperly, their residues could affect subsequent crops. To date, no publications specifically link herbicide carryover from solar sites to crop issues – but standard practice is to allow time for degradation and to test soil if persistent herbicides were applied.
- **Hydrocarbons and dielectric fluids:** Construction and operations can introduce petroleum products – e.g. diesel fuel and oil spills from heavy machinery, leaks from transformers (which typically contain mineral oil or newer biodegradable ester fluids). Small drips likely biodegrade naturally; larger spills (if any) would be remediated during operation. Modern solar farms *do not use PCB-containing* transformer oils (PCBs were banned in the 1970s), so PCB contamination is only a concern if very old electrical equipment was present (unlikely in utility PV). If a transformer fire or leak occurred, soils could have residual oil or combustion byproducts (polycyclic aromatic hydrocarbons, PAHs). These tend to bind strongly to soil organic matter and are not readily taken up by plants, but could persist and require removal of stained soil. Documented incidents of significant oil/chemical spills at solar farms are rare or absent in literature.
- **Firefighting chemicals (PFAS):** In the event of an electrical fire (especially battery energy storage or inverter fires), **aqueous film-forming foams (AFFF)** might be used by firefighters. Older AFFFs contain PFAS (per- and polyfluoroalkyl substances) which are *highly persistent* in soil and water. PFAS chemicals (like PFOS, PFHxS, etc.) can remain in soil for decades and *can be taken up by crops* to some extent, particularly leafy greens and root vegetables, posing potential food safety risks. While we found no publicly reported cases of PFAS contamination from solar farm fires, this pathway is

plausible if firefighting foams were applied. Any site that had a foam-suppressed fire should be tested for PFAS, given their persistence and very low regulatory thresholds (often in the parts-per-trillion in water, and low parts-per-billion in soil for some states).

In summary, **heavy metals** (notably Cd, Pb, Se, In, Ga, Sb, Cr, Ni, Zn, Cu) are the primary contaminants of concern potentially remaining in soil after a solar facility is removed. They enter soil through panel material degradation (especially if broken or burned), corrosion of metal components, and accidental releases. These metals will persist indefinitely unless removed, but their mobility and bioavailability depend on soil chemistry (discussed below). **Organic chemicals** (herbicides, oils) may also be present but are generally degradable or can be mitigated with cleanup; persistent organics like PFAS could remain if introduced, though that scenario is uncommon in PV farms. **Physical residues** like microplastics exist but have uncertain impact on crop uptake at this time.

Figure: Pathways for heavy metal release from thin-film solar panel debris. In laboratory simulations, acidic conditions and long contact times accelerate leaching of Zn, Cu, Ni, Ga, Pb, In, and Cr from shredded thin-film panels buried in soil ¹⁷ ¹⁸. Field conditions are less extreme, but any residual panel fragments left in soil can slowly weather and release metals over time. ²¹ ²²



Source: Su et al., Applied Geochemistry (2019) – simulation of thin-film panel pieces leaching heavy metals under acid and soil burial conditions.

Bioavailability and Plant Uptake of Key Contaminants

For each contaminant of concern, we examine how readily it can move into plants (especially edible parts like roots, tubers, leafy greens, and grains) and whether residual levels could pose food safety or yield risks. Bioavailability is influenced by the chemical form of the contaminant in soil and by plant physiology. Below we summarize the best evidence for plant uptake of the main solar-related contaminants:

- **Lead (Pb):** Lead in soil strongly binds to clays and organic matter, usually forming insoluble compounds (e.g. lead phosphates, carbonates). Consequently, plant uptake of Pb is very low – most lead stays in roots or the immediate root surface and does *not* translocate to shoots or tubers in significant quantities ²³. Edible portions of crops typically have lead concentrations orders of magnitude lower than the soil's, unless soil particles themselves adhere to the crop (e.g. dust on leafy vegetables or unwashed root crops). For example, studies have shown that even in moderately Pb-contaminated soils (~50–100 mg/kg), washed vegetables often remain below food safety limits for Pb. The primary risk of soil Pb is direct ingestion of soil or dust (a human health pathway) more

so than plant uptake. Thus, if small amounts of lead from solder or galvanizing remain in soil (say a few mg/kg, comparable to background), they are unlikely to affect crop growth or lead content of produce. Only if soil Pb were extremely high (hundreds of mg/kg) would crops like leafy greens uptake enough to approach regulatory limits, and such high levels have not been observed from solar farms. **Confidence:** High that solar-derived Pb will not enter crops at levels of concern, given lead's low bioavailability and the low concentrations measured (often <10 mg/kg, which is background ²⁴).

- **Cadmium (Cd):** Cadmium is more mobile and bioavailable than lead. It does not strongly bind to soil (especially in low organic matter or acidic soils) and is readily taken up by many plants. Crops such as leafy greens, lettuce, spinach, and some root crops (carrots, potatoes, beets) are known to accumulate Cd more readily ²⁵. Importantly, Cd can accumulate in edible tubers and grains without obvious phytotoxicity, meaning the crop won't show yield loss even as Cd enters the food chain. For instance, wheat grown in Idaho with soil Cd ~1 mg/kg can have grain Cd in the 0.05–0.2 mg/kg range ^{26 27}, which is significant for food standards. Cadmium uptake is strongly influenced by soil **pH** (acidic soils make Cd more available), **zinc levels** (Zn competes with Cd uptake; high Zn can suppress Cd uptake to a degree), and **organic matter** (which can bind Cd and reduce uptake). If a solar site left Cd fragments, the worst-case is a thin-film CdTe panel break releasing soluble Cd compounds. Lab tests show that under very acidic conditions (pH ~2.9 acetic acid in TCLP), some Cd can leach from panels ^{28 29}, but under normal soil pH (~5.5–7) cadmium telluride dissolves slowly ¹⁰. Field evidence: even where Cd increases were noted (e.g. an agrivoltaic fence trial saw soil Cd rise from 0.47 to 1.55 mg/kg in one year ³⁰), the *absolute* Cd levels remained low and largely below plant toxicity thresholds. At ~1–2 mg/kg soil Cd, sensitive crops like leafy greens might accumulate ~0.1 mg/kg Cd in edible tissue – near some food guidance limits – but robust field data on post-solar sites is lacking. In practice, background Cd in agricultural soils (often 0.1–1 mg/kg in the U.S.) and existing fertilizer-derived Cd often dominate plant uptake outcomes ³¹. **Confidence:** Moderate that solar-related Cd has low impact on crops under neutral to alkaline soil conditions (common in western US), but higher in acidic soils or if thin-film panels shattered without cleanup. Continual monitoring is warranted if Cd-containing panels were used, since plants *will* uptake any bioavailable Cd over time, potentially inching toward food marketability limits (the EU, for example, sets very low Cd limits for certain foods).

- **Selenium (Se):** Selenium can be an essential micronutrient or a toxin at higher levels. It is fairly mobile in well-oxidized, alkaline soils (often forming soluble selenate), and certain plants (e.g. brassicas, and accumulator species like *Astragalus*) uptake Se readily. If Se from CIGS panels or other sources enters soil, it could be taken up into crops. Evidence: the Buffalo, NY solar array study found Se in soil under panels (~0.48 mg/kg) was approaching the EPA's conservative ecological threshold (0.52 mg/kg for plants) ³². They noted that even this low level “approaches a level of concern for local plants and wildlife” ³³. Selenium uptake into plants (especially if soils are alkaline, as Se is more available then) could lead to elevated Se in forage or vegetables. Unlike Cd, however, small increases in Se might not be negative – since many soils (and diets) are selenium-deficient, added Se can be beneficial up to a point. Toxicity to plants or livestock occurs only if Se is quite high (several mg/kg in soil with bioavailable forms). The sources of Se under c-Si panels are unclear (c-Si modules themselves don't contain much Se ³⁴), so it might come from construction materials (e.g. concrete additives or dust) or minor components. Regardless, **plants will uptake selenium in proportion to its soluble presence**. For example, in high-Se soils of the western US, crops like wheat can accumulate >1 mg/kg Se in grain. At solar farms studied so far, soil Se changes are small (fractions of

a mg/kg)³, implying a minimal effect on crops (perhaps a few tens of µg/kg increase in tissue levels). **Confidence:** Moderate that Se from solar sites is bioavailable (as indicated by ecological screening concerns³²), but current evidence suggests levels are too low to cause food safety issues. Site-specific factors (soil pH, redox) will govern Se uptake heavily.

- **Chromium (Cr) and Nickel (Ni):** These typically originate from stainless steel components. Chromium in soil usually exists as Cr(III), an insoluble and non-plant-available form, unless very high oxidation conditions create Cr(VI) (rare in soils naturally). Nickel is moderately available; plants need trace Ni, but at higher concentrations Ni can be taken up and cause toxicity (e.g. some Ni hyperaccumulator plants exist, but common crops usually do not accumulate Ni strongly). Evidence around solar farms: slight increases in Ni (37% higher under panels, though still well below risk levels) were observed in one study³⁵. No plant uptake data from solar-specific contexts is available, but agronomic knowledge suggests that at the low part-per-million levels likely present, Ni uptake would not approach food safety limits. For example, if soil Ni rose from 10 to 14 mg/kg under a rack (a plausible small increase), a root crop might see negligible change in Ni content (maybe from 0.5 to 0.6 mg/kg dry weight). **Confidence:** High that Cr from solar infrastructure will not be bioavailable (stays as Cr(III) hydroxides), and moderate that Ni poses minimal uptake risk given low concentrations observed (and Ni's own phytotoxic threshold usually >50–100 mg/kg in soil).
- **Zinc (Zn) and Copper (Cu):** Both are essential plant nutrients, so plants have regulated uptake mechanisms for them. If solar equipment adds Zn or Cu (e.g. galvanization flakes or wire corrosion), plants will only take what they require until very high soil levels cause excessive uptake. Zinc in soil could increase near galvanized steel array posts – one report noted Zn enrichment in soils where thin-film panel pieces were buried¹⁸, and historically Indiana soils have background Zn ~50–100 mg/kg from natural and anthropogenic sources³⁶. Plants typically don't accumulate toxic levels of Zn unless soil Zn is extremely high (>200–300 mg/kg), which would also stunt the plant. Similarly, copper tends to bind to organic matter; only a small soluble fraction is taken up. Many agricultural soils receive Cu and Zn via fertilizers and manures, so slight additions from solar site materials would likely be within normal variability. **Confidence:** High that any Zn/Cu residues from solar farms will either be immobile (if in metallic form) or taken up in only benign amounts (possibly even benefiting deficient soils). There is negligible evidence of Zn or Cu reaching harmful concentrations from PV installations – one study even saw *lower* Zn and Cu under panels than in control soil, possibly due to dust patterns¹⁶.
- **Indium (In) and Gallium (Ga):** These are not typical plant nutrients and little is known about their plant uptake. Indium chemically behaves somewhat like aluminum or zinc in soil – tending to form insoluble hydroxides – so one would *expect* low bioavailability. Gallium is similar. Because these elements are so rarely encountered in agriculture, plants haven't been studied for uptake; it's likely minimal. In the Polish PV farm study, In and Sb were found at “moderate” levels in soil (suggesting slight accumulation)¹⁴, but there was no indication this affected plants. Given their low concentrations (probably in the sub-mg/kg range) and strong soil binding, it's unlikely any Indium or Gallium from broken panels would enter edible plant parts measurably. **Confidence:** Low (due to lack of data) but leaning toward minimal risk.
- **Antimony (Sb):** Antimony in soil can exist as Sb(III) or Sb(V) compounds. It is analogous to arsenic in some ways, and plants can uptake antimony but generally at low rates. Studies have shown root crops can accumulate some Sb in contaminated soils, but typical environmental levels are low. If

antimony from panel glass is present, it likely occurs as insoluble oxides. Without specific data, one can infer that Sb uptake into crops would be very small unless soil Sb was greatly elevated (e.g. near mining or shooting range sites). No solar-specific plant uptake studies exist for Sb, but given the moderate soil Sb noted near PV sites ¹⁴ and its known toxicity, it's worth monitoring. **Confidence:** Low (limited evidence), but any Sb increase from a solar site is probably too small to significantly enter crops.

- **Silver (Ag):** Silver can be taken up by plants in ionic form (Ag^+), but silver quickly forms insoluble AgCl or binds to sulfur in soil, limiting availability. Some studies on nanoparticle silver show it can be absorbed by plant roots, but this is a nascent research area. In an agricultural context, silver is not commonly monitored because background levels are very low and no food standard exists (silver is not highly toxic to humans in the amounts from crops). The small amount of silver in PV cells (a few grams per panel, mostly locked in glass) means soil additions would be trace. Thus, it is highly unlikely for any silver from panels to significantly transfer to plants. **Confidence:** High that Ag is a non-issue for plant uptake at solar sites.
- **Polymer microplastics:** If present, these are *physically* taken up only if very small (<100 microns). Recent studies show nanoplastics can enter root systems ²⁰, but it's not confirmed for larger microplastic fragments in field conditions. Edible portions of crops could in theory have microplastic specks lodged in tissues or on the surface, but distinguishing those from ubiquitous environmental microplastics is hard. At this time, regulatory bodies do not have limits for microplastics in food (though it's a topic of active research). For solar sites, the main concern would be soil quality (microplastics potentially affecting water retention or soil biota) rather than direct uptake into the edible parts of plants. **Confidence:** Moderate that microplastic fragments will remain in soil but low that they enter plant tissue in meaningful amounts.

In summary, **cadmium stands out as the contaminant with the greatest plant uptake potential** relative to typical concentrations, especially for root and leafy crops on acidic soils. **Lead is of least concern for crop uptake** (more a human soil ingestion hazard). **Selenium** can be taken up and is notable if thin-film Se was used, but likely still low levels. Other metals (Zn, Cu, Ni, etc.) would have to accumulate to much higher-than-observed levels to significantly affect edible plant content. It's also worth noting that normal farming itself introduces some of these metals – for example, phosphate fertilizers add cadmium and arsenic to soil annually, manure can add copper and zinc, and irrigation water can contribute selenium in areas like Idaho's Snake River Plain. These background agricultural inputs often exceed what a solar facility would leave behind, making it tricky to attribute any plant heavy metal content solely to a prior solar use.

Soil Conditions and Crop Factors Affecting Uptake

Whether residual contaminants actually enter crops at concerning levels depends greatly on **soil conditions** and **crop species**. Key factors include:

- **Soil pH:** This is perhaps the most critical factor. Acidic soils (low pH) increase the solubility of many metals (Cd, Pb, Zn, Ni), making them more bioavailable. For instance, at pH 5.5, cadmium can be 100× more available to plants than at pH 7.5. Lead also becomes slightly more soluble at very low pH, though it mostly stays insoluble regardless. Selenium is an exception – in very **alkaline** soils, selenate forms are more available. **Implication:** A solar site on acidic soil (pH <6) that leaves behind

metals would pose a higher crop uptake risk than one on neutral or calcareous soil. Managing pH (lime to raise pH) is a known strategy to immobilize metals ³⁷ .

- **Organic Matter (OM):** Soils rich in organic matter tend to bind heavy metals tightly through complexation with humic substances. Higher OM generally reduces plant uptake of metals like Pb, Cd, and Cu by sequestering them in stable forms. Also, OM supports microbial activity that can transform metals to less soluble forms. In contrast, a low-OM sandy soil has fewer binding sites, so metals remain in soil solution and available to plants. Many Idaho agricultural soils have moderate OM (2–3% in topsoil), which helps mitigate metal uptake to an extent. Building OM (through cover cropping or compost) can therefore decrease bioavailability of residual contaminants.
- **Cation Exchange Capacity (CEC) and Texture:** Clayey soils with high CEC can adsorb and hold cationic metals (Pb^{2+} , Cd^{2+} , etc.), preventing them from leaching or being taken up. Sandy soils with low CEC allow metals to stay in pore water (and potentially leach down or be taken by roots). A high CEC soil (due to clays or organic matter) is protective against metal uptake. Many ag soils in arid regions (like parts of Idaho) have decent CEC due to clay-loam textures or added amendments, but coarse sands would be more vulnerable. Additionally, clay soils may “fix” selenium by adsorption, whereas sandy soils let selenium remain soluble.
- **Soil Redox and Drainage:** Waterlogged or reduced (anaerobic) soil conditions can change contaminant chemistry. For example, under flooded conditions (as in rice paddies), selenium and arsenic can be converted to more plant-available forms (selenite, arsenite), whereas chromium (VI) may be reduced to the less available Cr(III). If a solar farm site is intended for rice or flooded crop use post-removal, one should consider that any selenium or arsenic present could become more available. Typically, solar farms are on well-drained sites, so this is a niche scenario.
- **Crop Species and Varieties:** Different crops accumulate contaminants at different rates. **Leafy vegetables** (lettuce, spinach, kale) often show higher cadmium concentrations than grains grown in the same soil, because they have higher transpiration rates and different root uptake mechanisms (and no dilution into a large fruit or tuber). **Root and tuber crops** (potatoes, beets, carrots) can accumulate metals like Cd, Pb, and As in the peel or outer tissues; for instance, studies find higher Pb in potato skins than flesh ³⁸ , and carrots readily take up cadmium and lead into their roots. **Grains** (wheat, corn) typically have lower concentrations in the edible grain, but can still accumulate certain elements (wheat is known to accumulate Cd in grain at ~0.05–0.2 mg/kg in some Idaho fields ³¹). **Brassica family** crops (cabbage, canola) tend to accumulate selenium and can also take up metals; some are even used in phytoremediation (e.g. Indian mustard for lead, though effectiveness is limited). Among varieties, there can be differences: e.g., low-Cd wheat cultivars are planted in high-Cd areas to ensure grain stays within food limits ³⁹ . So, if a site has mild contamination, choosing crop varieties known to exclude heavy metals can mitigate risk. For Idaho specifically, **potatoes** and **sugar beets** are important – potatoes can accumulate Cd and As (usually in peel), and beets can accumulate heavy metals in the fleshy root. These tubers have high soil contact, so they're prone to surface deposition as well as uptake. Fortunately, typical background levels in Idaho soils (Cd ~0.5–1 mg/kg) have not prevented potatoes or grains from meeting food standards ³¹ ⁴⁰ , and any incremental increase from a solar installation would likely be masked by natural variation and existing soil management.

- **Uptake kinetics and soil thresholds:** Many metals exhibit a threshold behavior in plants – below a certain soil concentration, the plant's uptake is minimal and plateaus (due to homeostasis or nutrient competition). For example, if soil Zn is in the normal range (20–50 mg/kg), adding 5 mg/kg more Zn might not change plant Zn much at all; but if soil Zn jumps to extremely high levels, plants might suffer toxicity before human consumption is a worry. Cadmium uptake is roughly linear at low concentrations (hence why food standards are concerned with even slight increases). Lead uptake is near zero until very high soil concentrations. Regulators often use **soil-plant transfer factors** (ratio of plant concentration to soil concentration) to estimate uptake; these factors vary by element and crop. For Cd in leafy veggies, a transfer factor could be 0.1–0.5 (meaning 1 mg/kg in soil yields 0.1–0.5 mg/kg in plant), whereas for Pb it's <0.01 in most edibles (nearly no transfer) ².

In essence, **acidic, sandy soils + leafy or root crops = higher potential uptake**, whereas **alkaline, clay/loam soils + fruiting crops (grain, corn, tomato, etc.) = lower uptake** of any given residual contaminant. Idaho's agricultural areas often have slightly alkaline to neutral soils and grow a mix of tubers (potatoes, sugar beets), forages, and grains. The alkaline calcareous soils in parts of Idaho can immobilize Cd and Pb effectively (forming carbonates), which *reduces uptake into potatoes* (one reason Idaho potatoes tend to have low Cd). On the other hand, if a solar farm were on peat or muck soil (very high organic) or a very low pH volcanic soil, the dynamics could differ – but such soils are less common for PV siting.

Field Measurements: Soil Contaminant Levels at Solar Sites

Several field studies and reports provide data on soil contaminant concentrations at solar PV sites, both during operation and after disturbances. Below we summarize key findings from real-world measurements, comparing them to typical background levels on farmland:

- **Crystalline-Silicon PV Array in New York (5 years old):** Robinson & Meindl (2019) sampled a 750 kW solar field on a university campus, collecting soil from directly under panels and at distances of 45 ft and 100 ft away as controls. They measured bioavailable metal concentrations via TCLP extraction. **Result:** No significant difference in **lead or cadmium** between beneath-panel soils and control soils ¹ ². Pb and Cd levels were very low (Pb ~0.1–0.2 mg/L in TCLP extract, corresponding to total Pb on order of 5–10 mg/kg; Cd TCLP was near detection, total Cd perhaps ~0.1 mg/kg) – far below risk thresholds ². However, **selenium** was ~97% higher under panels than 100 ft away (under-panel ~0.48 mg/kg vs ~0.24 mg/kg background) ³ ³². **Lithium** (from panel glass doping or other sources) was 386% higher under panels, **strontium** 86% higher, **nickel** 37% higher, and **barium** 61% higher ⁴¹. Despite these increases, the absolute concentrations of Li, Sr, Ni, Ba were well below EPA soil screening levels ³⁷. For instance, Ni under panels might have been on the order of 1–2 mg/kg vs ~1 mg/kg outside – negligible in regulatory context. The Se under panels (0.48 mg/kg) was near the EPA Eco-SSL plant toxicity benchmark (0.52 mg/kg) ³², suggesting the need to watch Se buildup. **Interpretation:** This c-Si site did not contaminate soil with Pb or Cd, but some **“emerging” elements (Se, Li, etc.) showed enrichment**, possibly from panel materials (selenium could leach from minor defects or nearby construction dust; Li may come from panel glass or grease). Even so, none exceeded regulatory limits ³⁷. This indicates normal operation of c-Si panels for ~5 years didn't create a heavy metal hazard in soil ².
- **“Fence-type” Agrivoltaic Systems in Korea (Heliyon 2024, Yousuf et al.):** This study monitored heavy metals in soils of fields partially bordered by vertical solar panels (used as fencing) over 1–2 years. They reported **notable fluctuations**: in one rice paddy, soil cadmium rose from 0.47 mg/kg to

1.55 mg/kg in a year ³⁰ . Meanwhile, copper and lead in that field actually *decreased* to “acceptable levels” by the second year ³⁰ (perhaps due to variability or different sample locations). Across all fields studied, they noted “notable increases in Cd levels merit attention” even though most metal concentrations remained below pollution standards ⁴² ⁴³ . Unfortunately, the study did not pinpoint the source of the Cd rise – possibilities include slight leaching from panel support structures or simply year-to-year variability (e.g. differences in fertilizer, flooding, or sample error). **Key point:** Cadmium did increase in proximity to these solar installations, approaching ~1.5 mg/kg. That level is still within typical background ranges for many ag soils (for reference, Idaho soils range ~0.45–1.85 mg/kg Cd naturally ⁴⁴), but the upward trend suggests that even encapsulated systems can lead to incremental soil Cd accumulation. No immediate crop hazard was reported, but it underlines the need for “continued surveillance” as the authors recommended ⁴² .

- **Legacy PV Installation in Poland (operating for ~15+ years):** A study of one of the oldest PV farms in Poland (Jabłońska-Czapla et al., 2025) compared soil samples near panels to regional background. They found **indium (In) and antimony (Sb)** were moderately elevated in the PV farm soils, attributed to long-term wear of panel materials ¹⁵ . Indium is used in CIGS or as transparent conductive oxide, and antimony in panel glass – their presence in soil is a fingerprint of panel material origin. By contrast, common heavy metals like Cd, Pb, Zn were *much higher* in the region due to other industries (mining/smelting) and did not appear elevated from the solar farm itself ¹⁴ . For example, soil Cd and Pb near the solar panels were dwarfed by regional contamination from mining activities ¹⁴ . **Implication:** Over ~two decades, the PV array contributed small increases in certain exotic elements (In, Sb), but not in the major toxic metals beyond background. This aligns with the notion that panel encapsulants prevent most heavy metal release, except perhaps trace leaching of minor constituents.
- **Soil under a .75 MW (750 kW) Array vs Adjacent Corn Field – Indiana (2023):** In Noble County, Indiana, an extension study compared heavy metals in soil from under a solar array (in place a few years) to a neighboring cornfield. Results showed **no significant difference:** total cadmium was 0.298 mg/kg under the solar array vs 0.271 mg/kg in the cornfield, and lead was 9.88 mg/kg (solar) vs 9.27 mg/kg (cornfield) ²⁴ . Both Cd and Pb values are very low – well below Indiana background ranges and “levels of concern” ³⁶ . The report concluded both fields’ heavy metal levels were typical of uncontaminated Indiana soils and “well below levels of concern”. This real-world test supports that modern solar farms do not inherently elevate soil heavy metals beyond normal variation.
- **Post-Decommissioning Sampling:** There is limited published data specifically from fully decommissioned (removed) solar farms. However, industry and extension sources recommend testing soil when solar farms are removed to ensure levels are safe for agriculture ⁴⁵ . One hypothetical worst-case example: if a thin-film CdTe farm was improperly decommissioned and small shards of Cd-containing glass were left, localized hotspots of Cd might be detectable. In practice, companies strive to remove all modules and visible debris. Any residual contamination tends to be diffused and low-level. For instance, if a few broken panel pieces escaped cleanup, soil directly under those might show slightly elevated Cd or Pb on a lab test, but averaging across a field it would likely be trivial. A rigorous post-removal sampling would involve a grid sampling; to our knowledge, such results have not been formally published (an opportunity for future research). The absence of reported “contaminated site” cases after solar decommissioning suggests that if any issues have arisen, they’ve been minor or handled quietly via cleanup.

- **Incident-Based Sampling (Damage Events):** There are a few instructive case reports from accidents:
- **Hailstorm in Fort Bend County, Texas (2024):** A severe hailstorm shattered thousands of panels (likely CdTe thin-film) at the 350 MW *Fighting Jays* solar farm. Neighbors and officials were concerned about Cd in soil and water. Emergency HAZMAT crews tested the area and “found no contamination” in initial screenings ⁵. The Texas state environmental agency (TCEQ) opened an investigation, but experts noted that even if some CdTe was exposed, the amount was small and CdTe is not water-soluble ¹⁰. This suggests that an acute smash event did *not* immediately spike soil or well water Cd levels detectably.
- **Grass Fire after Hail (2023, Texas):** In a related incident, hail-damaged panels led to electrical arcing and a grass fire in Van Zandt County, TX ⁴⁶. No data on soil tests were published, but the concern was potential combustion of panel materials. Fire can oxidize CdTe to more mobile forms, but the burnt area was likely limited and any contaminated ash could be removed.
- **Tornado in Illinois (2023):** A tornado hit a solar farm, scattering panel debris into adjacent fields. The cleanup effort focused on picking up debris; no contamination data released, but it exemplifies a scenario of panel pieces distributed in farmland. The expectation is if debris is promptly collected, little residual contamination remains beyond perhaps microscopic particles.
- **Other Long-Term Soil Changes:** Beyond chemicals, solar arrays can alter soil microclimate, as noted in a 7-year Italian study (Moscatelli et al., 2022) where soil under PV had higher pH, lower organic carbon (–61%), and reduced nitrogen (–50%) and microbial activity compared to open fields ⁴⁷ ⁴⁸. These changes can indirectly influence contaminant behavior (e.g. loss of organic matter could make metals more mobile). The Italy findings were significant enough that **Italy banned new ground-mounted PV on prime agricultural land** to protect soil health ⁴⁹ ⁵⁰. It’s worth noting these were changes due to shade and soil disturbance, not toxin release, but they underscore that PV installations can have lasting soil impacts unrelated to toxic contamination. For chemical residuals, the Italian context did not report heavy metal buildup; the concern was more soil quality degradation.

Comparison to Background Farmland Levels: In most cases, the concentrations of metals measured at solar sites fall within typical background ranges for agricultural soils: - Lead: Often <10 mg/kg at solar sites ²⁴, which is normal (U.S. background soils ~10-30 mg/kg Pb). No site reported lead in the hundreds of mg/kg, which would indicate serious pollution. - Cadmium: Typically around 0.1–0.5 mg/kg in uncontaminated soil. Solar sites have shown 0.1–0.3 mg/kg, occasionally up to ~1.5 mg/kg in a hotspot ³⁰. By comparison, many ag fields in Idaho and the West have ~0.5–1 mg/kg from geogenic and fertilizer sources ³¹. So solar contributions are at most incremental. Even the high of 1.55 mg/kg in the fence study is similar to the high end of natural Idaho soils (~1.8 mg/kg) ³¹. - Selenium: Background Se varies by region (some western soils are naturally high). The 0.5 mg/kg near panels in NY ³² is notable because northeastern U.S. soils are usually low in Se. But it’s still a low absolute level; western soils can have 1–2 mg/kg naturally in seleniferous areas. Cropping history (e.g. irrigation with Se-rich water) can also raise Se. - Other metals (Zn, Cu, Ni, Cr): Values under solar arrays have been reported in ranges like Zn ~50–60 mg/kg, Cu ~5–15 mg/kg, Ni ~5 mg/kg, Cr ~5 mg/kg ⁴ – all within normal soil background for those elements. For perspective, the EPA regional screening level (residential soil) for zinc is around 2,300 mg/kg (for human health), and for copper many states use ~3,000 mg/kg as a not-to-exceed for soil reuse. Solar site levels are two orders of magnitude below those numbers.

Post-Damage vs Background: In the Texas hail case, regulators compared water and soil samples to standards and found nothing alarming ⁵. If a catastrophic event had left, say, visible cadmium on the ground, one might find soil Cd in the tens of mg/kg immediately under a shattered panel piece. But even then, dilution across the field and remedial action (removing topsoil in that spot) would mitigate it. The lack of public reports of, for example, “farm soil had to be removed due to solar panel contamination” suggests that exceedances of regulatory thresholds are extremely rare or nonexistent in documented cases.

In conclusion, *real-world measurements support that utility-scale solar farms have not caused systemic soil contamination*. Minor elevations in certain metals have been observed under arrays, but they remain below stringent environmental thresholds and often within natural variability ³⁷. The one area to watch is **cadmium in thin-film installations**, where a combination of lab and incident evidence indicates a potential (though small) risk of soil Cd increases if many panels break. Even then, the levels tend to stay comparable to background agricultural soils and far below EPA risk-based soil concentrations for human health (EPA’s residential soil screening level for Cd is about 71 mg/kg for a 1×10^{-6} cancer risk, and 70 mg/kg was noted as a conservative screening level in one report ³⁶ – solar sites are at ~1 mg/kg or less).

Regulatory Thresholds for Agricultural Reuse and Food Safety

When evaluating former solar sites for agricultural use, several types of regulatory or guideline thresholds may apply:

- **EPA Soil Screening Levels (SSLs/RSLs):** The U.S. EPA publishes *Regional Screening Levels* (RSLs) for contaminants in soil, which are risk-based concentrations for residential or industrial land use. For example, the **EPA residential soil RSL for lead** is 400 mg/kg (based on blood lead goals), and for **cadmium** it’s around 71 mg/kg (non-cancer endpoint) ³⁶. These are levels at which further investigation is warranted, not hard cleanup standards. All reported solar-site metal levels are well below such values – usually by one or more orders of magnitude. EPA also has **Ecological Soil Screening Levels (Eco-SSLs)** for protection of plants, soil invertebrates, and wildlife. These are often much lower than human health levels. Earlier we noted the Eco-SSL for Cd to protect plants is 0.36 mg/kg ⁵¹, and for Pb to protect birds/rodents is 11 mg/kg ⁵¹. Some near-panel samples approach the plant Eco-SSL for Se (0.52 mg/kg) ³² or had Cd ~1 mg/kg exceeding the plant Eco-SSL of 0.36 mg/kg, but these guidelines are very conservative and not regulatory in the strict sense. They indicate that, ecologically, a buildup of those elements *could* eventually impact sensitive species if it continued unchecked. In practice, slight exceedances of Eco-SSLs are not uncommon in agricultural lands due to legacy inputs (e.g. many farm soils exceed the Cd 0.36 mg/kg plant benchmark but still grow crops fine).
- **State Cleanup Levels:** Many U.S. states set soil cleanup criteria for different land uses. For instance, California has *Total Threshold Limit Concentrations* (TTLc) – e.g. 1000 mg/kg Pb and 20 mg/kg Cd, above which soil is considered hazardous waste for disposal. New Jersey’s residential cleanup standards are around 400 mg/kg Pb, 2 mg/kg Cd; Texas has protective concentration levels, etc. For agricultural reuse, states may default to residential standards (since growing food is akin to a sensitive use). In **Idaho**, there aren’t unique agricultural soil standards outside of federal Superfund guidelines, but Idaho DEQ would likely require meeting background or regional screening levels if a solar site had a spill. Notably, **Idaho’s natural background for Cd (up to ~1.8 mg/kg) and Pb (often ~10-20 mg/kg)** provides context – any solar site soil that matches those background levels would be considered clean. If a contaminant were above background but below risk-based levels, usually it’s

evaluated case-by-case. So far, documented cases show solar sites fall within background ranges for heavy metals ²⁴. Therefore, *exceedance rates* of regulatory thresholds are effectively zero in the literature – no reports of solar sites exceeding state cleanup levels for metals. The only “exceedance” to note is relative to Eco-SSL: one could say X% of studied sites had Cd over 0.36 mg/kg (plant Eco-SSL). But those sites are still far below human health criteria.

- **European Union Limits (Soil and Food):** The EU does not yet have a binding soil quality directive for heavy metals, but many countries set guidance. For example, the Netherlands has intervention values (e.g. ~100 mg/kg Pb, ~1 mg/kg Cd for soil intervention depending on land use). Germany has precautionary soil values around 50 mg/kg Pb, 1 mg/kg Cd for sensitive land use. None of the measured solar site values approach these. In terms of **food safety**, the EU sets maximum cadmium content in food crops (e.g. 0.1 mg/kg fresh weight for potatoes and many vegetables, 0.2 mg/kg for cereals, 0.3 mg/kg for leafy greens). Wheat from high-Cd Idaho soils sometimes nears the 0.2 mg/kg limit ³¹, which is why low-Cd varieties are recommended ⁴⁰. If a solar site’s soil Cd was, say, 0.5 mg/kg vs a background of 0.3 mg/kg, the difference in crop Cd might be small but could be relevant for strict markets. However, **in documented cases, solar sites have not been shown to push crop metal levels over food limits**. For instance, if potatoes typically have 0.05 mg/kg Cd in Idaho, a slight soil increase likely wouldn’t exceed the 0.1 mg/kg Codex guideline for tubers.
- **Exceedance Rates in Documented Cases:** To date, **no published case has found a post-solar soil contaminant concentration exceeding EPA or state cleanup thresholds** for reuse. Even after severe damage, authorities in Texas reported no contamination above actionable levels ⁵. Ongoing monitoring in research settings has mostly reported “below pollution concern standards” ⁵². For example, Yousuf et al. noted heavy metals remained *mostly below standards*, with the caveat of rising Cd requiring attention ⁵³. One might interpret that as a trend to watch rather than an exceedance. The **Italy ban** on PV on ag land wasn’t because of measured toxin exceedances, but preventative due to observed soil degradation and the *potential* for contamination ⁴⁹ ⁵⁰. So the “exceedance rate” is essentially zero for numeric standards, but the “detection rate” of slight increases is >0 (we do detect some increases in elements like Cd, Se in some studies).
- **Food Residue Regulations:** If crops are grown, the ultimate test is whether produce meets food safety standards for contaminants like lead, cadmium, etc. No known instances of crops grown on former or existing solar sites being rejected for heavy metal contamination have been reported. Given the low soil levels observed, it is highly unlikely any exceedance of food MRLs (Maximum Residue Levels) would occur. For example, even in contaminated soils with 3–5 mg/kg Cd, potatoes often remain <0.1 mg/kg Cd in tuber ⁵⁴. Solar sites haven’t shown soil Cd anywhere near that high. If a site had an extreme event – say a large battery fire with PFAS – the relevant food safety concern might be PFAS in produce (which some states like Maine now regulate in dairy and crops). That’s a different regulatory arena (parts-per-billion levels), but again, it’s hypothetical for solar PV unless firefighting foam was used.

In summary, **solar farms as currently operated are meeting environmental criteria for soil contamination**, with a substantial safety margin. Agricultural reuse can generally proceed under existing guidelines so long as standard site cleanup is done. Precautionary screening (soil testing) is still advised upon decommissioning, to document that soils are “clean” relative to state background or risk-based levels ⁵⁵. This provides assurance to landowners and regulators. The evidence to date strongly suggests that in

the U.S., **utility PV installations have not triggered any regulatory soil cleanup actions** related to toxic contaminants.

Event-Driven Risk Scenarios

Unplanned events – hailstorms, fires, floods, tornadoes, or vandalism – can breach the physical integrity of PV systems and create acute contamination pathways that are absent in normal operations. We examine how each event type might change the risk profile:

Hailstorms and Storm Damage

Severe hail can shatter PV module glass, exposing the internal cell materials to the elements. Large hail (>1 inch) is uncommon but not unheard of – in fact, recent events have exceeded design expectations ⁵⁶ ⁵⁷ . When hail destroys thousands of panels, two immediate pathways arise: **(1)** fragments of module glass, encapsulant, and cell pieces scatter on the soil surface; **(2)** rainwater can percolate through broken modules, leaching soluble compounds into soil.

Contaminants of concern: For c-Si panels, the main concern is lead solder and small amounts of tin, silver that could leach out of cracked cells. For CdTe panels, cadmium becomes the prime concern. In a Texas hailstorm case (2024, Fort Bend Co.), the farm used CdTe thin-film modules and residents feared Cd would leach into groundwater ⁵⁸ ⁵⁹ . Experts pointed out that cadmium telluride is encapsulated in layers and not readily water-soluble ¹⁰ . Indeed, in that incident, emergency crews found no measurable contamination in initial soil and water tests ⁵ , and it was noted any Cd release would likely be very small and slow to migrate. This aligns with a lab finding that even under acid rain conditions, only minuscule Cd might leach from broken CdTe glass (most stays locked in or precipitates as Cd compounds).

Physical extent: Hail damage tends to be *distributed across the array*. Unlike a localized spill, you have many small “source points” (each broken panel) over acres. This widespread but low-level distribution might actually reduce risk – contaminants are not concentrated. However, cleanup is challenging: picking up glass shards across hundreds of acres is labor-intensive, and some tiny fragments will inevitably be left in the soil.

Mitigations: After a hailstorm, operators typically remove and replace broken panels. Large fragments are cleared; small debris might be buried or left. In some cases, scraping the top inch of soil in areas of thick debris could be done, but that’s rarely reported. The key mitigation is that the new panels and rain will essentially “rinse” the area over time, with any leached metals diluting. If one were cautious, one could do soil sampling a few months post-event. To our knowledge, data from such sampling has not been made public, except assurances like in Texas that nothing was detected acutely ⁵ . In any case, hail risk is one of the more credible ways a solar farm *could* contribute contaminants, especially if thin-film modules are used over agricultural soil.

Specific example – Idaho context: Idaho does get hail occasionally, though giant damaging hail is less common than in the Great Plains. If a hailstorm did shred panels on an Idaho farm, the likely module type is c-Si (most Idaho projects use silicon panels). So the main contaminant might be lead. A single c-Si panel contains perhaps 10-20 grams of Pb solder. If 100 panels broke and somehow all their lead leached to soil (an extreme, unrealistic assumption), that’s ~1-2 kg of Pb spread over, say, 1 acre (~4000 m²), which would average 0.5 mg Pb per kg soil – a trivial addition relative to background (~10,000 mg naturally present per acre at 5 mg/kg). Realistically, much of that lead remains attached to shards and can be picked up. Thus,

hail damage to c-Si is unlikely to create hazardous Pb hotspots. For thin-film (CdTe), the math is similar: each panel might have ~10-15 g of CdTe compound (which is ~5-6 g Cd). If thousands shattered, the Cd is widely dispersed and mostly still adhered to glass pieces. Only a very small soluble fraction would be in the soil. The Texas case suggests even sensitive tests didn't find it in water ⁵ .

Conclusion (hail): *Short-term risk:* Low to moderate. There is no evidence of acute toxicity to crops or people documented after hail events – no fish kills, no crop die-off, etc. *Long-term risk:* Slight accumulation of heavy metals in soil could occur if not all debris is removed. Over decades and multiple hail events, theoretically Cd or Pb could build up in soil below panels, but this would require repeated damage without cleanup. Modern risk management (insurance, etc.) ensures that catastrophic hail events are rare and addressed when they do occur.

Fire (Wildfire or On-site Fire)

Fires can happen at solar farms due to electrical faults, wildfires sweeping through, or as secondary effects of storms (e.g. a lightning strike). Fire introduces three concerns: **(1)** combustion of panel materials can volatilize or concentrate contaminants; **(2)** ash and smoke can deposit pollutants on soil; **(3)** firefighting efforts (water and foam) can spread contaminants or introduce new ones (PFAS).

Module combustion: When PV modules burn (which can happen especially with backsheet ignition or DC arcs), the plastics (EVA, backsheet) and sealants burn off, potentially releasing fumes, and the metals in cells and solder can either volatilize or remain in the ash residue. Studies show that >99.9% of Cd in CdTe panels stays encapsulated even if the panel glass melts ⁷ . It tends to get locked in the molten glass rather than released as vapor. Nonetheless, a fire could oxidize Cd and other metals to more leachable forms in the leftover ash. For instance, lead solder could oxidize to PbO or other compounds that are more soluble than metallic lead. If that ash sits on soil and then is rained on, you could locally spike soil Pb or Cd levels.

Real incidents: In May 2023, a wildfire in California's Mojave area burned through a large solar farm (mostly c-Si panels). There was concern about toxic debris, but the primary issue turned out to be air quality from burning plastics; no major soil contamination was reported publicly. Another case: a 2023 grassfire in Texas ignited some broken panels (from the hail event), possibly releasing fumes, but again we lack specific soil data. What we do have is analogous events like structure fires: when a house with lead paint burns, the ash in the vicinity can have high lead that requires cleanup. So if a significant portion of a solar array burned, one should test soils for metals in the fallout zone.

PFAS from firefighting foam: If fire crews used AFFF or similar foam on an electrical or battery fire, they would introduce PFAS to the site. PFAS chemicals persist and can leach to groundwater or be taken up by crops. For example, elsewhere, at a battery storage fire in Moss Landing, CA (2022), firefighters used foam and later heavy metals (and presumably PFAS) were found in runoff and nearby ecosystems ⁶⁰ . For a solar farm, responders might avoid foam on just PV panel fires (water is typically used on grass fires or they let minor electrical fires burn out once de-energized, due to electrocution hazard with water). However, if the site had a substation or battery energy storage system (BESS) co-located, foam might be applied. PFAS contamination is an emerging regulatory focus – some states have extremely low soil standards (parts per billion) and would require soil removal if exceeded. There's no known case of PFAS sampling at a solar farm, but the risk is analogous to any industrial site where AFFF was used.

What changes under fire: After a fire, you have potentially more mobile forms of metals in soil (ash with oxides), loss of vegetation (leading to erosion that could spread contaminants), and possibly new chemicals (PAHs from incomplete combustion, PFAS from foam). Plant uptake of heavy metals might actually increase if ash raises soil pH (ash is alkaline, which usually *decreases* metal availability – so in that sense, maybe not). But ash can also supply soluble salts that mobilize some metalloids. One study on wildfire ash deposition found increased soil Pb and Zn in topsoil that had to be remediated in building fires; by analogy, a very intense solar farm fire could deposit enough Cd/Pb in topsoil to warrant scraping it off.

Mitigation: Following a fire, the typical mitigation is to remove all debris and visibly impacted soil. If panels with Cd or Pb burned, those areas might be excavated slightly or at least till-mixed with clean soil to dilute. Because such fires are rare, guidance is sparse. But general post-fire environmental assessment (like after California wildfires) includes testing soils for heavy metals and PAHs if structures burned. It's prudent to do the same for a solar site. The cost is usually minor unless an extreme concentration is found. For example, if testing finds, say, 200 mg/kg Pb in ash patches (which is above natural ~10 mg/kg but below hazardous waste criteria), one might still choose to shovel up those patches to ensure safety for farming.

In summary (fire): Fire events pose a **moderate contamination risk locally** – more than normal operation, but manageable with cleanup. No evidence suggests widespread contamination of an entire site from a fire; it's confined to the burn area. Crops sown after a fire should be tested for any unusual uptake if there was known residue, but generally if cleanup was done, the risk to crops is minimal. The most unique risk is PFAS, which requires specialized remediation (often removal of soil or immobilization via activated carbon in situ). PFAS could affect the marketability of crops (some processors test for PFAS now), so it's a consideration if foam was deployed.

Flooding and Stormwater Runoff

Flood events can impact solar farms built on floodplains or flat ag land. Floodwater could introduce contaminants *to* the site (e.g. upstream industrial pollutants depositing in sediment) or spread any on-site contaminants *off* site. The solar infrastructure itself typically doesn't contribute new contaminants during a flood, except if any chemicals stored on site (fuel, etc.) were released by the flood – which is uncommon since solar farms have minimal chemical storage.

One concern is that floodwater interacting with damaged panels might leach metals more aggressively. For instance, if a bunch of broken panel pieces are submerged in floodwater, the water could pick up Cd, Pb, etc. Then as waters recede, those metals could settle in soil elsewhere (perhaps in farm fields downstream). This is a very hypothetical pathway; no empirical data is available. But conceptually, **acidic floodwater** (if, say, it mixed with acid rain or mine drainage) could leach metals from panel debris. Normal floodwater is not particularly acidic, so leaching would be limited.

Post-flood sampling: After major hurricanes or floods, environmental agencies sometimes test soils for pollutants. In a solar context, we haven't seen specific reports. There was a case during Hurricane Maria (2017 in Puerto Rico) where solar panels were scattered; cleanup focused on debris, with no noted soil toxicity issues.

Stormwater runoff (non-flood): Even routine rain can cause runoff from panels to soil. A study in Poland collected runoff water from panel surfaces and found **no elevated concentrations** of metals in the rainwater that dripped off modules ⁶¹ ⁶². This suggests that intact panels do not shed heavy metals via

rain. Only if panels are degrading (e.g. anti-reflective coatings weathering) might runoff carry something like trace indium or tin. In that Polish study, runoff met drinking water standards for metals ⁶¹. That's reassuring.

Erosion and dispersion: Floods could cause erosion of topsoil at a decommissioned site, potentially spreading any contaminants. But since we're generally talking low-level contaminants, the main risk of erosion is agronomic (loss of fertile soil) rather than spreading hazardous waste.

Bottom line (flooding): Floods do not seem to introduce novel contamination from solar equipment, but they can redistribute whatever is there. Good practice after a flood would be to inspect for any dislodged infrastructure (did any old wiring, etc. get unearthed and washed away?) and test downstream sediments if a large solar farm with known hazardous materials was inundated. No red flags have been recorded in literature, so flood-related contamination is probably a **low risk** scenario.

Tornadoes, High Winds, and Debris Scatter

Tornadoes or extreme wind gusts can rip panels from racks and scatter them across the landscape (as seen in some Midwest events). The contamination considerations here are similar to hail: broken pieces strewn about. The difference is pieces might travel further off-site, meaning a broader area of low-density debris.

If a solar farm's panels (especially thin-film) were strewn into neighboring crop fields, there is potential for those fields to have residual glass and semiconductor pieces that could leach contaminants. The immediate remedy is usually manual cleanup – which is sometimes imperfect. Tiny fragments could be missed and later get tilled into soil.

One documented vandalism incident in the same vein: in North Carolina, individuals shot some panels, causing them to shatter (like mini hail hits). The local soil directly under those panels could get a small amount of released material, but this is hyper-local.

Regulatory response: After significant wind events, any debris that leaves the solar site is generally considered solid waste that must be cleaned up by the operator (often mandated by decommissioning clauses or local ordinances). If a neighbor's land got littered, the company would collect it. We did not find reports of heavy metal testing in those scenarios – likely because the visible debris is the obvious issue (and liability), not invisible contamination.

Conclusion (wind scatter): The contamination risk is **low**, given the limited quantity per fragment and likelihood of cleanup. It's more of a nuisance and safety issue (sharp debris for livestock or machinery). Soil tests would probably not detect anything above background once debris is gone, except maybe directly under where a panel shattered and lay for a while (even then, any leaching would be minimal unless months of rain occurred before removal).

Improper Disposal and Abandonment

Though not exactly an "event of nature," improper handling at end-of-life can create contamination scenarios. For example, if a bankrupt operator simply walked away and panels were left to degrade on site (or were bulldozed and buried on the property), that could lead to gradual contaminant release.

Illegal dumping: If solar panels (especially broken ones) were dumped in a pit on farmland, over time metals could leach out. The 2019 study by Su et al. simulated exactly this: panels treated as “domestic trash” and buried, showing metals leaching into soil over months ⁶³ ¹⁸. They confirmed that thin-film panels in particular *will* pollute soil when left buried, with soil concentrations of Zn, Cu, Pb, In, Ga, Ni rising in proportion to the amount of panel material added ⁶⁴ ¹⁸. This is a clear case of “improper waste handling” leading to contamination. Fortunately, in the U.S., utility-scale projects have decommissioning requirements to prevent this outcome. Panels are supposed to be reused or recycled, or at least taken to proper landfills (and even there, TCLP testing is done to classify them).

Abandoned site: If a solar farm were abandoned (no upkeep) for many years, you might get slow-release contamination: backsheets cracking, rain ingress corroding internal metals. It would be like an accelerated aging scenario. The soil under panels could accumulate some metals in bioavailable form after, say, a decade of broken/unmaintained modules. While no utility-scale examples exist yet (since most are new), one can look at **older off-grid panels** or **poorly maintained installations** for hints. So far, we haven’t seen reports of contamination from that either, but it’s plausible in theory (especially for older technology panels that had more hazardous content).

Regulatory frameworks: Many states now classify used solar panels as **Universal Waste** (or plan to) ⁶⁵ ⁶⁶. That encourages proper recycling and tracking. If an owner abandoned panels, state environmental agencies could enforce cleanup under solid waste or even Superfund authority if contaminants posed a threat. But given the economic drivers, abandonment of valuable panels is rare – more likely they’d be removed and sold or recycled if a company failed.

In essence, **improper decommissioning is one of the few ways significant contamination could occur**, as demonstrated by lab simulations ⁶⁴. It is preventable with enforcement of decommissioning plans (e.g. bonds to ensure site restoration).

Overall, among abnormal events, **hail and fire are the most significant for contamination potential**, with hail being more about Cd/Pb release and fire introducing ash/foam issues. **Storm scatter** mostly expands the area of concern but not the per-area severity. **Flooding** is a minor factor environmentally for PV specifically. And **poor disposal** is a controllable human risk that should be addressed via policy.

Each of these scenarios underscores the importance of having an **Emergency Response and Remediation Plan** for solar farms. Such plans should outline debris cleanup procedures, soil sampling after major incidents, and criteria for further action (e.g. if soil Cd exceeds a certain ppm after a hailstorm, triggers remediation). From the evidence gathered, when these events have occurred, the resultant contamination has been either non-detectable or easily mitigated. However, because long-term data are sparse, these events remain as theoretical risk scenarios that merit preparedness.

Knowledge Gaps and Research Needs

Despite the emerging body of research, there remain significant **knowledge gaps** regarding solar farm residuals and agriculture. Addressing these would improve confidence in reusing land and inform best practices. Key gaps include:

- **Long-Term Post-Decommission Data:** We lack studies that sample soil *before PV installation, during operation, and after decommissioning*. Most current studies either compare under-panel vs nearby (with the array still present) or simulate worst-case in lab. There is almost no published data following a site that was returned to farming. A **defensible Idaho field study** could fill this gap by taking baseline soil samples on farmland slated for solar, monitoring soil during the project's life, and then sampling again after removal (with proper controls in place). Such a study should check not just total metals but also plant-available fractions and any crop tissue if planting is resumed. This would conclusively show whether any residual differences exist and if they matter for crops.
- **Thin-Film vs c-Si in Field Conditions:** While lab tests indicate thin-film panels *could* leach more hazardous elements if broken, we have minimal field evidence quantifying this under real weathering. How does a shattered CdTe panel on a field actually affect soil 1 year, 5 years later? Are there measurable Cd or Te halos around where fragments lay? Similarly, for CIGS – does soil under long-term CIGS installations show accumulations of Cu, Se, In? Only isolated data points exist. More field sampling at sites known to use thin-film (perhaps some First Solar CdTe farms in the Southwest) would be valuable. This might involve intentionally sacrificing a panel, grinding it and mixing in a small soil plot to simulate breakage, then measuring over time (a controlled field experiment).
- **Bioavailability and Uptake in Situ:** There is a disconnect between soil concentration data and actual plant uptake data in the context of solar sites. None of the studies grew crops in the soil to test if the small increases in, say, selenium or cadmium translated into higher plant concentrations. It would be beneficial to conduct pot or field trials with soil collected from under old solar arrays, planting representative crops (like lettuce, potatoes, wheat) to directly measure uptake and compare to control soil. This would tie the environmental concentrations to food safety outcomes.
- **Confounding factors and attributions:** Solar farms often involve land grading, added gravel, concrete footings, etc. It's not always clear whether observed soil chemistry changes are due to panel materials or these construction inputs. For instance, higher lithium or barium under panels might originate from concrete or limestone gravel dust (concrete often contains lithium compounds and barite). To distinguish sources, more complete chemical fingerprinting and possibly isotopic analysis could be done. Knowing whether the contaminants are panel-derived or construction-derived can shape mitigation (e.g., if it's from concrete, focusing on concrete removal or sealing might help).
- **Polymer degradation products:** Beyond just “microplastics,” we don't know if any UV stabilizers, flame retardants, or polymer additives in backsheets and cables leach into soil as they age. Modern backsheets may contain fluoropolymers that could degrade into PFAS compounds over decades (e.g., some PVDF or PTFE fragments). This is speculative, but worth investigating given the persistence of PFAS. Analytical methods could test soil under very old panels for trace PFAS or other organics to see if polymer weathering leaves any residues.

- **Cumulative effects of multiple stressors:** If a site experiences several events – say minor breakage over years, plus regular temperature cycling – could multiple small releases accumulate to a significant soil burden? The current research is often one-off or short term. A more cumulative risk assessment is needed for a site left in place for 30 years with occasional repairs and storms. Does soil under the oldest PV arrays (25+ years) show any higher contaminant levels than at 5–10 years? This chronological data is missing. Engaging sites from the early 1990s (if any still exist in the U.S.) would be illuminating.
- **Remediation effectiveness:** In the rare event a solar site soil *does* exceed a threshold, what are the best remediation practices specifically in an ag context? There's theory (lime, phytoextraction, etc.), but field trials at solar-contaminated soils haven't been reported. For example, if a spot had 5 mg/kg Cd from a broken panel pile, would planting sunflowers for two years significantly reduce it (phytoremediating) or is excavation the only viable step? Also, if microplastic fragments are an issue, can standard tillage dilute them or must they be physically removed by screening soil? These practical questions remain untested in solar settings.
- **Local ecological impacts:** Most focus has been on crops and human health, but what about soil organisms? Could earthworms or soil microbes accumulate these metals or be harmed by them? The Italy study showing reduced microbes under panels might be partly due to contaminants or just microclimate. Perhaps follow-up research could measure heavy metals in earthworm tissue from under a solar array vs outside, to see if they're picking up anything. Worms and microbes are important for soil health when land is returned to farming.
- **Idaho-specific research:** There is essentially no published study on solar-agricultural land transition in Idaho or the Intermountain West. Given Idaho's unique combination of crop types (potatoes, sugar beets) and soil conditions (loess soils with calcareous subsoils, often irrigated), research here would be valuable. Questions like: Does the slight alkalinity of many Idaho soils actually prevent any detectable metal uptake? Are there any local factors (e.g. high background selenium in southern Idaho from irrigation water) that could either mask or exacerbate any solar contributions? A field experiment on an Idaho solar farm – even a small one – where soil and possibly crop tissue are sampled over time would address concerns directly relevant to the region.
- **Data transparency and incident reporting:** A gap in knowledge is simply due to lack of publicly available data from industry and regulators. For instance, the Texas hail incident – TCEQ likely did some analysis, but details aren't public beyond “no contamination found.” Pushing for more transparency or citizen science sampling after such events could fill in those blanks. Many solar companies do TCLP tests on their panels for disposal classification; aggregating those results (perhaps anonymously) could show which panels tend to leach above hazardous limits. One reference noted a statistical evaluation finding some new panels have a small probability of failing TCLP for lead ⁶⁷ ⁶⁸ – getting more of that kind of data could inform whether upcoming panel designs (like lead-free solder) are reducing future risks.
- **Microplastic uptake and soil biota effects:** As an emerging field, research specific to agricultural soils with PV-derived microplastics is needed. If we find that backsheets shed, say, polyfluorinated bits that persist, do they affect soil water or root growth? It's a stretch, but something to keep an eye on.

- **Weathering studies in situ:** Complementary to lab leaching, placing sample coupons of panel materials in real field conditions (sun, rain) and testing runoff over time would help quantify how much (if any) metal comes off an aging but intact panel. This could validate the assumption that intact panels truly do not leach. The Polish runoff test was one data point ⁶¹; more such studies across climates would bolster conclusions.

Overall, the knowledge gaps revolve around moving from theoretical or lab results to **empirical, field-verified outcomes**, especially over longer timescales and after actual decommissioning. Filling these gaps would allow stakeholders in agriculture (farmers, landowners, extension agents) to make decisions based on evidence rather than worst-case assumptions or industry assurances alone.

What a Defensible Idaho Field Study Would Look Like: Ideally, a multi-year study starting *now* on a utility-scale solar project in Idaho. Before construction, thoroughly sample the soil (for heavy metals, organic contaminants, baseline nutrients, pH, OM, etc.) on a grid. Retain control plots at field edges that won't be under panels. During operation, perhaps sample soil yearly under a subset of panels (and at control plots) to watch for any drift. Also, install passive dust collectors to see if dust deposition from panel wear occurs. When the project is decommissioned (say after 20-30 years, or if a smaller test array is disassembled sooner), sample the same grid points again and compare to baseline. Additionally, perform a bioassay: plant a sensitive crop like lettuce or spinach in soils from under panels vs control soil in a greenhouse to directly measure uptake differences. Ensure the study has replication and statistically robust design. Including a thin-film section if possible (even a few CdTe panels among mostly c-Si, as a test plot) would be very insightful. Such a study would likely involve a partnership between a university (for scientific rigor) and the solar operator (for site access and funding). The result would be a highly credible dataset to answer definitively whether solar installations leave residual soil contamination that affects agriculture in Idaho's context.

Remediation and Mitigation Strategies for Residual Contamination

If post-solar soil testing ever finds contaminants above acceptable levels for farming, there are several remediation methods to consider. The choice depends on the specific contaminant, its concentration, the area affected, and how quickly the land needs to be returned to production. Here we outline potential remedies, evidence for their effectiveness, and practical considerations (cost, time):

- **Soil Removal ("Dig and Haul"):** This is the most straightforward method for localized hot spots. Contaminated soil is excavated and disposed of at a proper facility (hazardous waste landfill if levels are high enough, or solid waste landfill if not). This method guarantees removal of the contaminant but at the cost of losing topsoil. It's best for small areas or spill sites. *Use case:* If a transformer leaked PCB oil and left a patch of soil with PCBs or if a pile of broken CdTe panels left one spot with, say, 10 mg/kg Cd, one might dig out that area (maybe the top 6 inches over a few square meters) and backfill with clean soil. **Evidence:** Standard practice in remediation – effective but expensive per volume (roughly \$50–\$200 per ton for excavation and disposal, plus soil replacement costs). Feasible timeline: immediate (days to weeks) for small areas. Obviously, not suitable for widespread low-level issues because you can't remove an entire field's topsoil without huge cost and agricultural detriment.
- **Containment/Stabilization:** Instead of removing metals, you can chemically stabilize them in situ so they are not bioavailable. Common techniques include **liming** (to raise pH and precipitate metals as

hydroxides/carbonates) and adding **phosphate amendments** (like rock phosphate or bone meal) which bind lead and cadmium into insoluble phosphate minerals. Also, organic matter or biochar additions can immobilize metals by adsorption. *Use case:* If broad areas of soil have moderately elevated metal levels (just above a threshold for crops), soil amendments can often bring the bioavailable fraction down. For example, adding 1-2% (w/w) of high-phosphate compost has been shown to significantly reduce lead uptake in garden crops in urban soils, by forming lead phosphate ³⁷. **Evidence:** The EPA and USDA have documented success in using P amendments and pH adjustment for lead in community gardens and some field trials for cadmium. For cadmium, raising soil pH above 7 and ensuring sufficient zinc and organic matter in soil can drop plant Cd uptake substantially (plants preferentially take up zinc, and high Zn suppresses Cd). This approach doesn't remove the contaminant, but it effectively "locks it up." Cost is relatively low (lime and phosphate are cheap) and it can be done quickly (a one-time application, though one must maintain pH long-term). Timeline: results in immobilization within weeks of mixing the amendments, and can be a lasting solution if soil conditions remain stable.

- **Phytoremediation:** Using plants to extract or stabilize contaminants. Some plants hyperaccumulate metals – e.g., certain willow species and **Brassica juncea** (Indian mustard) can accumulate lead or cadmium; sunflowers and maize have been used to take up lead and radionuclides in some projects; alpine pennycress (*Noccaea* spp.) accumulates zinc and cadmium extremely well (but it's a small plant, not high biomass). *Use case:* For a relatively low contamination spread over a large area where excavation is impractical, growing a series of hyperaccumulator crops and removing the biomass might gradually reduce soil levels. For example, on cadmium: a Chinese study used a *Sedum* species to phytoextract Cd from farmland soil with some success (on the order of removing a few tenths of a mg/kg per year) ⁶⁹. **Evidence:** Phytoremediation has worked in certain scenarios (notably for phytoaccumulating arsenic or nickel using specialist plants). For cadmium and lead, it's notoriously slow. Pb is hard because plants don't readily take it up, so often chelating agents (like EDTA) are used to solubilize it – but that can cause groundwater contamination as a side effect, so it's risky. Cadmium can be phytoextracted better; for instance, high-biomass plants like willow or switchgrass can uptake Cd, but it might take many cropping cycles to significantly reduce soil concentrations. One paper reported that after 3 years of Indian mustard cropping, soil Pb dropped ~13% and Cd ~10% in a moderately contaminated plot ⁷⁰. That's meaningful but not a complete cleanup. The upside is that it's relatively low cost (just seeds and fertilizer, and disposal of contaminated plant matter, which might be handled as hazardous waste if metals are high). The downside is it's slow – expect multiple years or even decades for large reductions, and one must ensure the plants themselves don't enter the food chain or cause secondary problems. Phytoremediation could be a complementary strategy to polish off residual contamination after other methods (e.g., excavate hot spots, then phyto for the mild remainder).

- **Soil Washing or Leaching:** This involves extracting contaminants from soil using chemical solutions. It's more of an active engineering approach: soil is excavated, washed with an acid or chelator to dissolve metals, then the clean soil (minus some fines) is put back, and the metal-laden washwater is treated. This is used in some Superfund sites for lead or heavy hydrocarbon removal. It's expensive and not typically done on agricultural land unless absolutely necessary, because it can disrupt soil structure and fertility. For a solar farm scenario, soil washing is unlikely to be warranted because contamination levels would almost never be that high. It's mentioned for completeness: if, hypothetically, a huge number of CdTe panels were pulverized into a field and plowing just mixed Cd

throughout several acres at levels like 10+ mg/kg, soil washing could remove a chunk of that Cd. But this scenario is highly unlikely.

- **Activated Carbon or Biochar for Organics:** If the issue is organic contaminants (like herbicide residues or PCBs or PFAS), mixing activated carbon or biochar into soil can bind those compounds strongly, reducing bioavailability. For PFAS, some soil stabilization products (activated carbon, ion-exchange resins) are being tested to lock PFAS in soil and prevent uptake by plants or leaching. If firefighting foam contaminated a site, one possible remediation is to till in carbon amendments to sequester PFAS (and possibly grow a sacrificial crop to uptake some, although phytoremediation of PFAS is not very effective for long chains). For herbicides, often the best remedy is time – most degrade naturally. But if one were in a hurry, one could add microorganisms (bioaugmentation) or stimulants to accelerate degradation for certain compounds. E.g., if residual diuron (a persistent herbicide) was present, adding a carbon source and keeping soil moist could help microbes break it down faster.
- **Microplastic removal or management:** There is currently no great solution for microplastics in soil. Physical sieving of soil can remove larger plastic pieces, but small particles are essentially permanent. The best “remediation” is prevention (clean up panel debris and plastic trash). If microplastic contamination was truly concerning, one could strip off the top inch of soil where most plastic resides – but you’d remove organic-rich topsoil too, harming fertility. Given no evidence of harm from panel-derived microplastics, active remediation is not called for; leaving them in place might be acceptable or they could be diluted by mixing the soil profile.
- **Monitoring and natural attenuation:** In many cases of mild contamination, regulators may opt for a natural attenuation approach with periodic monitoring. Essentially, you let natural processes (dilution, leaching, biological uptake in non-edible plants, etc.) gradually reduce risk, while ensuring through testing that nothing is worsening. For example, if soil Cd came back slightly above a screening level but crops are not yet being grown, one could wait a few years, then retest – expecting perhaps that leaching and plant weed uptake might have reduced it. This only works if contaminant levels are low to begin with and not posing immediate risk.

Costs and timelines: As noted, excavation is quick but costly per volume (~\$100+ per cubic yard disposed for hazardous soil). Phytoremediation is cheap (seeds and labor) but can take years for measurable change. Stabilization (lime/phosphate) is very cost-effective – agricultural lime costs maybe \$50/acre to apply; rock phosphate similar – and works within a growing season; its “cost” is mainly that you’ve permanently tied up those metals in soil (which is fine if the land will remain ag or open space). For PFAS, activated carbon soil blending has been pilot-tested – costs are medium to high because carbon isn’t cheap and large quantities are needed to treat soil. But if only a small zone was impacted by foam, it might be doable.

What threshold triggers remediation? For agriculture, one might use food standards as a guide: e.g., if predicted or measured crop concentrations would exceed food safety limits, that’s a clear trigger. Another trigger could be hitting state cleanup standards. For example, if post-solar soil had lead above 200 mg/kg in a garden scenario, many extension services would advise remediation because of potential risk to children, even if crops don’t uptake much. For cadmium, if soil is above ~2–3 mg/kg, some agronomists would raise an eyebrow for sensitive crops destined for EU export. In the context of Idaho and many states, if soil contaminant levels exceed natural background significantly, the responsible party might be expected to remediate to background levels especially on agricultural land. Ultimately, the decision threshold might

involve: Is the contaminant concentration likely to harm crops (toxicity or yield loss)? Will it make crops non-compliant for market? Will it pose health risks to farmworkers or consumers? Usually for metals, the crop and consumer safety drives the lowest thresholds.

Supported remediation methods evidence: Summarizing: - *Lead*: Best addressed by immobilization (phosphate and pH adjustment) because phyto uptake is too low to clean it quickly. Many studies (EPA, etc.) confirm phosphates can reduce Pb bioavailability by 50–90%. - *Cadmium*: Immobilization via liming and Zn addition competes Cd out of plants. Phytoextraction can gradually reduce Cd (certain Brassica or willow, but need repeated harvests). One Chinese field trial combined liming + hyperaccumulator plants and reduced soil Cd by ~20% in a few years ⁷¹ ⁷². That's promising if time allows. - *Selenium*: Phytoremediation is actually quite effective for Se because certain plants (like mustard, canola) accumulate Se. In fact, *B. juncea* has been used to reduce Se in drainage-impacted soils in California ⁷³. If a solar site somehow had high Se, planting a series of Se-accumulating crops and removing them could be a viable strategy (and possibly even economically yield selenium as a byproduct). - *Organic contaminants*: Bioremediation (e.g., planting a cover crop and stimulating microbes) is often used on fuel spills, etc. For instance, planting alfalfa or switchgrass in a hydrocarbon-contaminated soil can improve degradation rates by supporting microbial communities. No solar-specific organic issues have been noted beyond herbicides, which degrade on their own typically. If herbicide carryover was an issue (say a persistent herbicide prevented crop growth initially), the remedy might simply be to plant a tolerant cover crop or keep soil fallow until the herbicide breaks down, possibly aiding with irrigation to speed hydrolysis.

Remediation timeline examples: If a decommissioned site in Idaho was found to have, say, 1.5 mg/kg Cd (background ~1) and stakeholders wanted to lower it to <1 mg/kg for peace of mind, one could attempt a phytoremediation: perhaps Indian mustard which can accumulate ~0.1% Cd in its biomass in ideal conditions. If you grow 10 tons/ha biomass, 0.1% Cd would be 10 kg Cd per ha removed – far more than actually present (soil 1.5 mg/kg in top 15 cm is ~45 kg Cd/ha total, which is an overestimate because typically Cd is lower). Those numbers suggest phyto might in theory remove a large fraction in a few crops. But in reality, plants likely won't accumulate to that extreme from low concentrations. It might take a decade of cropping/harvest cycles to noticeably drop total Cd. So in most cases, if the soil is “slightly above ideal but not truly hazardous,” the easiest path is to **dilute and immobilize**: add clean topsoil or compost (dilution) and lime/phosphate (immobilize) and just resume farming. The contaminant gets diluted to background and locked away – effectively rendered moot. This approach has precedent in urban agriculture (you often mix compost into mildly lead-tainted soils to dilute Pb and bind it, making it safe for gardening).

In summary, **if exceedances occur, there are proven methods to address them**: - *For metals*: adjust soil chemistry (pH, P, OM) to immobilize, or remove hotspots, or use plants over time. - *For organics*: wait or stimulate breakdown; only in rare persistent cases (like PFAS) might removal be needed. - *For physical debris*: mechanical removal is the only option (hand-pick large pieces; no practical way to remove microplastics beyond soil replacement).

Crucially, given the low levels typically involved with solar residuals, **preventative measures** and **prompt cleanup after incidents** are usually sufficient to avoid needing heavy remediation. For example, sweeping the site with magnets or vacuums after decommissioning could capture residual metal fragments; ensuring all panels and pieces are removed prevents most problems from arising.

Idaho-Specific Considerations

Idaho presents a unique context for evaluating solar-agricultural interactions. The state's agriculture (famous for potatoes, but also sugar beets, barley, wheat, alfalfa, etc.) and its soil and climate characteristics influence both the risk of contamination and the strategies to manage it. Here are Idaho-specific points:

- **Soil Types:** Much of southern Idaho's farmland lies on the Snake River Plain, with soils derived from loess and volcanic materials. These soils often have a silt loam texture, good fertility, and are somewhat calcareous (containing lime) in the subsoil. pH in these cultivated soils typically ranges from neutral to mildly alkaline (pH 7.0–8.0) due to low rainfall and presence of carbonates. This is *good news* for metal immobilization – as noted, higher pH locks up Cd and Pb in less available forms. Northern Idaho (Palouse region) has more acidic to neutral silt loams, but that area has seen less utility solar development so far (more rain, more clouds). Eastern Idaho has some calcareous soils in arid basins, and southeastern (around Pocatello) has phosphate-rich soils (which have naturally high Cd content from phosphate rock). Thus, if a solar farm were built in SE Idaho near phosphate geology, the background Cd might be elevated anyway, but also high phosphate in soil would bind some metals. Idaho soils also tend to have decent organic matter in areas with long-term farming (because of crop rotations, manuring, etc.), though some soils are low OM.
- **Climate and Irrigation:** Idaho's arid climate means most southern Idaho farms are irrigated. Irrigation water quality becomes a factor: Snake River water and well water can contain selenium, molybdenum, and other trace elements from natural sources. Long-term irrigation can actually add selenium to soils (a known issue in places like the Twin Falls area, where selenium in groundwater has caused concern for wetlands). If a solar farm was installed and then removed, the subsequent irrigation of crops could leach or dilute any residual contaminants relatively quickly. Conversely, in a rain-fed system contamination might linger longer in the topsoil. Idaho's freezing winters and hot summers cause freeze-thaw and wet-dry cycles that can physically break down any small panel debris faster (aids in weathering). But since moisture is limited outside of irrigation, leaching of metals is also limited – contaminants tend to stay where they are put unless actively moved by irrigation or heavy rain.
- **Crop Sensitivities:** **Potatoes** are a central crop – they have a relatively shallow root zone (most roots in top 1-2 feet) and they can accumulate some cadmium, especially in the tuber peel. However, Idaho potatoes historically have low heavy metal contents; for example, one study found Idaho potato tubers had around 0.02–0.06 mg/kg Cd in flesh, well under any regulatory limits (owing to soil management and variety choice). Potatoes are more sensitive to soil contamination in terms of yield when it comes to herbicide carryover – a persistent herbicide in soil is a bigger practical worry (because it could cause crop injury) than metals at the levels we're discussing. **Sugar beets** similarly might uptake some metals into their flesh, but processing (sugar extraction) leaves most metals in the pulp and not the sugar. Still, beet pulp is used for animal feed, so if it had elevated metals it could be a concern for feed safety. **Malting barley and wheat** grown in Idaho are tested for cadmium by some buyers, because high Cd can affect export (the Strawn et al. 2022 study explicitly aimed to ensure Idaho wheat stays within EFSA limits for baby food ³⁹). Thus, if a solar site were returned to small grain production, there might be interest in testing grain Cd to ensure it's on par with regional norms. Overall, Idaho's major crops would likely not be adversely affected by the slight metal residuals from a solar farm, given how they currently tolerate background metal levels that are

higher in some cases. But verifying by testing the first crop or two after solar removal could provide assurance to producers and buyers.

- **Background Levels and Regulatory Thresholds in Idaho:** Idaho does not have unique heavy metal standards for agricultural soils beyond federal guidelines, but being a state with mining history, people are aware of metal contamination issues (e.g. Silver Valley's legacy Pb contamination). On agricultural land, the expectation is that soil contaminants should not exceed natural background significantly. For instance, if a site had lead at 50 mg/kg, that might be above typical background (~20 mg/kg) and warrant a look, whereas in an industrial state like New Jersey 50 mg/kg might not raise eyebrows. Idaho's DEQ would likely use EPA's risk-based values if an issue came up. If an old solar site were suspected of contamination, Idaho DEQ could invoke the Risk Evaluation Manual and compare soil data to say EPA Region 9 PRGs (predecessor to RSLs). The conservative residential number for Cd (71 mg/kg) and Pb (400 mg/kg) would probably be the metrics. Given solar is nowhere near that, a more relevant set of thresholds could be the Idaho RBCA (risk-based corrective action) levels used for petroleum sites, but for metals. In absence of direct guidelines, often the rule is "cleanup to background" for metals. So the background levels mentioned (Cd ~0.5-1, Pb ~10) effectively become the target.
- **Potato Export Market Sensitivity:** An angle to consider: Idaho's potatoes and other products are exported worldwide. The EU, for example, has considered setting stringent limits on **heavy metals in fertilizers and soils**, and they already have product limits. If rumors or perceptions arose that land once used for solar panels might have cadmium contamination, some international buyers could be skittish (even if scientifically it's fine). This is more of a socio-economic concern than a technical one: it underscores why it's important to have data to show that the land is clean. A proactive approach Idaho could take is to develop guidelines or a certification for "solar land reuse" – e.g., require a soil test panel (for heavy metals, pH, etc.) at decommissioning and make the results public. If those show, as expected, no significant contamination, it helps maintain market confidence.
- **Incidents in Idaho:** To date, we did not find any reported incident of environmental contamination from Idaho's solar farms (which, as of mid-2020s, there are several utility-scale farms in southern Idaho, though none extremely large like in CA or TX). Idaho's climate does bring frequent dust storms and the occasional wildfire. Dust storms could sandblast panels causing abrasion – potentially releasing tiny bits of coating, but that would be minuscule. Wildfire risk is real (dry grasses around solar farms could burn late summer). An Idaho-specific point: many solar farms here incorporate sheep grazing for vegetation control. If a panel broke, would sheep ingest fragments? Unlikely, but if they did, that's another pathway (livestock ingestion of contaminants). There's no known case of that, and sheep are removed if something like that happens.
- **State or Local Regulations:** Some Idaho counties considering solar projects might inquire about bonding for decommissioning and soil restoration. Providing them with evidence (from this report and future studies) that residual contamination is minimal will help streamline approvals. If a specific contaminant were a concern (say Cd from thin-film), local authorities could require those panels to be UL certified as non-hazardous or that the developer conduct soil sampling after X years of operation.

In essence, **Idaho's environment tends to mitigate a lot of the potential contamination issues** – alkaline soils, ample phosphorus, and controlled irrigation all reduce the bioavailability of heavy metals. The biggest Idaho-specific “contamination” problems historically have been things like selenium in runoff and mercury in irrigation tailwaters (from other sources), not things like lead or cadmium in fields. The introduction of solar farms doesn't seem poised to create a new contamination problem in Idaho's agricultural landscape. The key for Idaho will be monitoring and communication: ensuring that when farmland hosts solar for 20 years and then goes back to crops, both the farmer and the market can be confident the soil is as productive and safe as ever.

Idaho could also leverage its strengths – for example, University of Idaho's Extension or Idaho National Lab environmental scientists – to be at the forefront of studying solar-ag land transitions, thus providing locally relevant data to confirm the safety (or identify any unexpected issues early).

Practical Recommendations for Sampling and Management Post-Decommissioning

To ensure a smooth transition from solar back to agriculture, a structured **sampling plan and decision framework** is recommended at the time of decommissioning (and perhaps beforehand for baseline). Here's a practical guideline:

1. Pre-Decommissioning Survey: *Timing:* Once the solar farm is nearing its end or when decommissioning is planned, conduct an initial site assessment. Identify any known incident spots (e.g. where a transformer spilled or a large area of panels broke in a storm) – those warrant focused sampling. Also review maintenance records for any chemical applications (herbicides, etc.).

2. Sampling Design: Divide the site into decision units based on land use or features. For example: - Areas under the arrays (former panel rows) vs aisle/between-row areas (if differences in drip lines or panel runoff might cause patterns). - Former equipment areas: inverter pads, transformer locations, battery storage pads (if any), operations & maintenance (O&M) yard. - Reference area: an adjacent never-developed strip of land or nearby field with similar soil to serve as a control/background.

Within each area, use a **grid or random composite sampling** approach. For a large site, a grid of say 1 sample per acre or 1 per 2 acres is a starting point. If the site is 100 acres, 50-100 samples might be collected and composited into perhaps 10 composite samples for lab analysis (compositing helps average out small-scale variability, though it could dilute hotspots – so if a hotspot is suspected, sample it discretely).

3. Depth of Sampling: Typically sample the topsoil (0–6 inch or plow layer) since that's where contaminants would accumulate and where crop roots primarily are. If any reason to suspect deeper contamination (unlikely, except maybe oil that could leach down or very sandy soil leaching metals), one could take 6–24 inch samples as well. For metals, top 6" is usually sufficient because they don't leach far in most soils.

4. Analytes (What to Test For): - Heavy Metals panel-related: At minimum, test total concentrations of Cd, Pb, and Se, as these are the top concerns for thin-film vs c-Si differences. Also include As, Cr, Ni, Cu, Zn to cover the galvanized steel/stainless contributions (and because these often come together in lab packages). Including Sb and In might require a special request ICP-MS scan since standard suites may not cover them, but it's worth doing if thin-film panels were present. Mercury (Hg) is *not* typically from PV, but

many labs include it in heavy metal scans – Hg wasn't identified as a solar issue in our research, so it's optional. - **Extractable/Bioavailable Metals:** In addition to total metals by strong acid digestion, consider a DTPA-extractable metals test (common in agricultural labs for micronutrient assessment). DTPA extraction gives an index of plant-available fraction of metals like Zn, Cu, Mn, Fe – and can also pull some Cd, Pb. If there's concern about crop uptake, this might be more directly relevant than total metal. For example, soil might have 0.5 mg/kg total Cd, but if DTPA-extractable Cd is only 0.05 mg/kg, that suggests low bioavailability. Many agronomy labs can report this. - **Organics:** If herbicides were used, test for any long-residual herbicide compounds (e.g. atrazine, simazine if used; or any herbicide the operator used regularly). If a transformer failure happened pre-2000 (rare), test PCBs. If a big fire occurred with foam, absolutely test for PFAS (specifically PFOS, PFOA, and any newer ones like PFHxS, HFPO-DA/GenX). PFAS analysis requires specialty labs. Also, if there was a fire or extensive backsheet burning, one could test soil for PAHs (polycyclic aromatic hydrocarbons), which are byproducts of combustion; however, in a grass fire, PAHs likely low unless lots of plastic burned. - **General soil health parameters:** pH, organic matter, cation exchange capacity, etc., should be measured too, because if these have changed during solar usage (like the Italy case of lost carbon), it's important for guiding restoration (e.g. you might need to add compost if OM is depleted). - **Microplastics:** There's no standard test yet for microplastics in soil that's widely available, and it's usually research-level (involves density separation and microscopy or spectroscopy). Given no guidelines on levels, this can be omitted from routine, but visually inspecting soil for plastic pieces and maybe sieving >2 mm debris out to quantify large pieces is a pragmatic approach.

5. Laboratory and QA/QC: Use a certified environmental lab. Ensure detection limits are low enough to compare to background and regulatory levels (e.g. need Cd detection limits in the 0.1 mg/kg range or lower to be meaningful). Split a few samples and send duplicates to check consistency. Also collect a sample of known clean soil (or use standard reference material) to spike in the batch for quality control.

6. Criteria for Action: Before sampling, define what levels would trigger concern. For instance: - If any sample's Pb exceeds, say, 100 mg/kg (which is well above background, though below residential risk threshold), maybe that triggers a targeted cleanup of that spot – because Idaho's background is low, 100 would be unusual unless something happened. - If any sample's Cd exceeds 2 mg/kg, perhaps take a closer look (resample or consider phyto if widespread). Certainly if it exceeded 5 mg/kg, that would be a red flag relative to normal ag soil. - Compare results to **Idaho's natural background** (from NRCS soil surveys or studies like the Idaho wheat study ³¹) and to **risk benchmarks** (EPA RSLs, Eco-SSLs, etc.). If below both, no action needed. - If slightly above background but below risk levels: maybe just document it and recommend monitoring after a few crop cycles. - If above risk levels (very unlikely), plan for remediation as discussed earlier.

7. Documentation and Communication: Prepare a report of the findings to satisfy stakeholders (landowner, regulatory agencies). This might include maps of any contaminant that's above background, etc. Given public interest, making a summary available can help dispel myths. For example, "Soil tests at XYZ Solar Farm (decommissioned) showed cadmium levels in the same range as nearby undisturbed farm soil, and all other parameters indicate the land is safe for farming."

8. Remediation Steps if Needed: Based on the criteria, implement remediation: - If only a couple spots are elevated, dig those out or treat them (spot treatment). - If a general mild elevation is present (e.g. everything ~20% over background), one might simply advise a one-time addition of soil amendments when the land is tilled to ensure no uptake issues – for instance, adding some phosphorus fertilizer broadly which farmers do anyway, serving the dual purpose of crop nutrition and immobilizing any lead/cadmium that

might be there. - If herbicide residues are found, maybe delay planting sensitive crops for a year or two or plant a cover crop to bioassay remaining herbicide (this is standard for fields coming out of CRP or industrial use).

9. Post-Remediation Verification: If any active remediation is done, re-sample those areas afterward to confirm success (especially if soil was excavated or heavily amended).

10. Crop Monitoring: It's prudent to test the first harvest of any sensitive crop on the site. For example, if planting potatoes, test tubers for Cd and Pb (there are food labs that can do this). Or test leafy greens if those are grown. This provides an extra layer of assurance that the produce is safe. Given that the soil is likely fine, this is mostly to build confidence.

Timeline: The sampling itself should be done as close to or immediately after removal of equipment as possible, before the site is plowed or replanted – to capture any stratification or localized effects. Remediation (if needed) can then be done in the next suitable window (e.g., if in fall, maybe remediate over winter or early spring). The goal would be to not unduly delay the return to agriculture; ideally, the season after decommissioning, the land could be cropped. Most of the strategies (except phytoextraction which is slow) allow for that quick turnaround.

Special considerations for Idaho – costs and expertise: Soil testing for metals is not very expensive (perhaps \$100–\$200 per sample for a full suite; doing composites can reduce cost). Given large acreages, the budget for a robust sampling campaign might be a few thousand dollars – which is minor in decommissioning budgets often in the hundreds of thousands for equipment removal. Thus, it's entirely feasible to include this in project closure costs. The data not only protect the landowner but also give the solar developer a record that they left the site clean (useful for liability closure).

Remediation cost could be trivial (if none needed) or moderate. For example, applying 1 ton/acre of lime costs maybe \$50/acre; compost maybe \$30/yard delivered – doing an entire site might be tens of thousands if one amended everything, but likely not necessary everywhere. Excavating a small area (a few tons) might cost a couple thousand dollars including disposal. These are small compared to overall site restoration (which includes removing piles, fencing, etc.).

In conclusion, the practical approach is **“trust but verify”**: assume the site is not contaminated but verify through testing; if anything unexpected is found, address it with well-established soil remediation tools. So far, evidence suggests nearly all cases will pass with flying colors. But this systematic checking builds trust with the agricultural community and preempts any future liability (for instance, if years later someone finds a metal and tries to blame the solar farm, you have baseline exit data).

By following these recommendations, the transition of solar lands back to Idaho's crop production can be managed confidently. The careful sampling and any needed remediation ensure that agricultural productivity and food safety remain uncompromised, maintaining Idaho's reputation for clean, quality farm products.

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