Science of the Total Environment 1002 (2025) 180576

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Identifying organic contaminants at trespass cannabis grows on federal land in California, USA

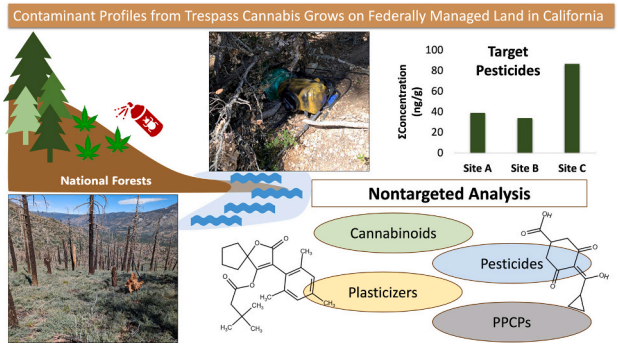
Gabrielle P. Black [a,*], Matthew De Parsia [a], Matthew Uychutin [a], Mourad Gabriel [b], Ivan Medel [b], Greta Wengert [b], Clayton D. Raines [c], Dana W. Kolpin [d], Laura E. Hubbard [e], Michelle L. Hladik [a]

[a] US Geological Survey, California Water Science Center, Sacramento, CA, United States of America
[b] Integral Ecology Research Center, Blue Lake, CA, United States of America
[c] US Geological Survey, Eastern Ecological Science Center, Kearneysville, WV, United States of America
[d] US Geological Survey, Central Midwest Water Science Center, Iowa City, IA, United States of America
[e] US Geological Survey, Upper Midwest Water Science Center, Madison, WI, United States of America

HIGHLIGHTS

- Pesticides quantified in topsoil from inactive trespass cannabis plots
- Pesticides in topsoil had a maximum concentration of 38 ng/g.
- Plasticizers and pharmaceuticals were identified using nontargeted analysis.
- Cannabinoids were detected in topsoil at trespass grows.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Illegal cannabis grows
Pesticides
Rodenticides
Nontargeted analysis
Mass spectrometry

ABSTRACT

Despite the legalization of recreational cannabis in California, USA, illegal cannabis cultivation remains pervasive, partly through the establishment of illegal cultivation on public lands (trespass grows). These operations often illegally divert water for irrigation and perform unauthorized applications of chemical fertilizers and pesticides. This work investigates a broad suite of these chemicals, focusing on their persistence in topsoil and presence in water and bed sediment in adjacent streams. Quantitative analyses of pesticides were conducted (183 compounds in water; 176 in topsoil/bed sediment), supplemented by qualitative nontargeted screening at three trespass grows that had no active cultivation for 8 months to 2 years. Targeted multi-residue analysis of topsoil detected the insecticides bifenthrin, cyfluthrin, malathion and imidacloprid (with concentrations up to 38 ng/g dry weight, d.w.), and the fungicides fluopyram, myclobutanil, and triadimefon (concentrations up to 8.1 ng/g d.w.). No pesticides were detected in the companion water or streambed sediment samples from adjacent streams. In addition, no water samples were found to have measurable estrogenic activity. Nontargeted screening uncovered additional pesticides (i.e., spiromesifen, trinexapac) in the topsoil and cannabis-related compounds (i.e., cannabidol, delta9-tetrahydrocannabinol) in both topsoil and streambed sediment suggesting the likelihood of

* Corresponding author at: 6000 J St, Placer Hall, Sacramento, CA, 95819, United States of America.
E-mail address: gnpecora@ucdavis.edu (G.P. Black).

https://doi.org/10.1016/j.scitotenv.2025.180576
Received 28 April 2025; Received in revised form 10 September 2025; Accepted 19 September 2025
Available online 25 September 2025
0048-9697/Published by Elsevier B.V.

offsite transport of cannabis related compounds. Phthalate plasticizers, rubber-related compounds, pharmaceuticals and personal care product chemicals were detected in topsoil, water, and streambed sediment and may be related to extensive irrigation infrastructure installed at these trespass grows. This work begins to establish a contaminant profile associated with illegal cannabis growing activities, providing a foundation for future research focused on their potential ecological impacts.

1. Introduction

California is the state with the most *Cannabis* (hearefter, cannabis) cultivation in the United States. Despite the legalization of recreational cannabis use in California in 2016, approximately 90% of this cultivation is grown illegally, amounting to roughly 5000 metric tons annually (ERA Economics, 2025). In 2021, the United States Drug Enforcement Agency (DEA) reported that over 5 million illegally cultivated plants had been seized by law enforcement agencies, constituting nearly 90 % of the seized plants nationwide (DEA, 2021). Often, these plants are seized from illegal grows located on federal public land (often referred to as "trespass grows") that alter the natural landscape.

Widespread illegal cannabis cultivation on both public and private land poses immediate environmental risks within ecologically sensitive habitats. In 2016, satellite imagery was used to identify over 4000 grows in Humboldt County, California, one of the densest cannabis growing regions in the country (Butsic and Brenner, 2016). Overlaying geographic information system (GIS) layers, they reported that most of these sites (68 %) were more than 500 m from developed roads, many were situated on steep slopes, and ~5 % were adjacent to threatened fish habitat. It was predicted that the nearly 300,000 associated plants at these sites would consume over 700,000 m^3 of water over a single growing season. Water for irrigation is frequently diverted from low-flow, headwater streams as cannabis plants require ~22.7 L of water per plant per day during the roughly 150-day growing season. In many instances, this exceeds 7-day flow averages of streams in Northern California (Bauer et al., 2015; Zheng et al., 2021). Other ecological impacts include the application of pesticides and fertilizers to maximize crop yield, vegetation clearing, and other manipulation of the landscape to create optimal growing and camouflage conditions (Wang et al., 2017; Wartenberg et al., 2021). When sites are abandoned or shut down by law enforcement, resources for site remediation are not always available. Thus, unused chemicals and fertilizers, garbage, and infrastructure are left on the landscape for prolonged periods of time (Milestone and Schifsky, 2012; Thompson et al., 2018; Wengert et al., 2018).

Cannabis cultivation is susceptible to rodent pests, a variety of detrimental insects (aphids, spider mites, white flies, leaf miners, thrips, mealy bugs) and fungal infections (powdery mildew, brown blight, gray mold) (McPartland and McKernan, 2017; Punja, 2021; Punja et al., 2019; Stone, 2014). Recently, multiple studies have identified pesticide residues, including those that are not registered for use, in distributed cannabis flower (Craven et al., 2019; Evoy and Kincl, 2020), including insecticides, fungicides, herbicides, synergists, and plant growth regulators (Dryburgh et al., 2018; López-Ruiz et al., 2022; Moulins et al., 2018; Pinkhasova et al., 2021; Rivera et al., 2025; Taylor and Birkett, 2020). These findings highlight two things, first that there is evidence that unregistered cannabis pesticides are being used during cultivation and second, that dispensaries may source illegally grown cannabis, as legal grows should only use registered pesticides. As data on pesticide residues in cannabis flower emerges, there remains a gap in the assessment of contaminants at the grow sites themselves. The only studies found to date (2025) measuring pesticides in environmental media (non-biological) at (or adjacent to) grows were published by Craven et al. (2021) and Medel et al. (2022). Craven et al. (2021) quantified pesticides at indoor registered and non-registered growing facilities in Canada and detected compounds including buprofezin, dimethoate, imidacloprid, malathion, myclobutanil, pyrethrin II, and spiromesifen. Medel et al. (2022) identified insecticides like diazinon and carbofuran using passive samplers in surface water downstream from trespass grows. Thus, organic, anthropogenic contaminants such as pesticides and pharmaceuticals are not well documented onsite at trespass grows, making it difficult to fully evaluate the ecological effect of these operations known to commonly take place on managed public land.

Some of the chemicals that are known to be used at these operations do have ecological significance, namely, rodenticides used at these sites have been linked to forest rodent mortality (Gabriel et al., 2012, 2013; Thompson et al., 2014) and biomagnification in avian predators like the northern spotted owl (*Strix occidentalis caurina*) and the barred owl (*Strix varia*) (Franklin et al., 2018; Gabriel et al., 2018; Hofstadter et al., 2021). Game cameras have been used to survey species present in the northern Sierra Nevada to model species-specific habitats in this high-intensity cannabis growing region where it was predicted that 39–74 % of "special status" species' (as defined by the California National Diversity Database, https://wildlife.ca.gov/Data/CNDDB) habitats are at high risk of overlap with grows (private and public land trespass; Rich et al., 2023). Additionally, Wengert et al. (2021) predicted that 40–48 % of modeled habitats for the endangered Pacific fisher (*Pekania pennanti*), the threatened Humboldt marten (*Martes caurina humboldtensis*) and the threatened northern spotted owl (*Strix occidentalis caurina*) overlapped with moderate- to high-likelihood areas of trespass grows. Furthermore, rodenticide residues have been detected in tissue samples of dead Pacific fishers and northern spotted owls collected near grow sites, providing further evidence of this intersection between sensitive species and illegal cannabis cultivation (Franklin et al., 2018; Thompson et al., 2014; Wengert et al., 2021).

In this study, we surveyed three trespass grows on National Forest System lands managed by the United States Forest Service in California. Pesticides and their transformation products were quantitatively analyzed in topsoil from each site, as well as surface water and sediment from streams adjacent to the sites. Complementary nontargeted analysis was performed to expand compound discovery to include other organic contaminants (e.g., other pesticides, pharmaceuticals, personal care products, cannabis-related compounds). We hypothesize that trespass grows left behind chemical residues months to years after the illegal activities ceased. Thus, the characterization of these contaminant fingerprints could allow researchers to evaluate their potential long-term ecological impact.

2. Materials & methods

2.1. Sampling

Three historically active trespass grows were sampled in California (Fig. SI-1): (1) Six Rivers National Forest (Site A, Fig. 1), (2) Shasta-Trinity National Forest (Site B, Fig. 2), and (3) San Bernardino National Forest (Site C, Fig. 3). Table 1 summarizes the closest private land, registered pesticide use (for compounds detected), paved road, and census designated place (unincorporated communities) as straight-line distances, demonstrating a low likelihood that the collected samples could be influenced by nearby activities such as agricultural or home pesticide use. Sample locations for each site are shown in Figs. 1 to 3, all sites were sampled once, and further sampling details can be found in Black et al. (2025).

Site A had been shut down by law enforcement approximately 21 months prior to sampling, Site B about 8 months prior, and Site C

roughly 24 months prior, establishing the duration of time following the last possible pesticide application. Site A had undergone basic reclamation, which is the removal of most non-hazardous infrastructure, debris, and materials, whereas Sites B and C still contained makeshift living quarters, pesticide and nutrient containers, backpack pesticide applicators, and other debris. All sites contained large dugout pits, or irrigation cisterns, used for holding diverted water.

Both Sites A and B were covered partially by forest canopy, but Site C was fully exposed. Site C was situated on a wildfire burn scar that had damaged the landscape several years prior to the site's establishment, resulting in little canopy cover and instead, was densely populated with post-fire emergent shrubs and felled, charred trees. Grow plots within each of the three sites were positioned on steep slopes (>20 %) and were uphill from small, sometimes intermittent/perennial streams.

At each site, at least one composite topsoil sample (~100 g) was collected, comprising of subsamples from 12 individual planting holes (selected by zig-zagging from the lowest elevation of the plot to the highest elevation). Shallow, hand dug indentations and remnants such as plant stalks, support stakes, or chicken wire provided evidence of where plants had been grown. From these locations, topsoil (top 5 cm) was collected using large, pre-cleaned stainless-steel scoops, combined in clean bowls or bags, homogenized, and placed into an 8 oz. high-density polyethylene (HDPE) sample container. At Sites A and B, where multiple plots were present, multiple composite topsoil samples were collected. Furthermore, topsoil samples were gathered near empty pesticide and nutrient containers. Background topsoil samples were

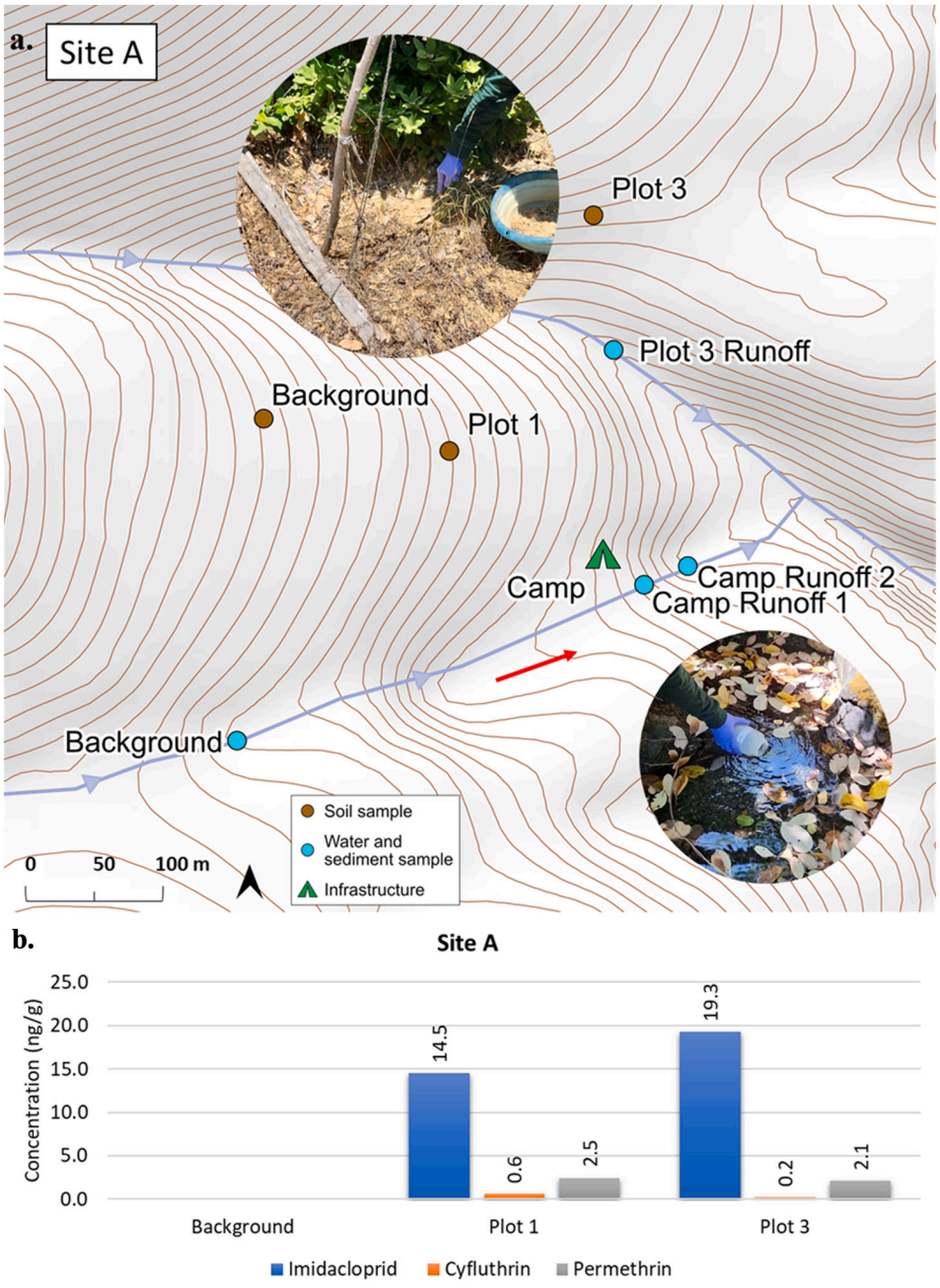


Fig. 1. (a) Map of Site A sampling points and (b) targeted pesticide analysis concentrations in topsoil samples. No targeted compounds were detected in water or sediment. Red arrow denotes general flow. The light blue lines are streams, and the triangles indicate flow direction on the streams. The red arrow denotes overall flow direction. Base map contours calculated from 2024 USGS 3D Elevation Program 1/3 arc sec elevation data (U.S. Geological Survey, 2025, USGS 3D Elevation Program Digital Elevation Model, accessed March 11, 2025). The brown lines are elevation contour lines (at intervals of 2.7 m).

collected from upslope locations to establish a comparative baseline. Samples were placed on ice for transport back to the laboratory and then frozen (−20 °C) until analysis.

Streams were present downgradient from each grow site. Discrete 1 L grab samples of water were collected in HDPE bottles in the centroid of flow at three points along the stream where field teams anticipated plot runoff, along with a background sample collected from a location upstream from any presumed plot-related influence. Bottles were rinsed three times with native water prior to collecting each sample. Immediately upstream from the water samples, sediment samples were collected after the water samples to avoid any disturbance due to water collection. A precleaned metal scoop was used to collect the upper-most layer of sediment from multiple locations within a 2-meter radius, combined in a clean silicone bowl or bag, homogenized and placed into an 8 oz. HDPE sample container. Due to low flow conditions in some instances, sediment was not always available or could not be easily sampled away from rocks. Samples were placed on ice for transport back to the laboratory and then refrigerated (4 °C) until analysis (within 48 h).

2.2. Sample preparation

2.2.1. Water sample chemistry

Water samples were extracted using the method published previously (Gross et al., 2024). Briefly, samples (1 L) were filtered, fortified with isotopically labeled surrogates (50 ng) and extracted using solid phase extraction (Oasis HLB, 6 cc, 500 mg, Waters Inc., Milford, Mass., USA). Cartridges were preconditioned with dichloromethane (6 mL), acetone (6 mL), and water (12 mL), samples were loaded, dried, and

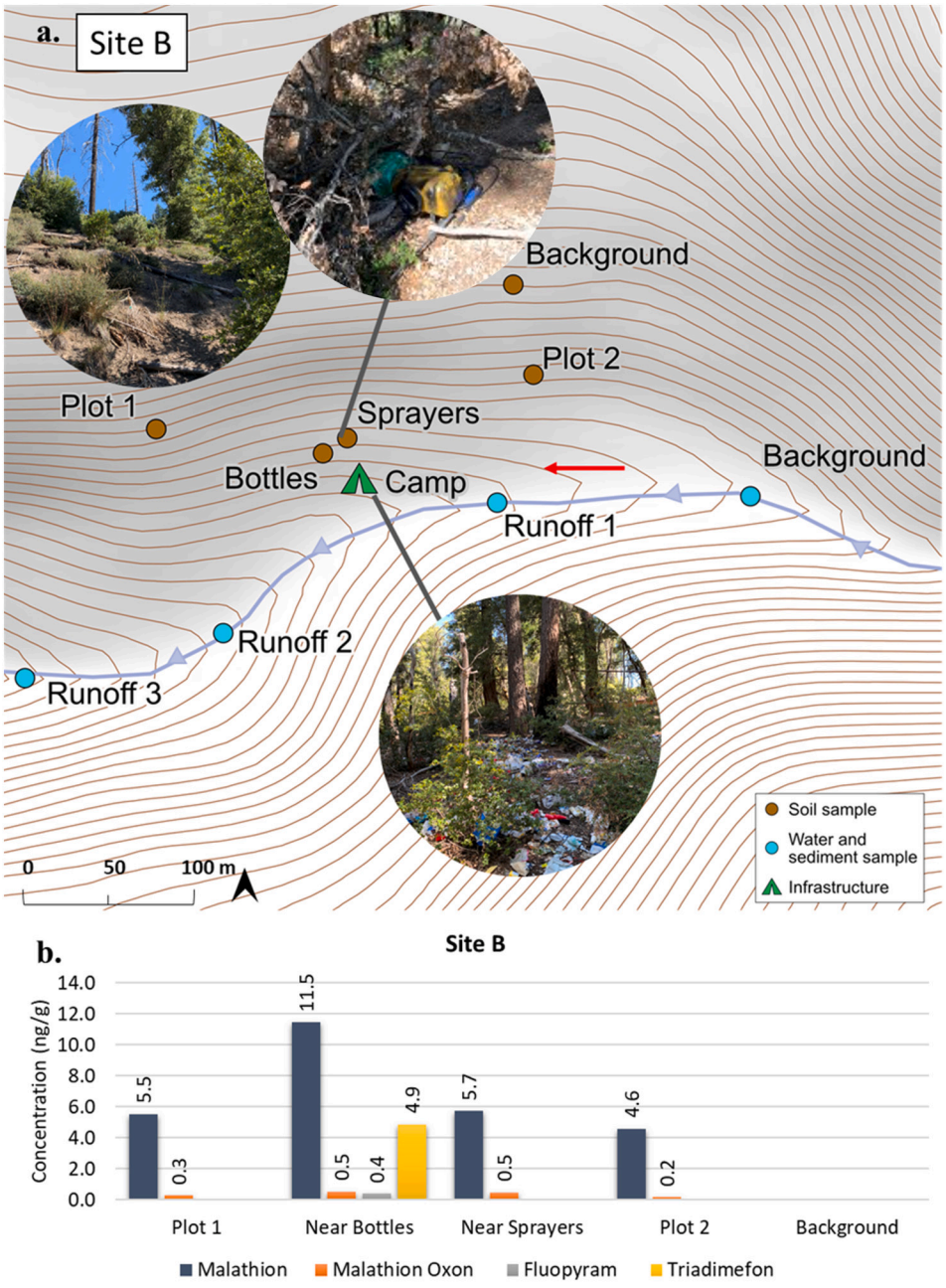


Fig. 2. (a) Map of Site B sampling points and (b) targeted pesticide analysis concentrations in topsoil samples. No targeted compounds were detected in water or sediment. Red arrow denotes general flow. The light blue lines are streams, and the triangles indicate flow direction on the streams. The red arrow denotes overall flow direction. Base map contours calculated from 2024 USGS 3D Elevation Program 1/3 arc sec elevation data (U.S. Geological Survey, 2025, USGS 3D Elevation Program Digital Elevation Model, accessed March 11, 2025). The brown lines are elevation contour lines (at intervals of 2.7 m).

eluted with 10 mL each of 1:1 dichloromethane:acetone and methanol and kept separate. Both elutions were concentrated to 0.2 mL and isotopically labeled internal standards were added to the dichloromethane:acetone elution and exchanged into acetonitrile. Aliquots of each elution were combined for nontargeted analysis and diluted 1:1 with organic-free water. 183 compounds were included in this method (Table SI-2).

2.2.2. Topsoil and sediment chemistry

Topsoil and sediment were freeze dried and extracted (5 g, dry weight) using an Energized Dispersive Guided Extraction (EDGE) method published previously (Black et al., 2023a). Briefly, the sample was fortified with 50 ng isotopically labeled surrogates, extracted with 30 mL acetonitrile at 100 °C, concentrated to 1 mL and cleaned using Carboprep 90 cartridges (graphitized carbon 500 mg, 6 cc Restek, Bellefonte, PA) preconditioned with 10 mL acetonitrile. Cartridges were eluted with acetonitrile and dichloromethane, exchanged into acetonitrile and concentrated to 0.2 mL. Isotopically labeled internal standards were added before analysis. 167 compounds were included in this method (Table SI-2). Percent organic carbon was also measured for all sediment and topsoil samples (SI Section 1).

Water, topsoil and sediment extracts were analyzed using liquid and gas chromatography tandem mass spectrometry with electrospray ionization in both positive and negative mode (LC-MS/MS [ESI+/ESI−]) and GC–MS/MS with electron impact ionization [EI]. Afterwards, 50 μL of each extract was diluted with 50 μL of organic-free water and

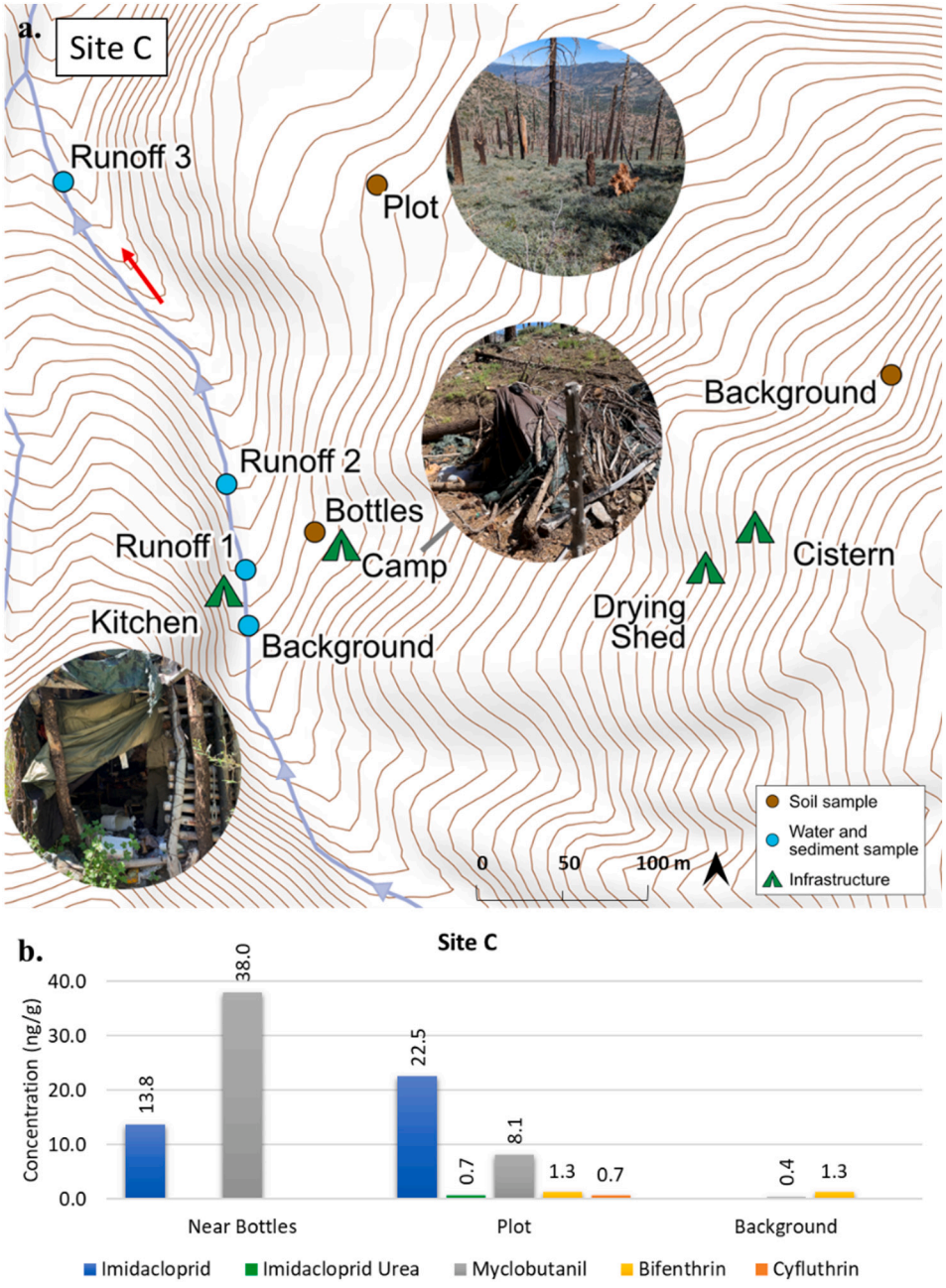


Fig. 3. (a) Map of Site C sampling points and (b) targeted pesticide concentrations in topsoil samples. No targeted compounds were detected in water or sediment. The light blue lines are streams, and the triangles indicate flow direction on the streams The red arrow denotes overall flow direction. Base map contours calculated from 2024 USGS 3D Elevation Program 1/3 arc sec elevation data. (U.S. Geological Survey, 2025, USGS 3D Elevation Program Digital Elevation Model, accessed March 11, 2025). The brown lines are elevation contour lines (at intervals of 2.7 m)

Table 1
Straight-line distances from each trespass site to neighboring points of interest.

Site	Distance to nearest registered use[a] (km)	Distance to nearest private land (km) (California Department of Forestry and Fire Protection, 2025)	Distance to nearest Census Designated Place (km) (U.S. Census Bureau, 2025)	Distance to nearest paved road (km) (U.S. Geological Survey, 2025)
Site A	62.0	1.6	25.0	0.7
Site B	63.0	1.6	8.0	4.0
Site C	26.0	5.6	9.3	1.8

[a] For a detected pesticide, data is from the most recent California Department of Pesticide Regulation Pesticide Use Report (California Department of Pesticide Regulation, 2025).

different isotopically labeled internal standards were added prior to liquid chromatography high resolution mass spectrometry (LC-HRMS, ESI+/ESI−) for nontargeted analysis.

A third extraction was performed to quantify 9 rodenticides (Table SI-4) in topsoil and sediment, adapted from Acosta-Dacal et al. (2021) (Table SI-3). Freeze-dried topsoil and sediment (2 g) were fortified with warfarin-d_5 and diphacinone-d_4 before adding 10 mL of 2.5 % formic acid in acetonitrile, vortexing briefly, and shaking for 2 min. Magnesium sulfate (6 g) and ammonium acetate (1.4 g) were added, briefly vortexed, shaken for 2 min, then sonicated for 15 min. Extracts were centrifuged for 5 min, and 2 mL of the supernatant was filtered through a 0.45 μm syringe filter. For analysis by electrospray ionization (positive and negative), 0.5 mL of the filtered extract was added to 0.5 mL of organic-free water and fortified with brodifacoum-d_5 and cholecalciferol-d_3 prior to analysis and used for internal calibration. For analysis by atmospheric pressure chemical ionization (APCI), extracts were exchanged into 10 % acetone in methanol.

2.2.3. Water samples estrogenicity

A bioluminescent yeast estrogen screen (BLYES) was used to evaluate potential estrogenic activity in water. Water samples were extracted using SPE and luminescence was quantified compared to a 1 nM estradiol control. More details are reported in Section 2 of the SI. Field blanks did not exhibit any activity, suggesting no estrogenic contaminants leached from the HDPE bottles during shipping and storage.

2.3. Data analysis

2.3.1. Multi-residue pesticides

Liquid and gas chromatography tandem mass spectrometry (LC-MS/MS and GC–MS/MS) were used to quantify 183 pesticides and pesticide degradates in water, and 167 in topsoil and sediment (Table SI-1) following methods published previously (Black et al., 2023a; Gross et al., 2024).

Briefly, separation was achieved using an Agilent (Santa Clara, CA) Infinity 1260 Bio-inert high performance liquid chromatograph coupled to a 6430 triple quadrupole mass spectrometer on an Agilent Zorbax Eclipse XDB-C18 column (2.1 mm × 150 mm, 3.5 μm), preceded by a Zorbax Eclipse XDB-C8 guard cartridge (2.1 mm × 12.5 mm, 5 μm). Analyses were performed in both positive and negative electrospray ionization (ESI) modes. Gradient regime and instrument parameters are reported in Table SI-3a. Data acquisition was performed in multiple reaction monitoring (MRM) mode, with monitored transitions listed in Table SI-2.

GC–MS/MS analysis was conducted using a Trace 1310 gas chromatograph coupled to a TSQ 9000 triple quadrupole mass spectrometer (Thermo Scientific, Waltham, MA) using an Agilent DB-5MS (30 m × 0.25 mm × 0.25 μm) column (Table SI-3b). Analyses were performed in electron impact positive ionization (EI) mode using selected reaction monitoring (SRM) mode (Table SI-2).

Target analyte concentrations were calculated using Agilent MassHunter Quantitative Analysis (v.10.1) and Thermo Fisher TraceFinder (v. 4.1) software. Concentrations were quantified using 9-point internal calibration curves ranging from 1 to 1000 ng/mL with linear $R^2 > 0.99$. Surrogate recoveries ranged from 88 to 98 % and fortified matrix recoveries ranged from 70 to 115 % across the multi-residue LC- and GC–MS/MS analyses ($n = 3$). No target analytes were measured in the method blanks (n = 3). For replicate field samples ($n = 6$) the relative percent difference ranged from 3 to 30 % for compounds detected.

2.3.2. Rodenticides

Nine rodenticides were quantified via LC-HRMS using a Thermo Scientific Vanquish HP-10 Liquid Chromatograph and Orbitrap Q-Exactive High Resolution Mass Spectrometer in positive and negative electrospray ionization and negative atmospheric pressure chemical ionization in Full Scan Data Dependent MS2 (FS-ddMS2) mode. Inclusion lists were provided to target MS2 experiments for target analytes. Separation was achieved on a Thermo Scientific Hypersil Gold Vanquish C18 column (100 × 2.1 mm, 1.9 μm). Operating parameters and chromatographic regimes are reported in Table SI-5. Normalized collision energies were optimized for each target and reported in Table SI-4. Concentrations were calculated using Thermo Fisher TraceFinder (v. 4.1) software with an internal calibration curve (linear $R^2 > 0.99$). Fortified spike recoveries ranged from 69 to 106 % ($n = 9$) except for chlorphacinone and diphacinone which were recovered at 22 % and 33 %, respectively. These two rodenticides are analytically challenging, often requiring their own dedicated method, therefore, they were only monitored qualitatively. Rodenticide surrogates had average recoveries of 93 % and 42 % for warfarin-d_5 and diphacinone-d_4, respectively (Table SI-4).

2.3.3. Quality assurance/quality control

Reproducibility was evaluated via environmental replicates and measured by relative percent difference (RPD) in calculated concentrations. RPDs across all replicates were <20 % except for two detections, one of bifenthrin and one of permethrin-$^{13}C_6$ that had RPDs of 30 % and 28 % between two replicates, respectively. All concentrations are reported as ng/g dry weight for topsoil and sediment (method detection limits = 0.1–2.6 ng/g; rodenticide method detection limits = 5.0–50 ng/g) and ng/L for water (method detection limits = 0.5–11 ng/L). No detections were observed in field or laboratory blanks. Average recoveries were calculated across three matrix spikes.

2.3.4. Nontargeted analysis

The nontargeted analysis (NTA) Study Reporting Tool (SRT) was used in the preparation of this manuscript (Peter et al., 2021). All extracts were analyzed via LC-HRMS in ESI+ and ESI− in Full Scan Data Dependent MS2 (FS-ddMS2) mode. Separation was achieved on a Thermo Scientific Hypersil Gold Vanquish C18 column (100 × 2.1 mm, 1.9 μm). Operating parameters and chromatographic regimes are reported in Table SI-6. Injection blanks and check standards were run every 10 injections. Extracts were injected in duplicate in randomized blocks separated by matrix.

Detailed alignment, data cleaning, feature prioritization, and annotation methods are reported in the SI Section S3 and Table SI-7. Briefly, features were aligned (MS-DIAL (v 4.60, Table SI-7)) and library screened through open-source spectral libraries. Data were cleaned using MS-FLO and further preprocessed using the U.S. Environmental Protection Agency's (EPA) INTERPERT NTA Tool (Supporting Information Section 3; Sobus et al., 2025). Features with a mean abundance greater than three times the mean abundance in the blanks were prioritized, and library matched compounds were investigated.

An initial screen of matches was performed, and confidence levels were tentatively assigned (Schymanski et al., 2014). Level 2a (library match) confidence levels were slightly modified to accommodate the

distribution in the quality of "library matched" features. Matches where *all* library fragments were matched at comparable ion ratios were assigned a level 2aα confidence score, which denotes an excellent spectral match. Level 2aβ was assigned to library matches where the molecular ion and *some*, but not all library fragments were matched, and/or fragment ion ratios were dissimilar due to a mismatch of collision energies between measured and reference spectra. A match with only a molecular ion and few to no matching fragments was assigned a 2aγ and not investigated further due to a high degree of annotation uncertainty. Examples of each 2a match are provided in Fig. SI-2a–c.

All initially assigned level 2aα and 2aβ annotations were modeled for retention time plausibility using the LC Retention Time Indexing model published by Aalizadeh et al. (2021). Simplified Molecular Input Line Entry System (SMILES) strings and retention times were entered into the model and results where the experimental and predicted retention times were accepted, or there was error but still accepted (box 1 and box 2 in the LC Retention Time Indexing) were considered plausible. All annotations that remained after this step were investigated more rigorously and compared to pure chemical standards and other online spectra where available.

3. Results

3.1. Targeted pesticides

Five insecticides (imidacloprid, malathion, bifenthrin, cyfluthrin, and permethrin) and two transformation products (imidacloprid urea, malathion oxon) were quantified in topsoil samples (Figs. 1b–3b, Table SI-8). Imidacloprid and cyfluthrin were the only compounds detected at more than one site and were found at similar concentrations at Sites A and C (imidacloprid = 17.5 ± 4.1 ng/g; cyfluthrin = 0.5 ± 0.3 ng/g). An empty bottle of malathion insect spray was found among the debris at Site B and malathion and its transformation product (malathion oxon) were detected at the highest concentrations near the empty bottles (malathion = 11.5 ng/g; malathion oxon = 0.5 ng/g) and sprayers (malathion = 5.7 ng/g; malathion oxon = 0.5 ng/g), but also at both plots (malathion = 5.0 ± 0.7 ng/g; malathion oxon = 0.2 ± 0.1 ng/g). Other pyrethroid insecticides were also detected, permethrin was found at Site A (2.3 ng/g) and bifenthrin at Site C (1.3 ng/g), both at higher concentrations than cyfluthrin found at Site A (0.2–0.6 ng/g). An empty bottle of gamma-cyhalothrin was found at Site C although no residues were detected in this study.

Fungicides fluopyram and myclobutanil were identified in topsoil samples at Sites B and C, respectively. At site B, fluopyram was detected at 0.4 ng/g near empty bottles. At site C, myclobutanil was detected at 38.0 ng/g near abandoned bottles, 8.1 ng/g in samples from the plot, and 0.4 ng/g in the background sample. Bifenthrin was also detected at Site C in the background sample at the same concentration detected from the plot (1.3 ng/g). This suggests that the background site was potentially not far enough removed from the cultivation area, or this location was part of a historical cultivation area as these plots are known to rotate and/or expand from year to year. This hypothesis is further supported by the concentrations observed for myclobutanil at the same site.

No targeted pesticides were detected in any water or sediment samples, or in any of the field blanks collected. No rodenticides were observed above detection limits.

3.2. Nontargeted analysis results

The number of aligned features (ions matched based on accurate mass and retention time) in the collected topsoil samples (n = 37,891) surpassed those aligned in water (n = 8595) and sediment (n = 23,844), resulting in more than twice the annotations at a level 2a or higher (Tables SI-9-11, Fig. 4). Annotated features (chemical identities assigned to detected features) more frequently originated from anthropogenic

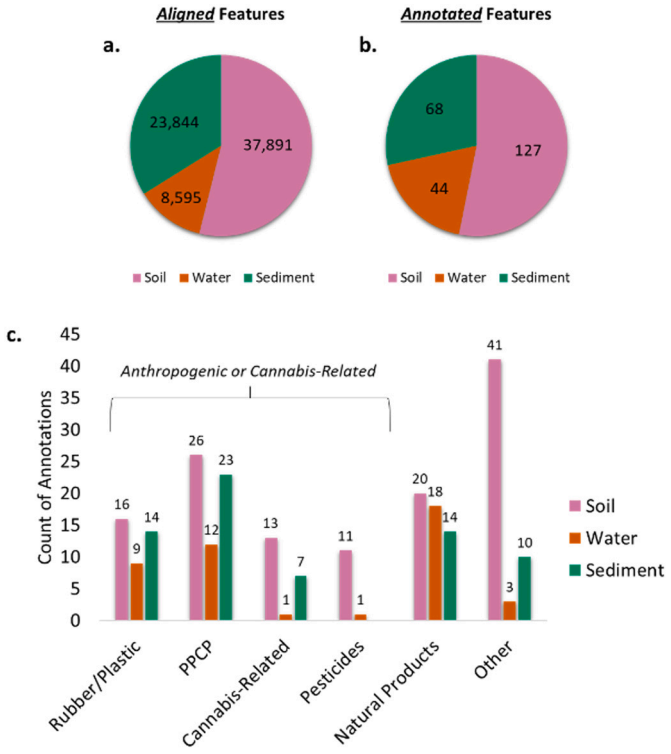


Fig. 4. Number of nontargeted features (a) aligned in each matrix, (b) annotated in each matrix, and (c) the count of annotations belonging to each class of compounds. Rubber/plastic annotations include phthalates and annotations like 1,3-diphenylguanidine and benzotriazole-3-sulfonic acid; Pharmaceuticals and personal care products (PPCP)) include various annotations associated with human activity and include ibuprofen, UV filters, caffeine, and fragrances; cannabis-related annotations include the main cannabinoids (delta9-tetrahydrocannabinol, cannabinol, and cannabidiol) but also others that have been identified in cannabis plants (e.g. myrcene); pesticides include herbicides, insecticides, fungicides, and plant growth regulators; natural products include annotations like amino acids and naturally occurring compounds; the "other" category is reserved for annotations that do not fit in any of the other categories and include annotations like diacetyl, coumarin, metenolone, and others.

sources in topsoils compared to the other matrices (Fig. 4). This is likely due to timing of sampling events and the lack of any recent plot- or camp-related runoff into nearby streams. There is, however, some evidence that previous plot-related runoff had entered these streams, as demonstrated by detections in the sediment discussed herein.

3.2.1. Pesticides

All pesticides that were detected in targeted analyses were also identified via nontargeted analyses except for the pyrethroid insecticides which are not amenable to the liquid chromatographic method implemented. Additional insecticides were detected in topsoil with nontargeted analyses. Spiromesifen (level 1) and pymetrozine (level 2aα) were found at all sites and DEET (*N*,*N*-Diethyl-*meta*-toluamide, level 2aα) at sites A and B. The plant growth regulator trinexapac (level 2aβ) that has been reported to be used in cannabis cultivation (Wu et al., 2022) and one of its transformation products (trinexapac-ethyl) was detected at site B near abandoned sprayers and bottles.

3.2.2. Cannabis-related compounds

Delta9-tetrahydrocannabinol (Δ^9-THC) is the major transformation product of cannabidiol and is the main psychoactive component of cannabis. In sediment samples, Δ^9-*trans*-THC (level 1) was detected at Site A. Myrcene (level 2aβ), a monoterpene and cannabis constituent was detected in sediment from Sites A and C and in water at Site B. Cannabinol (level 1), cannabidiol (level 1), Δ^9-*trans*-THC (level 1), and

myrcene (level 2aβ) were detected in topsoil at all three sites (Fig. 5).

Δ^9-THC exists in two main diastereomers (Δ^9-*trans*-THC and Δ^9-*cis*-THC), with two enantiomer pairs for each (+ and −). Additionally, cannabichromene and Δ^9-THC-stereoisomers, Δ^8-THC and Δ^{10}-THC, have also been observed at the same ion mass (*m/z* 313.2166, Fig. 6). Based on work by Schafroth et al. (2021) and confirmation of cannabidiol (Fig. 6a, peak b) and Δ^9-*trans*-THC (Fig. 6a, peak e) with pure chemical standards, it is hypothesized that either peaks c or d (Fig. 5a) could be Δ^9-*cis*-THC, which naturally occurs at less than half the abundance of Δ^9-*trans*-THC. Peaks f and g could be Δ^8-*trans*-THC and cannabichromene, respectively. Regardless of individual peak assignments, the abundance of *m/z* 313.2166 peaks provides evidence that cannabis-related compounds persist in the topsoil for prolonged periods of time (up to at least 2 years).

Other cannabinoids were also identified. Hypnohilin (level 2aβ), a cannabinoid, was detected in Sites A and B topsoil, caryophyllene oxide (level 2aβ), a cannabis terpene was detected in Site A and B sediment, and divarinol (level 2aβ) a minor cannabinoid, was detected in Site A sediment. Specifically for the detections of cannabis-related compounds at Site A, much of the sediment collected were closer to the "camp" (living quarters for growers), suggesting cannabis processing occurred near these areas. Regardless, it appears that cannabis-related compounds reached streams at each site, whether originating from cultivation, processing (e.g. trimming), or potentially personal use. Myrcene and divaricatinic acid (level 2aβ), another minor cannabinoid, were detected in the water collected at Site B.

3.2.3. Pharmaceuticals and personal care products

At each site, camps and living quarters were closer to streams than the plots themselves. Gabapentin (level 2aβ), an anticonvulsant used to treat neuropathy and pervasive environmental contaminant (Burns et al., 2018; Herrmann et al., 2015; Huerta-Fontela et al., 2011; Kasprzyk-Hordern et al., 2008, 2009; Writer et al., 2013; Zühlke et al., 2004) was identified in sediment at every site along with its pharmacological analog, gabapentin related compound E (2aβ) in Site A sediment and topsoil. A suite of pharmaceuticals were detected in topsoil samples at all sites including the anti-inflammatories enoxolone (level 2aα) and naproxen (level 2aβ), the barbiturate butabarbital (level 2aβ), and the antifungal griseofulvin (level 2aα) and its degradate dechlorogriseofulvin (level 2aα).

Common personal care product compounds were also detected in topsoil and include fragrance derivatives galaxolidone (level 2aβ) and methyl trans-styryl ketone (level 2aα) and the UV-filter 4-methylbenzophenone (level 2aβ). 2,4-dihydroxybenzophenone (level 2aα, UV-filter) was detected in water at Site B.

3.2.4. Plasticizers and rubber-related compounds

Phthalate and bisphenol plasticizers were found in topsoil, water, and sediment at all sites. Diethylene glycol dibenzoate (level 2aβ) and di-n-octyl phthalate (level 2aα) were detected across all sites and are often associated with polyvinylchloride (PVC) products. Other plasticizers included phthalic anhydride (level 2aα), tris(2-butoxyethyl) phosphate (level 2aα), and tris(2-chloroethyl)phosphate (level 2aα) in water; diethyl-, diphenyl- and diisopropyl-phthalate (level 2aβ) and bisphenol A (level 2aβ) in sediment; and mono(ethylhexyl)- and dicyclohexyl-phthalate (level 2aβ), phthalic acid (level 2aβ), bisphenol A (level 2aβ), and bisphenol AF (level 2aβ) in topsoil.

Benzothiazole-2-sulfonic acid (level 1) and 1,3-diphenylguanidine (level 1) were identified at all sites.

Despite the presence of known endocrine disrupting compounds, there was a noted lack of estrogenic activity as identified by the yeast bioassay in all water samples.

4. Discussion

Multiple organic contaminants were detected at each trespass grow site. Recently, several studies have investigated pesticide residues in cannabis products reaching dispensaries and all pesticides detected in this work have been previously detected in cannabis flower (Gagnon et al., 2023; Maguire et al., 2019; Moulins et al., 2018; Pinkhasova et al., 2021; Taylor and Birkett, 2020). No research to date, however, has measured this range of compounds in (non-biological) environmental media at trespass grows. Previous studies investigating pesticides in agricultural (not cannabis related) soils report higher concentrations for most of the detected compounds observed in this study. Woodward et al. (2022) measured 20.3 ng/g imidacloprid in California soil in a study that focused on application to lettuce via drenching. Another study reported the average concentration of imidacloprid across 11 studies of agricultural soils worldwide ($n = 845$ soil samples) was 88.6 ng/g, with an average maximum concentration of 431.8 ng/g (Sabzevari and Hofman, 2022). Average concentrations by the same study exceeded concentrations reported here for triadimefon (average maximum concentration = 8.5 ng/g) and bifenthrin (average maximum concentration = 34.7 ng/g). All compounds quantified in this study were below the average maximum concentrations reported across three or more studies by Sabzevari and Hofman (2022). While concentrations were generally lower than those found in agricultural soils worldwide, samples in this study were collected at least 8 months after the last possible

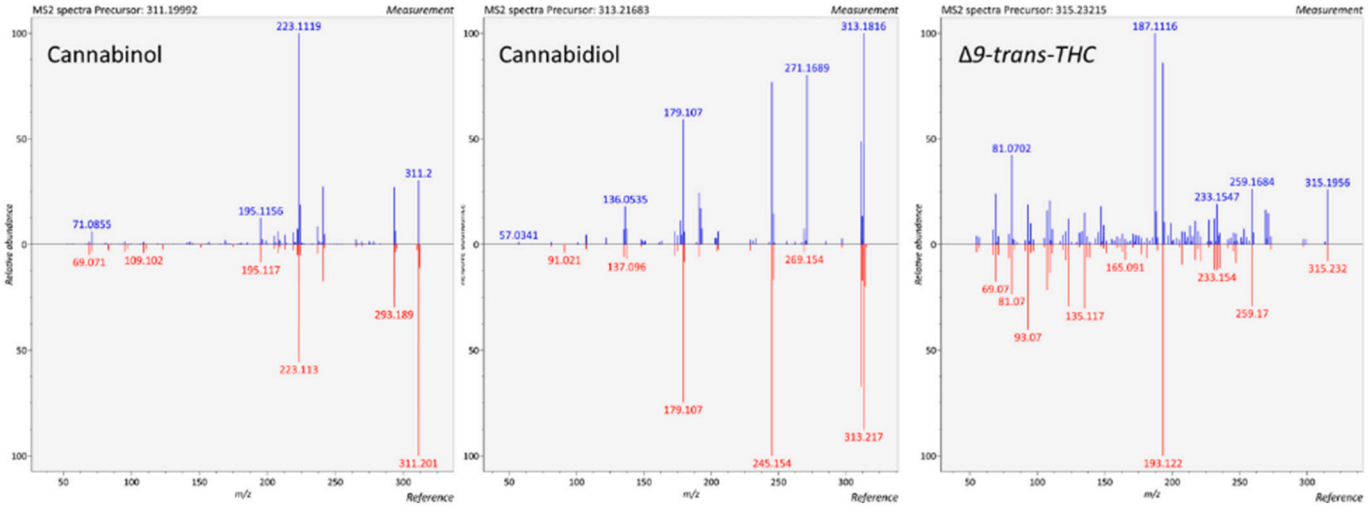


Fig. 5. Library matches (reference_ of main cannabis-related cannabinoids cannabinol, cannabidiol, and Δ9-trans-tetrahydrocannabinol (Δ9-trans-THC) in MSDIAL. All compounds were confirmed with a pure chemical standard.

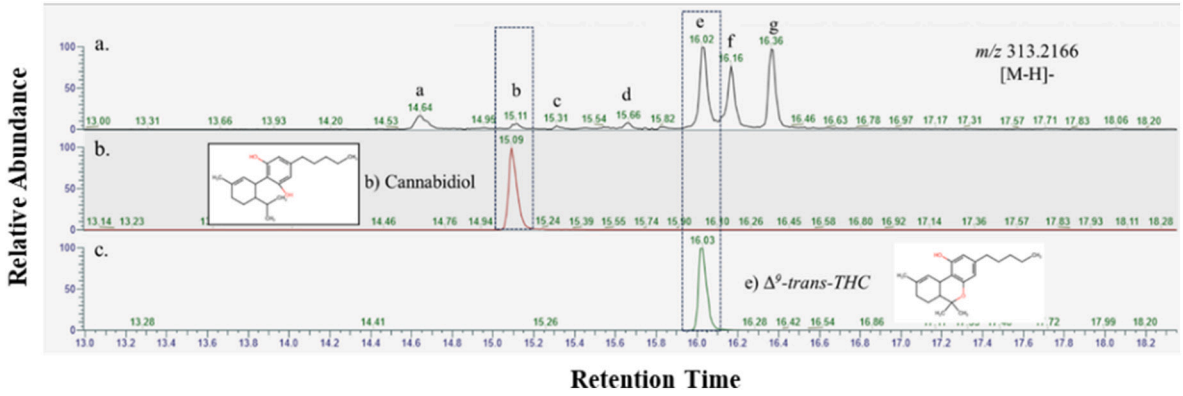


Fig. 6. Extracted Ion Chromatogram of *m/z* 313.2166 in ESI− (a) Site C plot, (b) pure chemical standard of cannabidiol, and (c) pure chemical standard of Δ9-trans-THC (tetrahydrocannabinol).

pesticide application, thus the maximum concentrations during active cannabis growing could have been greater that what was measured here. This is evidenced by the lack of any rodenticide detections despite finding a diphacinone-labeled container at Site B. Unlike insecticides and fungicides however, rodenticides may be applied to different areas of a plot (e.g. along the perimeter) and therefore not appropriately sampled and/or interaction with wildlife or soil biotransformation may have occurred during this timeframe.

Since chemical signatures are not yet well understood at trespass grows, nontargeted analysis allowed for a broader profiling of contaminants present for a prolonged period. The results of this study could be used to inform target analyte lists used in future studies. When evaluating nontargeted analyses, however, it is paramount to consider the chemical space of a given method (Black et al., 2023b). In this work, there is apparent bias towards pesticides and structural analogs as extracts prepared by a routine multiresidue methods meant to target specific pesticides were used for nontargeted analyses.

One of the compound classes captured by the topsoil and sediment method are cannabinoids. The detection of cannabinoids at cannabis farms is not unexpected, but this work documents their persistence even after 2 years post-reclamation (when all plants had been removed).

Of the nontarget annotations, griseofulvin is unique in that it has long been used as an orally administered antifungal medication to treat athlete's foot and ringworm (Aris et al., 2022), but it has also been used in agricultural applications to protect crops against fungal infections (Bai et al., 2019, 2024; Pan et al., 2012). Additionally, Punja et al. (2019) isolated *Penicillium griseofulvum* (whose secondary metabolite is griseofulvin) from harvested and trimmed *Cannabis sativa*. Along the same lines, the nephrotoxin and the mycotoxin, citrinin (level 2aβ), a metabolite of *Penicillium citrinum* was identified in topsoil samples. The presence of these two fungal metabolites suggests that "bud rot" or other fungal disease could have been present in the plants on site (Punja et al., 2019). Another plausible source is that law enforcement teams reported that plants are sometimes cut and piled to promote mold or fungal growth, thus ruining the crop if reclamation resources were unable to immediately remove the material.

At each site, multiple phthalate plasticizers were annotated. A recent study detected phthalate plasticizers in up to 80 % of edible and topical cannabis products tested ($n = 516$) (Gardener et al., 2022). At Sites B and C, which were un-reclaimed, a variety of plastics remained littered throughout the site including irrigation tubing, pesticide and fertilizer containers, mattresses, tents, chairs and more which could be additional sources of plasticizer leaching. At each site, water was diverted over long distances with polyethylene tubing and other plastics that are susceptible to leaching.

In general, more cannabis-related contaminants were identified/annotated in the topsoil samples compared to the companion water and sediment samples collected at each site. This could be because samples were collected during the dry months of June and August (e.g., when sites had not received rainfall in over 60 days). This, in conjunction with the amount of time that had passed since growing operations were active (8–24 months), makes it difficult to draw any conclusions regarding surface runoff of contaminants. While selecting sites for this study, it was challenging to find sites with adjacent streams, so despite the prolific number of illegal grows in the state, it is difficult to sample during runoff events to characterize potential threats to aquatic ecosystems. Water samples collected during the wet season, and immediately following the first flush near recently active sites would aid in characterizing offsite transport. Additionally, evaluating soil samples from more recently active sites would provide a better understanding of organic compounds that are susceptible to off-site transport.

Our complementary use of targeted and nontargeted analysis provides characterization of the contaminant profile of trespass grows and highlights that organic chemicals that remain on the landscape for months or years after operations have ceased. The detection of pesticides, pharmaceuticals, plasticizers, and cannabinoids suggest potential lasting impacts on these ecosystems. Further work to include sampling at more recently active sites may help identify the actual concentrations on-site during active growing periods which may have more severe toxicological implications on the ecosystem than those observed in this study.

5. Conclusions

Pesticides, pharmaceuticals, plasticizers, cannabinoids and other anthropogenic organic contaminants were detected in topsoil, water, and sediment collected from trespass cannabis grows. Cannabis-related compounds were ubiquitously detected in topsoil samples from all three trespass grows. A combined approach using targeted and nontargeted analysis provided the first broad characterization of contaminant profiles at trespass grows operated on public land. Substantially more contaminants were identified in topsoil samples compared to water and sediment, potentially due to sample collection timing (dry season) and timespan since growing activities occurred. Nevertheless, this work identified over 200 organic chemical constituents that remained on the landscape 8 to 24 months after growing operations had ceased. Further research is warranted at more recently active grow sites to better evaluate contaminant profiles at these sites. Future work investigating adjacent streams, especially during storm events would also provide more information on potential offsite transport from trespass grows.

CRediT authorship contribution statement

Gabrielle P. Black: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Matthew De Parsia:** Writing –

review & editing, Methodology, Investigation, Conceptualization. **Matthew Uychutin:** Methodology, Investigation, Conceptualization. **Mourad Gabriel:** Resources, Conceptualization. **Ivan Medel:** Resources, Conceptualization. **Greta Wengert:** Resources, Conceptualization. **Clayton D. Raines:** Formal analysis. **Dana W. Kolpin:** Writing – review & editing, Funding acquisition, Conceptualization. **Laura E. Hubbard:** Funding acquisition, Conceptualization. **Michelle L. Hladik:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Support for this study was provided by the U.S. Geological Survey's Environmental Health Program under the Ecosystems Mission Area, the U.S. Forest Service and the Integral Ecology Research Center. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

All data described in this manuscript are publicly available in a U.S. Geological Survey Data Release (Black et al., 2025).

The authors would like to thank the U.S. Forest Service for their contributions to this work and Jon Sobus, Alex Chao, Troy Ferland and Heather Whitehead at the U.S. Environmental Protection Agency for their help facilitating data processing through the U.S. Environmental Protection Agency's INTERPRET NTA tool.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2025.180576.

Data availability

All data described in this manuscript are publicly available in a U.S. Geological Survey Data Release (Black et al., 2025).

References

Aalizadeh, R., Alygizakis, N.A., Schymanski, E.L., Krauss, M., Schulze, T., Ibáñez, M., McEachran, A.D., Chao, A., Williams, A.J., Gago-Ferrero, P., Covaci, A., Moschet, C., Young, T.M., Hollender, J., Slobodnik, J., Thomaidis, N.S., 2021. Development and Application of Liquid Chromatographic Retention Time Indices in HRMS-Based Suspect and Nontarget Screening. Anal. Chem. 93 (33), 11601–11611. https://doi.org/10.1021/acs.analchem.1c02348.

Acosta-Dacal, A., Rial-Berriel, C., Díaz-Díaz, R., Bernal-Suárez, M.D.M., Zumbado, M., Henríquez-Hernández, L.A., Luzardo, O.P., 2021. An easy procedure to quantify anticoagulant rodenticides and pharmaceutical active compounds in soils. Toxics 9 (4). https://doi.org/10.3390/toxics9040083.

Aris, P., Wei, Y., Mohamadzadeh, M., Xia, X., 2022. Griseofulvin: an updated overview of old and current knowledge. Molecules 27 (20). https://doi.org/10.3390/molecules27207034. MDPI.

Bai, Y.-B., Gao, Y.-Q., Nie, X.-D., Tuong, T.-M.-L., Li, D., Gao, J.-M., 2019. Antifungal activity of Griseofulvin derivatives against phytopathogenic fungi in vitro and in vivo and three-dimensional quantitative structure–activity relationship analysis. J. Agric. Food Chem. 67 (22), 6125–6132. https://doi.org/10.1021/acs.jafc.9b00606.

Bai, Y.-B., Yang, K.-M., Zhang, M., Li, Y.-X., Zhao, Y., Huang, L.-Z., Yang, H., Yang, X.-J., Li, D., Gao, J.-M., 2024. Synthesis and antifungal activities of novel griseofulvin derivatives as potential anti-phytopathogenic fungi agents. J. Agric. Food Chem. 72 (23), 13015–13022. https://doi.org/10.1021/acs.jafc.4c02826.

Bauer, S., Olson, J., Cockrill, A., Van Hattem, M., Miller, L., Tauzer, M., Leppig, G., 2015. Impacts of surface water diversions for marijuana cultivation on aquatic habitat in four northwestern California watersheds. PloS One 10 (3). https://doi.org/10.1371/journal.pone.0120016.

Black, G.P., Woodward, E.E., Sanders, C.J., Gross, M.S., Hladik, M.L., 2023a. Multiresidue extraction of current-use pesticides from complex solid matrices using energized dispersive guided extraction with analysis by gas and liquid chromatography tandem mass spectroscopy. Chemosphere 327, 138550. https://doi.org/10.1016/j.chemosphere.2023.138550.

Black, G., Lowe, C., Anumol, T., Bade, J., Favela, K., Feng, Y.L., Knolhoff, A., Mceachran, A., Nuñez, J., Fisher, C., Peter, K., Quinete, N.S., Sobus, J., Sussman, E., Watson, W., Wickramasekara, S., Williams, A., Young, T., 2023b. Exploring chemical space in non-targeted analysis: a proposed ChemSpace tool. Anal. Bioanal. Chem. 415 (1), 35–44. https://doi.org/10.1007/s00216-022-04434-4.

Black, G.P., De Parsia, M., Uychutin, M., Gabriel, M., Medel, I., Wengert, G., Hladik, M.L., 2025. Organic Contaminants at Trespass Cannabis Grows on Federal Land in California. U.S. Geological Survey Data Release, USA. https://doi.org/10.5066/P145RVZE.

Burns, E.E., Carter, L.J., Kolpin, D.W., Thomas-Oates, J., Boxall, A.B.A., 2018. Temporal and spatial variation in pharmaceutical concentrations in an urban river system. Water Res. 137, 72–85. https://doi.org/10.1016/j.watres.2018.02.066.

Butsic, V., Brenner, J.C., 2016. Cannabis (Cannabis sativa or C. indica) agriculture and the environment: A systematic, spatially-explicit survey and potential impacts. Environ. Res. Lett. 11 (4). https://doi.org/10.1088/1748-9326/11/4/044023.

California Department of Forestry and Fire Protection, 2025. Public Land Ownership. California State Geoportal. March 20. Https://Gis.Data.ca.Gov/Datasets/CALFIRE-Forestry::California-Land-Ownership/About.

California Department of Pesticide Regulation, 2025. Pesticide Use Reporting Database. March 6. https://www.cdpr.ca.gov/pesticide-use-in-california/pesticide-use-reporting/.

Craven, C.B., Wawryk, N., Jiang, P., Liu, Z., Li, X.F., 2019. Pesticides and trace elements in cannabis: analytical and environmental challenges and opportunities. J. Environ. Sci. (China) 85, 82–93. https://doi.org/10.1016/j.jes.2019.04.028.

Craven, C.B., Birjandi, A.P., Simons, B., Jiang, P., Li, X.F., 2021. Determination of eighty-two pesticides and application to screening pesticides in cannabis growing facilities. J. Environ. Sci. (China) 104, 11–16. https://doi.org/10.1016/j.jes.2020.11.004.

DEA- Drug Enforcement Administration, 2021. Domestic cannabis suppression/eradication program.

Dryburgh, L.M., Bolan, N.S., Grof, C.P.L., Galettis, P., Schneider, J., Lucas, C.J., Martin, J. H., 2018. Cannabis contaminants: sources, distribution, human toxicity and pharmacologic effects. Br. J. Clin. Pharmacol. 84 (11), 2468–2476. https://doi.org/10.1111/bcp.13695.

ERA Economics, L, 2025. California Cannabis Market 2024 Report.

Evoy, R., Kincl, L., 2020. Evaluation of pesticides found in oregon cannabis from 2016 to 2017. Annals of Work Exposures and Health 64 (7), 770–774. https://doi.org/10.1093/ANNWEH/WXZ075.

Franklin, A.B., Carlson, P.C., Rex, A., Rockweit, J.T., Garza, D., Culhane, E., Volker, S.F., Dusek, R.J., Shearn-Bochsler, V.I., Gabriel, M.W., Horak, K.E., 2018. Grass is not always greener: Rodenticide exposure of a threatened species near marijuana growing operations. BMC. Res. Notes 11 (1). https://doi.org/10.1186/s13104-018-3206-z.

Gabriel, M.W., Woods, L.W., Poppenga, R., Sweitzer, R.A., Thompson, C., Matthews, S. M., Higley, J.M., Keller, S.M., Purcell, K., Barrett, R.H., Wengert, G.M., Sacks, B.N., Clifford, de ana L., 2012. Anticoagulant rodenticides on our public and community lands: spatial distribution of exposure and poisoning of a rare forest carnivore. PLoS One 7 (7). https://doi.org/10.1371/journal.pone.0040163.

Gabriel, M.W., Wengert, G.M., Higley, J.M., Krogan, S., Sargent, W., Clifford, D.L., 2013. Silent forests? Rodenticides on illegal marijuana crops harm wildlife. Wildlife Prof. 46–50. www.wildlife.org.

Gabriel, M.W., Diller, L.V., Dumbacher, J.P., Wengert, G.M., Higley, J.M., Poppenga, R. H., Mendia, S., 2018. Exposure to rodenticides in northern spotted and barred owls on remote forest lands in northwestern california: evidence of food web contamination. Avian Conservation and Ecology 13 (1). https://doi.org/10.5751/ACE-01134-130102.

Gagnon, M., McRitchie, T., Montsion, K., Tully, J., Blais, M., Snider, N., Blais, D.R., 2023. High levels of pesticides found in illicit cannabis inflorescence compared to licensed samples in Canadian study using expanded 327 pesticides multiresidue method. Journal of Cannabis Research 5 (1). https://doi.org/10.1186/s42238-023-00200-0.

Gardener, H., Wallin, C., Bowen, J., 2022. Heavy metal and phthalate contamination and labeling integrity in a large sample of US commercially available cannabidiol (CBD) products. Sci. Total Environ. 851, 158110. https://doi.org/10.1016/j.scitotenv.2022.158110.

Gross, M.S., Sanders, C.J., De Parsia, M.D., Hladik, M.L., 2024. Techniques and Methods 5-A12 Water Resources Mission Area-Water Availability and Use Science Program Methods of Analysis-Determination of Pesticides in Filtered Water and Suspended Sediment using Liquid Chromatography-and Gas Chromatography-Tandem Mass Spectrometry.

Herrmann, M., Menz, J., Olsson, O., Kümmerer, K., 2015. Identification of phototransformation products of the antiepileptic drug gabapentin: Biodegradability and initial assessment of toxicity. Water Res. 85, 11–21. https://doi.org/10.1016/j.watres.2015.08.004.

Hofstadter, D.F., Kryshak, N.F., Gabriel, M.W., Wood, C.M., Wengert, G.M., Dotters, B.P., Roberts, K.N., Fountain, E.D., Kelly, K.G., Keane, J.J., Whitmore, S.A., Berigan, W.J., Peery, M.Z., 2021. High rates of anticoagulant rodenticide exposure in California Barred Owls are associated with the wildland-urban interface. Ornithological Applications 123 (4). https://doi.org/10.1093/ornithapp/duab036.

Huerta-Fontela, M., Galceran, M.T., Ventura, F., 2011. Occurrence and removal of pharmaceuticals and hormones through drinking water treatment. Water Res. 45 (3), 1432–1442. https://doi.org/10.1016/j.watres.2010.10.036.

Kasprzyk-Hordern, B., Dinsdale, R.M., Guwy, A.J., 2008. The occurrence of pharmaceuticals, personal care products, endocrine disruptors and illicit drugs in

surface water in South Wales, UK. Water Research 42 (13), 3498–3518. https://doi.org/10.1016/j.watres.2008.04.026.
Kasprzyk-Hordern, B., Dinsdale, R.M., Guwy, A.J., 2009. Illicit drugs and pharmaceuticals in the environment - forensic applications of environmental data, Part 2: pharmaceuticals as chemical markers of faecal water contamination. Environ. Pollut. 157 (6), 1778–1786. https://doi.org/10.1016/j.envpol.2009.02.019.
López-Ruiz, R., Marín-Sáez, J., Garrido Frenich, A., Romero-González, R., 2022. Recent applications of chromatography for analysis of contaminants in cannabis products: a review. Pest Manag. Sci. 78 (1), 19–29. https://doi.org/10.1002/ps.6599.
Maguire, W.J., Call, C.W., Cerbu, C., Jambor, K.L., Benavides-Montes, V.E., 2019. Comprehensive determination of unregulated pesticide residues in oregon cannabis flower by liquid chromatography paired with triple quadrupole mass spectrometry and gas chromatography paired with triple quadrupole mass spectrometry. J. Agric. Food Chem. 67 (46), 12670–12674. https://doi.org/10.1021/acs.jafc.9b01559.
McPartland, J.M., McKernan, K.J., 2017. Contaminants of concern in cannabis: Microbes, heavy metals and pesticides. Cannabis sativa L. - Botany and Biotechnology 457–474. https://doi.org/10.1007/978-3-319-54564-6_22.
Medel, I.D., Gabriel, M.W., Wengert, G.M., Filigenzi, M.S., Clifford, D.L., 2022. Passive monitoring of soluble pesticides linked to cannabis cultivation: a multi-scale analysis. Water Quality Research Journal 57 (4), 233–246. https://doi.org/10.2166/wqrj.2022.101.
Milestone, J.F., Schifsky, D., 2012. Continued Cultivation of Illegal Marijuana in U.S. Western National Parks. The George Wright Society.
Moulins, J.R., Blais, M., Montsion, K., Tully, J., Mohan, W., Gagnon, M., Mcritchie, T., Kwong, K., Snider, N., Blais, D.R., 2018. Multiresidue method of analysis of pesticides in medical cannabis. J. AOAC Int. 101 (6), 1948–1960. https://doi.org/10.5740/jaoacint.17-0495.
Pan, Z.-Z., Zhu, Y.-J., Yu, X.-J., Lin, Q.-F., Xiao, R.-F., Tang, J.-Y., Chen, Q.-X., Liu, B., 2012. Synthesis of 4′-thiosemicarbazonegriseofulvin and its effects on the control of enzymatic browning and postharvest disease of fruits. J. Agric. Food Chem. 60 (43), 10784–10788. https://doi.org/10.1021/jf302356x.
Peter, K.T., Phillips, A.L., Knolhoff, A.M., Gardinali, P.R., Manzano, C.A., Miller, K.E., Pristner, M., Sabourin, L., Sumarah, M.W., Warth, B., Sobus, J.R., 2021. Nontargeted analysis study reporting tool: a framework to improve research transparency and reproducibility. Anal. Chem. 93, 13870–13879. https://doi.org/10.1021/acs.analchem.1c02621.
Pinkhasova, D.V., Jameson, L.E., Conrow, K.D., Simeone, M.P., Davis, A.P., Wiegers, T. C., Mattingly, C.J., Leung, M.C.K., 2021. Regulatory status of pesticide residues in cannabis: Implications to medical use in neurological diseases. Current Research in Toxicology 2, 140–148. https://doi.org/10.1016/j.crtox.2021.02.007.
Punja, Z.K., 2021. Emerging diseases of Cannabis sativa and sustainable management. Pest Manag. Sci. 77 (9), 3857–3870. https://doi.org/10.1002/ps.6307.
Punja, Z.K., Collyer, D., Scott, C., Lung, S., Holmes, J., Sutton, D., 2019. Pathogens and molds affecting production and quality of Cannabis sativa L. Front. Plant Sci. 10. https://doi.org/10.3389/fpls.2019.01120.
Rich, L.N., Medel, I.D., Bangen, S., Wengert, G.M., Toenies, M., Tucker, J.M., Gabriel, M. W., Davis, C.L., 2023. Integrating existing data to assess the risk of an expanding land use change on mammals. Landsc. Ecol. 38 (12), 3189–3204. https://doi.org/10.1007/s10980-023-01780-1.
Rivera, A.B., Stephens, A.B., Conrow, K.D., Griffith, S.T., Jameson, L.E., Cahill, T.M., Sammi, S.R., Swinburne, M.R., Cannon, J.R., Leung, M.C.K., 2025. Regulatory trends of organophosphate and pyrethroid pesticides in cannabis and applications of the Comparative Toxicogenomics Database and Caenorhabditis elegans. Toxicol. Sci. https://doi.org/10.1093/toxsci/kfaf009.
Sabzevari, S., Hofman, J., 2022. A worldwide review of currently used pesticides' monitoring in agricultural soils. Sci. Total Environ. 812, 152344. https://doi.org/10.1016/j.scitotenv.2021.152344.
Schafroth, M.A., Mazzoccanti, G., Reynoso-Moreno, I., Erni, R., Pollastro, F., Caprioglio, D., Botta, B., Allegrone, G., Grassi, G., Chicca, A., Gasparrini, F., Gertsch, J., Carreira, E.M., Appendino, G., 2021. Δ9-cis-Tetrahydrocannabinol: natural occurrence, chirality, and pharmacology. J. Nat. Prod. 84 (9), 2502–2510. https://doi.org/10.1021/acs.jnatprod.1c00513.
Schymanski, E.L., Jeon, J., Gulde, R., Fenner, K., Ruff, M., Singer, H.P., Hollender, J., 2014. Identifying small molecules via high resolution mass spectrometry: communicating confidence. Environ. Sci. Tech. 48 (4), 2097–2098. https://doi.org/10.1021/es5002105.
Sobus, J.R., Sayre-Smith, N.A., Chao, A., Ferland, T.M., Minucci, J.M., Carr, E.T., Brunelle, L.D., Batt, A.L., Whitehead, H.D., Cathey, T., Boyce, M., Ulrich, E.M., McCord, J.P., Williams, A.J., 2025. Automated QA/QC reporting for non-targeted analysis: a demonstration of "INTERPRET NTA" with de facto water reuse data. Anal. Bioanal. Chem. https://doi.org/10.1007/s00216-025-05771-w.
Stone, D., 2014. Cannabis, pesticides and conflicting laws: the dilemma for legalized States and implications for public health. Regul. Toxicol. Pharmacol. 69 (3), 284–288. https://doi.org/10.1016/j.yrtph.2014.05.015.
Taylor, A., Birkett, J.W., 2020. Pesticides in cannabis: a review of analytical and toxicological considerations. Drug Test. Anal. 12 (2), 180–190. https://doi.org/10.1002/dta.2747.
Thompson, C., Sweitzer, R., Gabriel, M., Purcell, K., Barrett, R., Poppenga, R., 2014. impacts of rodenticide and insecticide toxicants from marijuana cultivation sites on fisher survival rates in the Sierra National Forest, California. Conservation Letters 7 (2), 91–102. https://doi.org/10.1111/conl.12038.
Thompson, C., Gabriel, M.W., Wengert, G.M., 2018. Effects of illegal marijuana cultivation on wildlife: pesticide exposure in a native carnivore and consequences for the species' survival. In: Where There's Smoke: The Environmental Science, Public Policy, and Politics of Marijuana, pp. 40–57. https://doi.org/10.2307/j.ctt20vxpz6.
U.S. Census Bureau, 2025. tl_2024_06_place, TIGER/Line Shapefiles. March 11. Https://Www.Census.Gov/Cgi-Bin/Geo/Shapefiles/Index.Php?Year=2024&layergroup=Places.
U.S. Geological Survey, 2025. The National Map: USGS Imagery Topo. March 20. Https://Apps.Nationalmap.Gov/Viewer/.
Wang, I.J., Brenner, J.C., Butsic, V., 2017. Cannabis, an emerging agricultural crop, leads to deforestation and fragmentation. Front. Ecol. Environ. 15 (9), 495–501. https://doi.org/10.1002/fee.1634.
Wartenberg, A.C., Holden, P.A., Bodwitch, H., Parker-Shames, P., Novotny, T., Harmon, T.C., Hart, S.C., Beutel, M., Gilmore, M., Hoh, E., Butsic, V., 2021. Cannabis and the environment: what science tells us and what we still need to know. Environ. Sci. Technol. Lett. 8 (2), 98–107. https://doi.org/10.1021/acs.estlett.0c00844.
Wengert, G.M., Gabriel, M.W., Higley, J.M., Thompson, C., Huffman, J., 2018. Ecological impacts across the landscape: trespass marijuana cultivation on western public lands. In: Where There's Smoke: The Environmental Science, Public Policy, and Politics of Marijuana, pp. 29–39. https://doi.org/10.2307/j.ctt20vxpz6.
Wengert, G.M., Higley, J.M., Gabriel, M.W., Rustigian-Romsos, H., Spencer, W.D., Clifford, D.L., Thompson, C., 2021. Distribution of trespass cannabis cultivation and its risk to sensitive forest predators in California and Southern Oregon. PLoS One 16 (9 September). https://doi.org/10.1371/journal.pone.0256273.
Woodward, E.E., Hladik, M.L., Main, A.R., Cahn, M., Orlando, J.L., Teerlink, J., 2022. Comparing imidacloprid, clothianidin, and azoxystrobin runoff from lettuce fields using a soil drench or treated seeds in the Salinas Valley, California. Environ. Pollut. 315, 120325. https://doi.org/10.1016/j.envpol.2022.120325.
Writer, J.H., Ferrer, I., Barber, L.B., Thurman, E.M., 2013. Widespread occurrence of neuro-active pharmaceuticals and metabolites in 24 Minnesota rivers and wastewaters. Sci. Total Environ. 461–462, 519–527. https://doi.org/10.1016/j.scitotenv.2013.04.099.
Wu, W., Shah, F., Ma, B.L., 2022. Understanding of crop lodging and agronomic strategies to improve the resilience of rapeseed production to climate change. Crop and Environment 1 (2), 133–144. https://doi.org/10.1016/j.crope.2022.05.005.
Zheng, Z., Fiddes, K., Yang, L., 2021. A narrative review on environmental impacts of cannabis cultivation. Journal of Cannabis Research 3 (1). https://doi.org/10.1186/s42238-021-00090-0.
Zühlke, S., Dünnbier, U., Heberer, T., 2004. Detection and identification of phenazone-type drugs and their microbial metabolites in ground and drinking water applying solid-phase extraction and gas chromatography with mass spectrometric detection. J. Chromatogr. A 1050 (2), 201–209. https://doi.org/10.1016/j.chroma.2004.08.051.