Examples of plastic trash on or near the banks of streams at cannabis cultivation sites in the Emerald Triangle (Humboldt, Mendocino, and Trinity Counties), CA, 2018–2019. Photo Credit: Kalyn Bocast, CDFW (top and center); CDFW staff (bottom)

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Potential impacts of plastic from cannabis cultivation on fish and wildlife resources

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Plastic is commonly used in many applications for the cultivation of cannabis. This document provides a synthesis of available scientific literature on how plastic, particularly that used in cannabis cultivation, may detrimentally affect wildlife, fish, and associated ecosystems, including entanglement and ingestion, leaching of chemicals into the environment, and alteration of soil properties.

Key words: cannabis, chemical additives, entanglement, fish, microplastics, monofilament netting, plastic, soil properties, wildlife

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Plastic is a chemically diverse group of synthetic polymer-based materials. Over 320 million tons of plastic are produced annually worldwide in sizes ranging from microplastics (< 5 mm in diameter; Barnes et al. 2009; Wagner et al. 2014; World Economic Forum 2018) to macroplastics (>20 mm in diameter). Because plastics are virtually non-biodegradable, they are mechanically broken down (e.g., physical fragmentation from weather such as hail) and are eventually released into terrestrial and aquatic ecosystems (Horton et al. 2017; Steinmetz et al. 2016; de Souza Machado et al. 2017). Given the mass production of plastic and its durability, plastic pollution has been identified as one of the most widespread and long-lasting anthropogenic changes to our planet's surface (Barnes et al. 2009). This anthropogenic change is a growing hazard for fish, wildlife, and the habitats upon which they depend.

This review provides a synthesis of available scientific literature on how plastic use in agriculture may impact wildlife, fish, and associated ecosystems to help identify the potential impact of plastic use from cannabis agriculture. The use of plastic materials in agriculture was first introduced in 1948 in the United States to cover greenhouses with cellophane (Scarascia-Mugnozza et al. 2011). The use of plastic in agriculture is now extensive and expanding. Plastic films (e.g., greenhouses, tunnels, and mulching) are used to protect crops from the environment and to create a controlled growing environment. Plastics are used to shield plants from extreme temperatures, wind, hail, wildlife damage, and to provide shading. Plastics are also used in piping, irrigation and drainage. Some reported benefits of using plastic in agricultural applications include increased yields, earlier harvests, reduction of herbicide and pesticide consumption, frost protection and water conservation, and preservation, transportation, and commercialization of food products (Scarascia-Mugnozza et al. 2011).

There is limited published information on outdoor cannabis cultivation practices. This review assumes that largely, cannabis cultivation is similar to other agricultural practices. At outdoor cannabis cultivation sites, cultivators may use, for example, plastic mulching to protect seedlings and shoots, polyvinyl chloride (PVC) pipes to transport water, plastic monofilament for plant support or erosion control, plastic netting to exclude birds and other wildlife, and an array of additional plastic products (e.g., fertilizer bags and pots). Polyolefins (i.e., plastics used for hoop houses) encompass both polyethylene (PE) and polypropylene (PP), with low-density PE being the largest component of plastic produced globally and one of the most common polymers recovered as aquatic debris (Rochman et al. 2013). Polyolefins degrade extremely slowly, meaning they can survive in the environment for 10s to 100s of years (World Economic Forum 2018).

Agricultural areas in particular, have been identified as a major entry point for plastics into continental systems (Horton et al. 2017). However, research on the impacts of plastics on the environment has predominantly focused on marine aquatic systems, with freshwater and terrestrial ecosystems only being considered in recent years (Wagner et al. 2014; Horton et al. 2017; de Souza Machado et al. 2017). Freshwater bodies often have comparable amounts of plastic to marine waters and approximately 80% of plastic pollution in the ocean comes from land via wind, direct runoff following rainstorms, and wastewater (Dris et al. 2015; Jambeck et al. 2015; Holland et al. 2016).

This review categorizes the harmful impacts of plastic use on the into three pathways: entanglement and ingestion by wildlife, leaching of harmful chemical additives into the environment, and alteration of soil properties. The review aims to serve as a starting point in documenting complex interactions between an emerging agricultural product and the environment. We have included examples from species that reside in and outside of California given many non-resident species share similar life history traits to resident species.

ENTANGLEMENT AND INGESTION BY WILDLIFE

UV radiation and temperature fluctuations fragment plastics on land while waves, wind, and UV fragment them in the ocean and freshwater lakes, creating smaller and smaller plastic particles. As the size of the plastic decreases, the number of wildlife species that could potentially ingest the plastic increases (Barnes et al. 2009; Horton et al. 2017). When plastics are ingested, they may clog feeding appendages or the digestive system, be retained in the gut, cross the gut wall into other body tissues, or be excreted at higher concentrations than when they were ingested (Barnes et al. 2009; Lwanga et al. 2017). Further, large plastic material (e.g., plastic mulch) can fragment into microplastics that are ingestible by a wider range of species, in turn facilitating their accumulation in the environment and in the food web (Barnes et al. 2009; Oehlmann et al. 2009; Steinmetz et al. 2016; Lwanga et al. 2017). In a farming landscape, for example, microplastic concentrations increased from soil to earthworm casts to chicken feces (Lwanga et al. 2017).

Wildlife species ranging from zooplankton to American robins (*Turdus migratorius*) to bull snakes (*Pituophis catenifer*) may ingest or become entangled in plastic, which may pose a considerable threat to the species (Barnes et al. 2009; Rehse et al. 2016; Gil-Delgado et al. 2017; Holland et al. 2016). Plastic that gets entangled around wildlife species' legs and feet may in time, tighten in response to swelling and can lead to necrosis of the limb (Burton and Doblar 2004). Entanglement may also result in severe lacerations, reduced mobility, or death (e.g., from strangulation or being trapped in the sun; Burton and Doblar 2004; Kapfer and Paloski 2011; Stuart et al. 2001). Table 1 includes examples from the available scientific literature of wildlife using plastic, becoming entangled in plastic, or ingesting plastic, and the effect of doing so.

Table 1. Examples of wildlife using plastic, becoming entangled in plastic, or ingesting plastic.

Taxa	Species	Effect	Source
Birds	Mourning dove (*Zenaida macroura*)	Documented becoming entangled in monofilament and then dying.	Parker and Blomme 2007
	Northern gannets (*Sula bassana*)	In two colonies of gannets, 97% of nests sampled had plastic incorporated in them including rope/line/netting (78%), plastic package strapping (12%), bags or sheets (7%) and hard plastic (3%).	Montevecchi 1991
	European coot (*Fulica atra*), mallard (*Anas platyrhynchos*), and shelduck (*Tadorna tadorna*)	There was a high prevalence of plastics in the birds' feces.	Gil-Degado et al. 2016
	Osprey (*Pandion haliaetus*)	Nestlings can become entangled in the bailing twine that has been incorporated into their nests and perish.	Blem et al. 2002
	Mallard (*A. platyrhynchos*), American black duck (*A. rubripes*), and common eider (*Somateria mollissima*)	Plastic was found in the stomachs of 46% of mallards, 7% of black ducks, and 2% of eiders analyzed.	English et al. 2015
	American crow (*Corvus brachyrhynchos*)	85% of crow nests along an urban to agricultural gradient contained anthropogenic material; the amount of material was higher in nests in agricultural areas than urban areas; all entangled nestlings failed to fledge.	Townsend and Barker 2014
	Ducks, geese, American robins (*Turdus migratorius*), and Eastern bluebirds (*Sialia sialis*)	Monofilament can become entangled around the distal legs and feet, where it tightens in response to swelling. This can lead to necrosis of the limb and eventual amputation.	Blem and Doblar 2004

Taxa	Species	Effect	Source
	California condor (*Gymnogyps californianus*)	Ingestion of anthropogenic garbage, including plastic, has slowed the development of feathers in some nestlings and resulted in the death of others; nestlings may be physiologically less able to regurgitate pellets or other indigestible material than adults.	Mee et al. 2007
	Great tit (*Parus major*)	Appeared to preferentially seek out anthropogenic material for nests; more anthropogenic material was associated with lower general arthropod diversity and higher levels of Siphonaptera (fleas).	Hanmer et al. 2017
Herpetofauna	Leatherback sea turtle (*Dermochelys coriacea*)	Ingested plastic can result in esophageal and gastrointestinal blockage and death.	Starbird and Audel 2000
	Coachwhips (*Masticophis flagellum*) and bullsnake (*Pituophis catenifer*)	Have become entangled in plastic netting, sometimes leading to death (e.g., from overheating after being entrapped in full sunlight).	Stuart et al. 2001
	Common gartersnake (*Thamnophis sirtalis*), northern watersnake (*Nerodia sipedon*), Western fox snake (*Pantherophis vulpinus*)	Have been found entangled in plastic netting.	Kapfer and Paloski 2011
Invertebrates	Earthworms (*Lumbricus terrestris*)	In a lab, there was a significant reduction in growth rates when exposed to microplastics; mortality was also observed with mortality increasing as concentration of microplastics increased; there were negative effects on burrow construction.	Lwanga et al. 2016
	Earthworms	Earthworm casts contained concentrated amounts of microplastics. This is a consequence of their direct ingestion of the soil.	Lwanga et al. 2017
	Earthworm (*Eisenia andrei*)	In a lab, worms were exposed to different concentrations of microplastics. There were no significant effects on survival or reproduction but there was damage to the gut and immune system.	Rodriguez-Seijo et al. 2017
	Zooplankton (*Daphnia magna*)	Ingestion of plastic particles at high doses lead to immobilization.	Rehse et al. 2016
Fish	Freshwater and marine teleost fishes	In natural settings, microplastics have been found to be ingested by several fish species, no matter the size, life stage or life history.	Hoss and Settle 1989; Eerkes-Medrano et al. 2015; Collicutt et al. 2019

LEACHING OF HARMFUL CHEMICAL ADDITIVES

Chemical additives such as Bisphenol-A (BPA), polybrominated diphenyl ethers (PBDE), or phthalate acid esters (PAE) are added to plastics to increase their functionality (e.g., elasticity, rigidity, and UV stability). Over half of all plastics are associated with hazardous monomers, additives, and/or chemical byproducts (Rochman et al. 2013). These hazardous monomers and additives are weakly bound or not bound at all to the polymer molecule (i.e., to the plastic) meaning that over time, they will leach out of the plastic and into surface waters, wastewater, groundwater, sediment, and soil (Clara et al. 2010; Steinmetz et al. 2016; Horton et al. 2017). Leached chemical additives may be carcinogenic or toxic and many function as endocrine disruptors that negatively impact developmental,

Table 2. Examples of how the leaching of chemical additives from plastics may impact wildlife.

Taxa	Species	Effect	Source
Mammals	Rats and mice	In a lab, adult exposure to BPA affected the male reproductive tract; developmental exposure affected the brain and metabolic processes.	Richter et al. 2007
	Rats	In a lab, high doses of DEHP led to rapid and severe changes in the testes of adult male rats and adverse responses in females (following pre- and post-natal exposure).	Talsness et al. 2009
	Mice, guinea pigs, and ferrets	In a lab, exposure to phthalates sometimes induced testicular injury.	Oehlmann et al. 2009
Herpto-fauna	African clawed frog (*Xenopus laevix*)	In a lab, BPA exposure led to teratogenic effects like crooked vertebrae, abnormal development of head and abdomen, and death of cells in the central nervous system.	Oka et al. 2003
	Moor frog (*Rana arvalis*)	In a lab, exposure to DEHP via sediment resulted in decreased successful hatchings with increasing concentrations.	Larsson and Thurén 1987
	Japanese wringled frog (*Rana rugosa*)	In a lab, DBP exposure caused delayed gonadal development in male tadpoles.	Ohtani et al. 2000
Inverte-brates	Ramshorn snails (*Marisa cornuarietis*)	In a lab, exposure to BPA caused superfeminization syndrome (i.e., aditional sex organs, enlarged accessory sex glands, enhanced egg production) outside of spawning season and increased female mortality.	Oehlmann et al. 2000

Table 2. continued.

Taxa	Species	Effect	Source
	Crickets	In a lab, ingestion of polyurethane foam led to bioaccumulation of chemical additives in crickets.	Gaylor et al. 2012
	Lugworms (*Arenicola marina*)	In a lab, worms that were fed polystyrene with sorbed chemical additives bioaccumulated the chemical additives.	Besseling et al. 2013
	Annelid (*Capitella capitata*)	In a lab, exposure to BPA caused premature metamorphosis of larvae.	Biggers and Laufer 2004
	Chironomid larvae (*insect*)	In a lab, exposure to BPA caused delayed larval emergence.	Watts et al. 2003
Fish	Carp, fathead minnow, rainbow trout	In a lab, BPA exposure had feminizing effects in vivo, induced synthesis of zona radiata proteins, and induced alterations in gonadal development and gamete quality.	Oehlmann et al. 2009
	Fathead minnow (*Pimephales promelas*)	In a lab, exposure to BPA increased percentage of spermatocytes.	Sohoni et al. 2001
	Common carp (*Cyprinus carpio*)	In a lab, exposure to BPA caused alterations in the gonadal structure of males and in some instances, intersex.	Oehlmann et al. 2009
	Common carp	In a lab, exposure to DEP caused changes in general behavior.	Barse et al. 2007
	Common carp	in lab, exposure to BPA caused gonad structural changes in males and decreased estrogen to androgen ratios in blood.	Mandich et al. 2007
	Brown trout (*Salmo trutta f. fario*)	In a lab, exposure to BPA caused reduced sperm quality, delayed ovulation in females, and inhibition of ovulation in females.	Lahnsteiner et al. 2005
	Brown trout (*Salmo trutta f. fario*)	In a lab, low exposure to BPA caused reduced sperm quality and delayed ovulation; higher exposure caused complete inhibition of ovulation.	Lahnsteiner et al. 2005
	Atlantic salmon (*Salmo salar*)	In a lab, exposure to DEHP in food during early life resulted in a small incidence of intersex.	Norman et al. 2007
	Three-spined stickleback (*Gasterosteus aculeatus*)	In a lab, exposure to phthalates caused alterations in shoaling and feeding behavior.	Wibe et al. 2004
	Fish in general	Phthalates have been detected in wild fish and have been found to bioconcentrate in the body tissues of some fish.	Oehlmann et al. 2009

metabolic, and reproductive processes (Richter et al. 2007; Oehlmann et al. 2009; Talsness et al. 2009; Flint et al. 2012; Lü 2018; Teuten et al. 2009). The adverse impacts of chemical additives can be even more acute in developing organisms given their greater sensitivity to drug and chemical exposure (Talsness et al. 2009). Exposure to very low doses of BPA (i.e., doses lower than those studied for toxicological risk assessment purposes) has been found to negatively impact experimental mammals, crustaceans, aquatic insects, and fish (Richter et al. 2007; Oehlmann et al. 2009). Phthalates like diethyl phthalate (DEP), diethylhexyl phthalate (DEHP), and dibutyl phthalate (DBP), alternatively, are known to negatively affect reproduction, to impair development, and/or to induce genetic aberrations in wildlife groups like molluscs, crustaceans, and amphibians (Oehlmann et al. 2009). Smaller-sized plastic has a greater likelihood of leaching chemical additives into the environment, owing to their larger surface to volume ratio (de Souza Machado et al. 2017). Table 2 includes examples from the available scientific literature of how the leaching of chemical additives from plastics may impact wildlife.

ALTERATION OF SOIL BIOGEOCHEMISTRY AND BIOPHYSICAL PROPERTIES

Plastic placed on top of soil (e.g., plastic mulch or monofilament erosion control), as well as other plastic used in cannabis cultivation (e.g., fertilizer bags and pots) have the potential to alter the soil's biogeochemistry and biophysical properties (Steinmetz et al. 2016; Horton et al. 2017; de Souza et al. 2018). Plastic mulches, for example, may induce changes in the soil microbial community. They may modify microclimate conditions (e.g., temperature and moisture), which in turn may increase biological degradation of litter and soil organic matter that in turn, deplete soil nutrients like carbon, alter root or soil fungi relationships, and decrease the abundance of ecosystem engineers like earthworms and nematodes (Steinmetz et al. 2016). Plastic mulches may also impact cannabis cultivation sites by enhancing water runoff into furrows or un-mulched areas. This has multiple impacts including increasing the areas' susceptibility to soil erosion, decreasing soil structural stability, and elevating pesticide loads in these bare ground areas (Steinmetz et al. 2016).

Plastic mulches, plastic monofilament, and the array of other plastic products used on cannabis cultivation sites will fragment over time (e.g., by UV radiation and temperature fluctuations) if they are not cleaned up on a regular basis. Soils will then function as the long-term sink for plastic fragments and debris left behind, with plastics persisting upwards of 100 years in the soil due to low light and oxygen contents (Horton et al. 2017; de Souza et al. 2018). Plastic particles can alter the soil's biophysical environment by changing: 1) soil bulk density- plastics are often less dense than many natural minerals predominant in soils, 2) soil moisture and evapotranspiration – some types of plastic can increase soil's water holding capacity while others can decrease it, 3) microbial activity, and 4) invertebrate activity (Lwanga et al. 2017; de Souza et al. 2018; Zhu et al. 2018). Exposing earthworms (*Lumbricus terrestris*) to microplastics, for example, changed the worms' burrow structure and in turn, soil aggregation and function (Lwanga et al. 2017). Microplastics in soil also impacted the activity of springtails (a hexapod), which then effected the springtails' gut microbiomes and ultimately their growth and reproduction (Zhu et al. 2018).

CONCLUSION

The use of plastic in agriculture is not unique to cannabis cultivation, but information on cannabis cultivation practices in California to date is limited. Although there has not been a formal survey of the use of plastic in cannabis cultivation, it is commonly believed to be widespread. In an online survey conducted in 2018, cannabis growers indicated that most cannabis (41%) was produced outdoors (open air, sunlight), followed by greenhouse (25%; partial or full sunlight) (Wilson et al. 2019). Both methods likely use plastic piping for irrigation and plastic monofilament netting as scaffolding to support plants. Many cannabis growers use hoop houses- greenhouses constructed by placing polyethylene plastic over a PVC arch frame. There are many important gaps in information regarding cannabis cultivation practices that, when answered, will help our understanding of how the environment may be affected by the use of plastic. This review assumes that cannabis cultivation practices are comparable to other agricultural practices. However, further research is required to determine if this assumption is valid. More information is needed on the type, amount, duration, and timing of plastic use on cannabis farms. Research on disposal methods of used plastic is essential. Agricultural plastic products are difficult to collect, recycle, and reuse (Steinmetz et al. 2016). As more information is gathered on the use of plastics in cannabis cultivation, it will be important to continue to synthesize the effects of such materials on wildlife, fish, and associated habitat. This will allow for the development of science-based best management practices to mitigate or avoid detrimental effects.

Author Contributions

Conceived and designed the study: LNR, MM, EF, ADB
Collected the data: LNR, EF, ADB
Performed the analysis of the data: LNR, EF, ADB
Authored the manuscript: LNR, MM, EF, ADB, EC
Provided critical revision of the manuscript: MM, EF, ADB, EC

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