Think Beyond PLASTIC

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Plastic Uses in Agriculture

Think Beyond Plastic Foundation
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Terminology and Abbreviations

ABS	Acrylonitrile butadiene styrene
AC	Acrylic
ACC	American Chemistry Council
BDE	Bromodiphenyl ether
BPA	Bisphenol A
CDC	Centers for Disease Control and Prevention
CE	Central Europe
CEO	Chief Executive Officer
CIS	Commonwealth of Independent States
COSHH	Control of Substances Hazardous to Health
CSO	Combined Sewer Outfall
DDE	Dichlorodiphenyldichloroethylene
DDT	Dichlorodiphenyltrichloroethane
DEHP	Di-(2-ethylhexyl) Phthalate
DNA	Deoxyribonucleic acid
EEC	European Economic Community
EDC	Endocrine Disrupting Chemical
EfW	Energy from Waste
EMF	Ellen MacArthur Foundation
EPA	Environmental Protection Agency
EU	European Union
FAO	Food and Agriculture Organization
FCB	Full Cycle Bioplastics
Fs	Furans
GEB	Global Environmental Benefits
GEF	Global Environmental Facility
GESAMP	Group of Experts on the Scientific Aspects of Marine Environmental Protection
GHG	Greenhouse Gas
GMO	Genetically Modified Organisms
HDPE	High density polypropylene
ILO	International Labor Organization
ISWA	International Solid Waste Association
LCA	Lifecycle Analysis
LDC	Less developed Countries
LDPE	Low Density Polypropylene
MSW	Municipal Solid Waste
MVP	Minimum Viable Product
NAFTA	North American Free Trade Agreement
NGO	Non Governmental Organization
NP	Nonylphenol
OECD	Organization for Economic Co-operation and Development
PBDE	Polybrominated diphenyl ether
PCB	Polychlorinated biphenyls
PCCD	Poly-Chlorinated dibenzo-dioxins
PCCP	Personal Care and Cosmetic Products
PCP	Personal Care Products
PE	Poly Ethylene
PES	Polyester

PET	Polyethylene terephthalate
PHA	Polycyclic aromatic hydrocarbon
PMMA	Polymethyl methacrylate
POP	Persistent Organic Pollutants
rPET	recovered Polyethylene terephthalate
PP	Polypropylene
PS	Polystyrene
PUR	Polyurethane
PVC	Polyvinyl chloride
RAPEX	Rapid Exchange of Information System
RIC	Resin Identification Code
STAP	Science and Technology Advisory Panel
SIDS	Small Island Developing States
TPS	Thermoplastic starch
UK	United Kingdom
UN	United Nations
UNEA	United Nations Environmental Assembly
UNEP	United Nations Environment Programme
USA	United States of America
WE	Western Europe

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Executive Summary

Plastic has become as ubiquitous and deeply embedded in agricultural food production as it has in the daily lives of people all over the world. Plastic, in its various forms, has been able to provide a unique combination of performance characteristics at relatively low financial costs to farmers compared to alternatives.

However, just as the ocean plastic crisis has prompted society to question the cost/benefit trade-offs of extensive plastic use in consumer products, this question is emerging for agriculture as well: **are the economic, environmental and human impacts of using plastic in agriculture, on balance, worth it?**

An estimated 10 million tons of plastic are used in agriculture around the world each year, and the market for agricultural plastics is estimated to be close to USD 10 billion. Over 40% of this demand is for plastic mulch film, which typically lasts for one growing season and then must be disposed.

Plastic is one reason that agriculture has been able to increase productivity without increasing acreage: it extends the growing season, improves yields and quality, and reduces spoilage in the field. It is relatively cheap compared to alternatives, and while disposal has not been easy, it has not been that hard either. Farmers bury it, pay to have it hauled away if they can afford it, or are quietly allowed to burn it when they can't.

Plastic is now used at every stage of the agricultural life cycle. Pre-planting may include fumigation film, nursery pots and seedling trays, and all of the plastic elements of an irrigation systems, from drip tape to channel liners to drainage pipes. The planting phase sees the introduction of plastic coverings or sheeting for greenhouses, hoop houses or tunnels, installation of plastic mulch film and netting, and may include plastic containers such as seed buckets.

In the growing phase, farmers may opt for a controlled-release fertilizer that uses a polymer coating to meter the release, but which leaves a plastic residue in the soil once it is spent. Containers for agrochemicals and other relevant substances are also used during this phase.

Harvesting and processing use nets, containers and crates, but in general this phase is not as plastic intensive and plastic items are able to be reused more.

Packaging, storage, distribution and shipping introduce plastic clamshells, crates, bags, and twine to package and transport the crops to market. Storage films are used to wrap silage and bales for protected storage outdoors over, potentially, years. Secondary packaging such as crates, film wrap, and bags is also used in transportation.

Yet even as the amount of plastic being used to produce food crops is growing each year, the risks and implications for the health of soils, ecosystems and humans are not yet well understood.

During its useful life, plastic mulch film has already been observed to impact soil health and soil quality as well as the microbial mix, though questions remain about the implications for crops over the long-term.

Additional challenges are presented after the useful life of plastics in agriculture. There is already substantial evidence that excessive plastic mulch residues on agricultural land in China are impairing crop growth, rather than helping it.

Soils have become a depository for plastic waste, some of it generated on the farm, and some of it generated elsewhere. Six key sources of microplastics for agricultural land have been identified: sewage sludge used as fertilizer, irrigation with treated wastewater, compost, plastic mulch film, and street litter and tire dust.

These microplastics in the soil are believed to pose a risk to microbial life as well as other life in the soil such as earthworms and nematodes. Because microplastics continue to absorb chemicals in the soil, they represent a pathway for agricultural chemicals to enter and accumulate in the food chain.

The waste footprint of plastic in agriculture is increasingly being recognized as significant, especially as recycling is not a viable option for most contaminated items, which are a significant share of what is being generated.

While agricultural plastics are relatively cheap to purchase, they do represent additional costs for farmers, who are already operating on thin margins, and they impose costs on the environment as they reach the end of their lives.

Impacts on human health are the most difficult to disentangle due to the complexity of the human and ecological systems. There are many plastic additives that are known to be problematic but it has not yet been established how the toxic aspects of plastic use and disposal will show up in terms of human health impacts.

To the extent that plastic is causing more pesticides and herbicides to runoff of fields into waterways, causing greater exposure to humans and river and marine life, this has potential implications for human health, but further research needs to be done.

Much more research is needed to further understand the implications of, and solutions for, the challenges of plastics in agriculture. Better information is needed about the amount of microplastic in the soil and the effect that it is having there. It is also imperative to better understand how the use of mulch film impacts soil health. And as biodegradable films are being developed to provide an alternative, it will be critical to understand how they are functioning on the ground.

More insight into various waste solutions is needed, as well as alternative to plastic for some of the more problematic applications of plastic in agriculture. It will be essential to fully assess the economics of potential solutions or alternatives in the appropriate context.

And finally, further research into the potential human health implications of the usage of agriculture in plastics is urgently needed.

Introducing large amounts of plastics into the systems and indeed the very soil in which our food is grown before the long-term implications were known can be seen as a sort of large-scale experiment. There is a lot at stake, and some of the early indicators are raising concerns about the potential impacts. Now is the time to address the most urgent questions so that decisive, informed action can be taken.

Introduction

Background

Since plastic was commercialized in the middle of the 20th century, its use has been steadily expanding in agriculture, and specifically in protected horticulture, due to its lightweight, inexpensive and versatile nature.

Globally, plastic production overall has grown from 2 million tons in 1950 to 381 million tons in 2015, a compound annual growth rate of 8.4% per year (Geyer, Jambeck, & Law, 2017). Global data on use of plastic in agriculture is limited, but in Europe, it is estimated to be 3.4% of plastic demand, after Packaging, Building & Construction, Automotive, Electrical and Electronic, and Household, Leisure & Sports. Plastic has enabled these sectors to lower costs, improve efficiency, innovate, and grow. This has been true for Agriculture as well, though this shift has been less visible to the general public in many cases.

Figure 1. Plastic Demand by Sector for Europe (EU28+NO/CH), 2017

Source: Plastics Europe Market Research Group and Conversion Market & Strategy GmbH

Just like other industries, agriculture is increasingly leaning on plastic for every segment of the value chain: pre-planting, planting, growing, harvesting, processing, packaging, transportation, and shipping. The applications for plastic include fumigation film, plastic mulch, netting, irrigation systems, greenhouses and hoop houses, row covers, bags and buckets for dirt and pesticides, as well as seedling trays, pots, and packaging for produce sold to consumers, to name a few.

Plasticulture, or the practice of using plastic in agriculture, has been beneficial to food production in a number of ways. It has enabled increased yields (without increasing acreage), time-shifting of harvests through greater thermal control, reductions in use of agrochemicals, and improved water efficiency, as well as the capacity to preserve, transport, package and commercialize various agricultural products (Scarascia-Mugnozza, Sica, & Russo 2011).

Plastic protects plants from adverse weather conditions and helps create optimal microclimates for crop growth. In cold regions, plastic shelters plants and warms the soil, extending growing seasons and optimizing yields. In warmer climates, plastic sheeting can serve as a sun-shade, preventing crops from scorching under direct heat. In food crop agriculture, vast regions of previously arid land have been transformed into agricultural powerhouses with the introduction of plastic mulching, greenhouses, and other applications.

However, despite its growing prevalence, very little is known about the long-term implications of the use of plastics in agriculture on soil, human and ecosystem health.

Objectives

This report primarily aims to describe the use of plastic in agriculture in order to then identify the areas that lend themselves best to innovation and replacement, reduction or redesign.

The secondary purpose is to assess the potential impact of agricultural use of plastic on soil, biota and ecosystems which will also serve as feedback into prioritization of innovation and recommended solutions.

This report is a first attempt to organize, examine and present data from existing sources on the uses of plastic in cultivation of food crops. Its goal is to:

(1) Develop an understanding of the *factors driving the growing use of plastics in food crops*, including price and performance characteristics, as well as global and local market trends;
(2) Develop a science-based foundation for *understanding the impacts* of this use on economics, human health and agricultural soils;
(3) *Inform decisions* regarding plastic use in agriculture based on economics, human and environmental health and global impact;
(4) *Identify gaps in knowledge and data*, in high priority areas such as impact of plastic's chemicals on the microbial life of soil;
(5) *Focus research towards high priority areas* and eventually widen the scope of study to incorporate non-food crops, livestock and other aspects of agriculture.

The findings of this paper can be utilized to develop a set of recommendations and interventions including, but not limited to, policy, innovation, further research, suitable replacement mechanisms and robust recycling options.

Areas of Specific Interest

There is a growing body of evidence documenting the negative externalities of the increased use of plastic in agriculture, but data are still sparse.

This report focuses on three areas:

- Impacts on soil health and microbes
- economic and environmental impacts of plastic waste collection and disposal,
- impacts on human health.

Target Audiences

This report intends to be useful to a range of audiences. In particular, these audiences were top of mind in the creation of this report because of the unique role each can play in informing and navigating the trade-offs that come with the use of plastic in agriculture and the development of solutions.

- **Scientists** can help address the research gaps identified here through new research and additional reviews or meta analyses of existing publications.

- **Farmers** can ask additional questions about the plastic they are purchasing and explore alternatives where they exist. Farmers can pay particular attention to their use of plastic and its pros and cons.
- **Entrepreneurs** can better understand what kinds of solutions are needed at each stage of the agricultural supply chain to minimize the negative externalities of plastic.
- **Major industry** can recognize and understand the unintended consequences of the use of plastic in agriculture and invest in developing alternatives that address them while maintaining the benefits of plastic in producing food at scale.
- **Civil society** can raise awareness of the trade-offs that farmers currently face in choosing to use, or not use, plastic in their operations and can help facilitate a societal discussion on what risks or negative impacts should be taken on as weighed against the imperative to produce enough food to feed a growing population.

Methodology

Data on the use of plastic in agriculture is not readily available. Therefore, in order to begin understanding how plastic is used, this paper incorporates a meta-analysis of existing literature on agricultural practices using plastics. It leverages the combined knowledge, expertise and guidance of an inter-disciplinary team of experts and advisors to answer the key research questions. Finally, it will examine two case studies of crops which represent two of the heaviest users of plasticulture— strawberries and tomatoes grown in the Salinas Valley of California—which are both high plastic-use crops. These examples will help illustrate how and why plastic is a preferred agricultural material and help develop a better understanding of the solutions that exist or may be developed.

The scope of this report was determined to focus on food crops rather than livestock or ornamentals in order to examine one clearly defined area that can be studied. The intention is that this can be a starting point and provide a pathway to research in other areas.

Specific methodology includes:

- Research, review and analysis of available literature on each of the research questions outlined above;
- Interviews with the expert panel and other experts as may be recommended by the advisors;
- Assessment of agricultural practices for two specific crops that are generally representative of typical agricultural practices (additional crops and geographies may be chosen for follow-on studies and subject to recommendation by Expert Panel).

Overview of Plastic Use in Agriculture

The Market for Agricultural Plastic

Global consumption of plastic in agriculture was 6.5 million tons annually in 2011 by one estimate (Scarascia et al., 2011). Another estimate, extrapolating based on the EU's demand for agricultural plastics of 1.6 million tons (approximately 3.4% of the EU's overall plastics demand, see Figure 1), placed world demand at approximately 8-10 million tons in 2015 (Cassou, 2018).

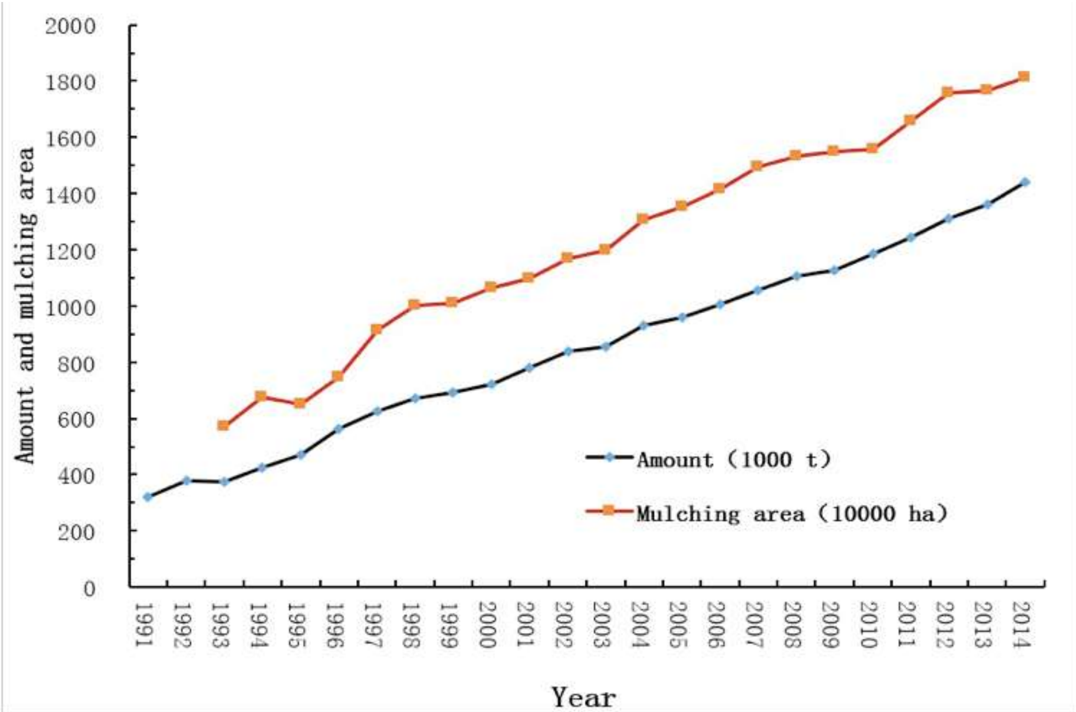
Film is estimated to be almost 50% of all plastic used in agriculture. The global agricultural plastic film industry was valued at approximately USD 5.87 billion as of 2012, corresponding to over 4 million tons sold, and was expected to nearly double by the end of the decade. Separately, Sintim and Flury (2017) projected that the global agricultural film market would reach 7.4 million tons in 2019 while Brodhagen *et al*. (2017) expect the entire agricultural plastic film market to reach USD 9.6 billion in 2019.

Over 40% of agricultural film was for plastic mulch film (Transparency Market Research, 2013).

As of 2004, approximately 130,000 tons of agricultural film were used in the US alone (Warnick *et al.* 2006), with more recent figures estimating approximately 454,000 tons annually (Grossman 2016).

China is believed to use more than 60% of the global production of agricultural plastic films (Transparency Market Research 2013), which equated to 1.25 million tons of plastic mulch film covering 19.8 million hectares of agricultural land in 2012 (Liu, He, and Yan 2014; Changrong et al., 2014; Liu et al.,2014). Separate estimates of plastic film usage in China in 2014 determined that 18.1 million hectares had been covered with 1.41 million tons of plastic film (Yang H D. et al, 2000). Plastic mulch in China covers an area half the size of California (Ng 2017). The amount of mulch used went from 300,000 tons in 1991 to about 1,400,000 tons, a 4.7x increase over 23 years (See Figure 2).

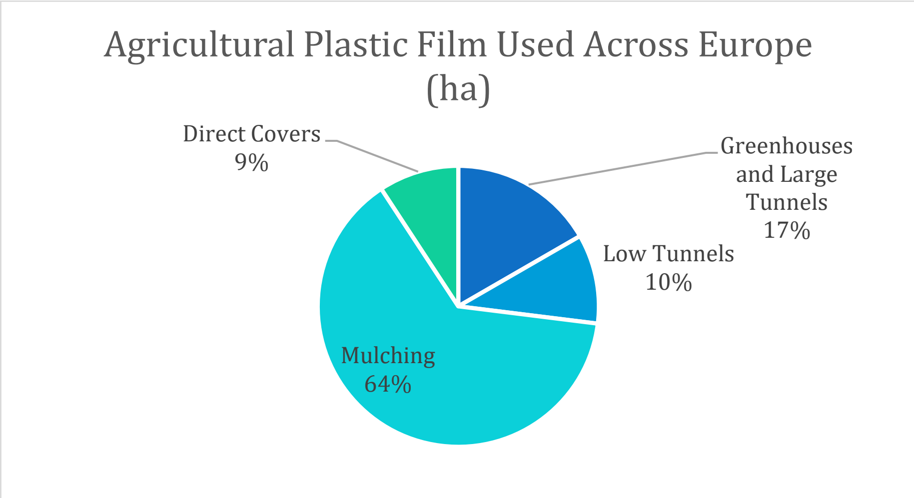
Figure 2: The amount and crop area covered with plastic film from 1992 to 2014 in China



Source: Wenqing et al. 2017

In Europe, plastic mulch film covers an area of roughly 427,000 hectares, which is four times more than what is used to cover greenhouses and six times more than that for low tunnels as of 2016. By all indications, usage is continuing to rise (Steinmetz *et al.* 2016). (See Figure 3)

Figure 3: Types of Agricultural Plastic Film Used Across Europe



Source: Data drawn from Scarascia-Mugnozza, Sica and Russo 2011

Common Plastic Polymers in Agriculture

Agriculture uses a wide range of polymers including Polyethylene (PE), Polypropylene (PP), Ethylene-Vinyl Acetate Copolymer (EVA), Polyvinyl Chloride (PVC) and, less frequently, Polycarbonate (PC) and Poly-methyl-methacrylate (PMMA). Glass-reinforced polyester (GRP) was commonly used but its use is falling. Biodegradable plastics are increasingly coming to market and hold both promise and potential complications. A description of each material is provided here.

The materials used to make agricultural covers are often low-density PE, ethylene-vinyl acetate (EVA), and ethylene-butyl acrylate (EBA) copolymers, while mulching film is typically comprised of linear low-density PE (LLDPE) (Briassoulis *et al.* 2013).

Polyethylene (PE) is a thermoplastic polymer from the polyolefin family. PE can be used as high-density polyethylene (HDPE = 0.94-0.96 g/cm3) or as low-density polyethylene (LDPE = 0.92-0.93 g/cm3). Another variation is linear low-density polyethylene (LLDPE), which produces a film of minimum thickness that retains its elasticity and puncture resistance (Steinmetz *et al.* 2016). LLDPE accounted for over 55% of the total market in 2012 (Transparency Market Research, 2013). PE is used in many agricultural applications because of its affordability, high impact resistance, workability, chemical resistance and electrical insulation properties (Steinmetz *et al.* 2016). LDPE films are commonly used in agriculture due to their highly modifiable nature: various additives to these films can help stimulate plant growth as well as help control water loss, soil temperature regulation, and the presence of weeds and insects. Additionally, LDPE plastics can be modified to prevent dripping and fogging, infrared penetration, and UV degradation. Fluorescent and ultrathermic films have also been developed (Briassoulis *et al.* 2013). HDPE is generally used for containers (including for pesticides), netting and irrigation pipes, though it can also be used for films where it can help reduce weight and cost and increase tear strength. Color additives can help regulate soil temperatures, stifle weed growth, and promote condensation which helps regulate water usage.

Polypropylene (PP), like PE, is also a thermoplastic polymer from the polyolefin family, but it is more commonly used for rope or twine, nets and piping, as well as some sheeting. This different portfolio is a reflection of its greater tensile strength, but lower impact strength, compared to PE. Given this, PP is typically extruded and used as fibers and filaments.

Ethylene-vinyl acetate (EVA) is a copolymer of ethylene and vinyl acetate. Vinyl acetate may constitute anywhere from 10 to 40% by weight, though 14% is typical for greenhouse film. EVA is well-suited to greenhouse or hoop house applications because it has high transmissivity of sunlight in the visible light range as well as in the photosynthetic activity range (PAR), 400-700 nm, and is effective at trapping heat and maintaining the desired temperature over time. It is also resistant to tearing and perforation, which are key for greenhouses.

Polyvinyl chloride (PVC) is the third most widely produced plastic, after PE and PP. PVC used to be made into films for greenhouse coverings but has now largely been replaced with other materials. PVC is currently used primarily for irrigation pipes and semi-rigid sheets for greenhouse cladding.

Polycarbonate (PC) requires the use of additives (stabilizers) or externally applied protections to prevent the material from yellowing and degrading as it ages. The most common application for PC is greenhouse covering, where it provides effective thermal insulation.

Polymethylmethacrylate (PMMA) is in the 'acrylic' family. PMMA is an essential polymer for sheets (single and double layer), and rods and it is prized for its exceptional transparency, like PC, though unlike PC, PMMA ages well. One drawback of PMMA is that it is susceptible to a range of solvents.

Glass reinforced polyester (GRP) was previously used in agriculture for containers and greenhouse coverings, but its use has decreased as it has been discovered that it ages poorly, creating problems over time.

In recent years, a variety of **degradable plastics** have been introduced to the market, but these materials have their own potential drawbacks. It is worth noting that the term "biodegradable" is not consistently defined and its use can be misleading. Biodegradable plastic mulch film, which is designed to be broken down by the resident microbial colonies in the soil, exhibits variable degradation rates, sometimes leaving fragments in the soil for long periods of time (Li, C.H., *et al.* 2014), creating soil contamination. Additionally, biodegradable plastic films have different gas permeability and thermal properties than non-biodegradable films, and they alter the microbial life of the soil they cover (Bandopadhyay *et al.* 2018).

Plastic Applications in Agriculture

Plastic has become ubiquitous in agriculture, and there are applications for plastic from pre-planting through the growing season through harvest, packaging and transport. This section provides an overview of each of the ways that plastic is currently commonly used in agriculture.

Plastic Film

Plastic films are used for plastic mulch, greenhouse or hoop house covering, low tunnels and as netting. Agricultural films and nets must meet specific mechanical requirements to ensure that their performance is in the expected range.

How long an agricultural film can last depends on a broad range of factors, such as material and any additives, thickness, how it is being used, exposure to agrochemicals, climate, sun exposure, weather, and more. Plastic mulch films are expected to last one growing season, roughly 3-4 months, while more durable applications like greenhouse coverings are targeted at 3-4 years. Nets typically last 5-10 years, and rigid sheets can last even longer.

Fumigation Film

Some non-organic fields are sometimes prepared for planting with fumigation—a process by which chemicals are applied to the soil to treat it for the possible presence of diseases likely to affect the crop. To keep chemicals from dispersing too quickly and to maximize the effects of their application, a layer of TIF (Totally Impermeable Film) is spread over the fields to trap the fumigants. For every acre of field being covered, approximately 43,560 square feet of film is required, give or take an allowance for overlap to prevent the fumigant from escaping.

Plastic Mulch

Plastic mulching was first introduced into agricultural applications to replace paper in the early 1950s and has replaced straw and other mulching materials in some contexts where superior impermeability and insulation is needed (Espi *et al.* 2006).

Plastic mulch is simple in design and consists of thin sheets of plastic which are laid over the soil in a field to provide a layer of protection for the crops, which are planted through holes in the film.

This mulch layer has many functions:

- provide insulation, improving thermal conditions for the plant's roots (it is used to warm the soil in cooler climates, allowing earlier planting; it is used to cool the soil and shade plants from harmful UV radiation)
- maintain humidity and prevent excess evaporation from the root zone
- protect fruit and berries from touching the soil and developing mildew
- suppress weeds and pests, minimizing competition for water and nutrients and limiting the need for herbicide and fertilizer use

Crops that have been mulched with plastic develop faster, are higher quality and produce higher yields (Steinmetz *et al.* 2016; Maughan and Drost 2016).

In China, plastic film mulching is reported to have increased grain and cash crop yields by 20%–35% and 20%–60%, respectively (Liu *et al.* 2014), which has effectively increased yield without the need for a subsequent increase in cropland area.

There are many different kinds of plastic mulch available today. Mulch films can be different colors for different functions.

- Black mulches absorb heat, warming the soil, but block light, which controls weed growth. Typically used in spring when the soil needs warming.
- White mulch or white-on-black mulch (co-manufactured) is used to decrease soil temperature during summer crop production.
- Clear mulch allows sunlight and infrared radiation to penetrate the plastic, making it the mulch that provides the greatest warming of all mulches however this also allows weed growth, requiring either herbicide use below the mulch or shade from the plant canopy to inhibit weed growth.
- Infrared Transmitting mulches can be green or brown and they aim to provide the soil warming benefits of clear mulch without the weed growth challenges.

- Red, yellow and silver mulches have been developed with a variety of distinctive characteristics meant to be beneficial in particular circumstances to support crop performance, though studies on inconclusive on their effectiveness.

Greenhouse/Hoop House Plastic

Also referred to as "high tunneling," Greenhouse and hoop house covering is another application for agricultural film and is typically one of four types of plastic: polyethylene, ethylene-vinyl acetate, polyvinyl chloride, and polycarbonate.

Greenhouse plastic is inexpensive and easily sourced, however, it can be susceptible to tearing and to becoming brittle in extreme weather conditions or because of exposure to UV radiation. Despite the need for maintenance and the regular replacement of used greenhouse plastics, the properties these plastics possess, as well as their low cost, make plastic a viable solution for farmers. Some manufacturers offer greenhouse films that have light-diffusing or infrared-blocking properties as well (Upson 2014), giving the film the much sought-after ability to help regulate temperature within the structure. Plastics can also be modified to have anti-static properties, repelling dust, dirt, and smog (Bartok 2013), as well as anti-fog properties which prevent droplets of water from falling on crops (Espi *et al.* 2006). Plastic films may also be modified to block certain ranges of UV light, which can limit the ability of certain fungi to reproduce as well as create an environment that is deterrent to certain insects, some of which are prone to transmitting viral diseases (Espi *et al.* 2006).

Typically used for 3-5 years or more, these plastics have different physical properties resulting in variable lifespans—polyethylene and copolymer plastic lasts approximately 1-2 years, polyvinyl can last approximately 5, and polycarbonate approximately 10 (polycarbonate plastic is not a film, but a double-walled plastic material).

Hoop houses (also known as high tunnels) are another source of plastic present during the growing phase, used to regulate temperatures on the crops they shelter. Hoop houses reduce the likelihood of pest interference, protect crops from storms and hail, and lower incidence of foliar disease. A well-managed hoop house can prolong a growing season, sometimes by up to 60 days (Upson 2014).

Low Tunneling

Low tunnels act as temporary greenhouses to protect crops through the winter or cold periods. They are typically constructed by placing a series of hoops along the row (for example, PVC piping anchored to rebar that has been pounded into the ground) and then running plastic over the hoops and fastening it at both ends. Asparagus and watermelon are commonly grown in low tunnels, as are other specialty crops.

Plastic Nets

Plastic nets are a steadily expanding application across Europe and are used in the cultivation of fruit trees to protect against hail, bird, and insect damage; in greenhouses to create screens that protect against insects and to provide shade and wind protection; and recently, to bind bales in place of string (Scarascia-Mugnozza, Sica, and Russo 2011). In Italy alone, approximately 5,300 tons of netting made of HDPE are produced annually (Castellano *et al.* 2008).

Plastic netting is seen as an environmentally-friendly option because it reduces the use of pesticides and leads to increased crop production. Netting can also shift the regular crop production period of a crop, leading to greater availability of in-demand crops.

Despite these benefits, plastic netting has a lifespan of approximately 6-10 years, after which it must be manually removed. Nets can sometimes be contaminated with organic materials and agrochemicals, making recycling challenging. Obtaining data on the usage of agricultural nets is difficult because in Europe, agricultural nets are also sold for several other purposes, such as shades parking areas, construction netting, window netting, and fishing netting, to name a few (Castellano *et al.* 2008).

Data describing the use of plastic netting in China, the US or other countries was not available, but would be a worthy topic of future research.

Water Reservoirs, Lined Canals and Irrigation Systems

One of plastic's most important roles in agriculture is promoting efficiency, and water use efficiency is critical in agriculture's ability to transform previously unusable land into a productive and profitable site. Irrigation pipes allow direct delivery of water to the soil at the root zone, preventing wastage and improving plant productivity and quality. There are a variety of different types of irrigation pipe, from drip tape to layflat hoses to PVC drainage pipes. While the more durable layflat hoses and PVC pipes have a reasonably long lifespan and can be reused (10- 20 years), drip tape can be a single-use product, depending on the crop. It is possible to recycle drip tape in the US today, but it comes with challenges: drip tape is very easily contaminated with dirt and agrochemicals, and it must be rolled and prepared for recycling. Additionally, farmers typically have to pay to have drip tape hauled away and recycled, making recycling a process that may not make financial sense to a grower.

Once the field is prepared, drip tape, oval hoses, layflats, mainlines and plastic mulches must be installed prior to planting. The installation of plastic drip tape and irrigation pipes "can cut irrigation costs by as much as one to two-thirds, while as much as doubling crop yield" (Scarascia-Mugnozza, Sica and Russo 2011).

Seed buckets, seedling trays and nursery pots

During fresh produce production, transplants are delivered in cardboard boxes that contain liners made of plastic.

As of 1992, there was an average of approximately 345 million pounds of plastic nursery containers produced (American Plastics Council 1992). These items are often contaminated, either by soil or agrochemicals, and as a result prove difficult to recycle.

Agrochemical Containers

In addition to the plastics that come into direct contact with crops, there are numerous agricultural plastics that play a supporting role in the form of agrochemical containers. The main function of plastics in these products is impermeability and resistance to corrosion. The plastics chosen for these products prevent the agrochemicals from leaking prior to their use, preventing unnecessary contamination. Fertilizer bags protect the products from storage hazards such as rain and water damage and are designed to be durable and resistant to puncturing. Agrochemical containers in the US must adhere to strict EPA regulations, specifically regarding the containers' rigidity, ability to withstand large temperature fluctuations, corrosion, and cracking. These plastics can be either single-use or refillable, and due to their nature as containers for fertilizer and agrochemicals, are often contaminated with residual chemicals and product (Briassoulis *et al.* 2013). There are strict regulations on the disposal of pesticide containers, and in California, these containers must be punctured, triple-washed, and returned to the manufacturer for disposal. This process represents labor that must be allocated towards the proper disposal of these materials. If the containers are to be reused, similar decontamination procedure regulations outlined by the EPA are in place to ensure that chemicals are not diluted, mixed, or altered (EPA CFR 2019).

Fertilizer Bags and Controlled-release Fertilizers

Once plants are established in the ground, pesticides and fertilizers may be applied to the soil. Not only are these products often transported in plastic containers, they can sometimes be a source of microplastic deposits due to the polymer coating found on some fertilizers. Controlled-release fertilizers use polymer coatings to supply mineral nutrients to crops gradually over time, which is better for the plants and reduces runoff and waste. While data on this application is not yet available, Trenkel (2010) estimated that the slow-release coating on fertilizers was depositing approximately 50 kg/ha per year.

Silage

Bale wrapping for silage or forage is designed to keep harvested forage at a consistent and low moisture level to avoid mold, which is made possible by the moisture barrier properties of the plastic wrap being used. Similarly, plastic wrap is used to wrap silage – a fermented forage product that contains a higher percentage of moisture. The plastic wrap ensures that the silage retains its moisture and ferments properly, preserving as many nutrients as possible within the forage for livestock to consume. Once wrapped, silage can be stored for several years.

Plastic Gloves

Farmworkers are sometimes asked to wear disposable plastic gloves to avoid transmitting pathogens to food.

Plastic Packaging

Once crops are harvested, they must be packaged and transported to their destination—the consumer. Plastic has several advantages as a packaging material, including its lightweight nature, affordability and flexibility (Pettinari *et al.* 2018).

At harvest time, additional plastic is introduced in the form of packaging, which is designed to protect the produce and increase efficiency during shipping. In strawberry production, plastic clamshells not only provide support during transport—they give consumers the ability to inspect their produce prior to purchase. In many cases, hand-picked crops are collected by workers wearing plastic gloves, which protect against contamination. Some types of produce are packaged for sale in the field, while others are processed at a different location.

Processing and packaging practices vary greatly depending on the produce being shipped, but in general, any potentially damaged, diseased, or over-ripe fruit is first removed to ensure that plant and human pathogen contamination is minimized (Malekian *et al.* 2015). In addition to this, cooling produce immediately after harvest significantly reduces the growth of microbial pathogens. Some produce is processed further after harvest, requiring peeling, washing, chopping, or other forms of preparation prior to packaging. These actions can sometimes cause damage to the produce, resulting in browning or discoloration. There are several treatments that can then be applied depending on the produce, including (but not limited to) applying an edible coating, plastic packaging with a controlled gas atmosphere inside (too much oxygen causes browning, too little causes anaerobic respiration, which leads to off-flavors and odors and an increasing susceptibility to decay), and the application of chemical enzyme inhibitors (Garcia and Barrett 2002). Produce may be placed in cold storage for a time prior to transport.

Plastic clamshells, are lightweight, cheap to produce and protect the produce inside. “Clamshell” refers to a one-piece hinged container that opens and closes. Their durability means that more produce can be shipped simultaneously, as it allows the clamshells to be stacked higher in transport. Plastic also preserves produce from spoilage and extends shelf-life, which can be integral when crops may spend extended periods in transit or warehouses prior to reaching the customer (Andrady and Neal 2009). Clamshells nest one inside the other, saving space for storage.

Plastic packaging is a popular material and includes clamshell-type boxes for produce that is delicate such as tomatoes, berries, grapes, as well as flexible packaging, and films. These materials are selected for their numerous advantages. Plastic is lightweight, durable, versatile, and requires less energy to produce than other materials, making it an appealing choice for producers (Citibank 2018). Plastic has high strength-to-weight and strength-to-stiffness ratios, meaning that the weight of the packaging can be significantly reduced without compromising what it is able to contain (Citibank 2018). Lower weight, among other characteristics, makes plastic the packaging choice with the lowest global warming potential compared to potential substitutes (Franklin Associates 2014) and plastic also has the added advantage of being flexible, making it more efficient to store and transport. The global flexible plastics industry was valued at approximately USD 131.24 billion in 2017 (Grand View Research 2018) and continues to be robust.

In addition to this, plastics protect the products they contain from damage in transport, are impermeable to gasses and contamination, and can be made transparent—a valuable trait for consumers who wish to be able to see all sides of the product they are purchasing. Plastic can be produced quickly, and weighs 3.5x less than alternative materials, making it a popular choice for packaging and transportation (Citibank 2018).

Transportation and Shipping

Depending on the type of produce in question, different transportation methods are employed to ensure that the produce remains at its freshest. One of the main priorities established by producers is to be able to move the product with minimal damage. To do this, produce is sometimes packed in clamshell boxes, which have a structural resistance to the pressure exerted on them from being stacked. Plastic crates and shipping wraps can also be used to facilitate transport.

Plastic in the Agricultural Lifecycle

Almost every phase of the agricultural lifecycle now incorporates plastic in some form. There are variations in the agricultural lifecycle are based on geography, crop type and regional practices. Modern agricultural techniques have come to rely on the properties of plastic to create more favorable conditions at every stage of production. Plastic's presence in agriculture begins before crops are even planted and lays the groundwork for a crop's productive success.

The table below offers an at-a-glance view of plastic use and benefits at each phase of the process. A further lifecycle assessment study should examine all of its impacts and attempt to quantify them.

The next section further examines each plastic application.

Table 1. Overview of Use of Plastic in Agricultural Life Cycle

Phase	**Description**	**Uses of plastic**	**Benefits**
Pre-planting	Prepare the ground for the introduction of crops, including laying infrastructure	• **Plastic fumigation film** is used to cover the ground and keep fumigants close to the soil	• Extends the effectiveness of chemicals by preventing unwanted gas exchange during fumigation

	such as hoses, pipes, and drip tape.	• **Water reservoirs and channel lining** support water storage and transportation	• Improves efficiency of water use
		• **Irrigation tapes and pipes, drainage pipes, microirrigation, and drippers** are installed to enable more efficient water management	• Improves efficiency of water use • Ensures water is present where needed (near plant roots) and not accumulating in problematic ways
		• **Nursery pots and starter trays** are used to start some crops out	• Provides affordable, lightweight starter pot
Planting	Crops are incorporated into the growing medium.	• **Plastic film mulch** is used to cover the soil around the plants	• Provides insulation and prevents excess evaporation from the root zone, protects fruit and berries from touching the soil and developing mildew, and suppresses weeds and pests, limiting the need for herbicide and fertilizer use, resulting in faster growth and higher yields
		• **Plastic films cover greenhouses, hoop houses, and high and low tunnels**	• Creates a barrier between the plant and the atmosphere, limiting evaporation and contributing to temperature regulation
		• **Plastic netting** provides a protective covering	• Provides durable partial shade and wind barrier, protection from hail, birds and some other pests • Reduces the need to use as much pesticide • Shifts the regular crop production period of a crop, leading to greater availability of in-demand crops
		• **Plastic seed buckets and** are used to transport seeds to equipment	• Prevents contamination of crops and protects fragile organic matter in transit
Growing	Crops are tended and allowed to grow for	• **Plastic containers (sacks, cans, tanks, and other containers)** hold	• Allows for safe transport of pesticides

	the duration of their productive season.	fertilizers and pesticides for application to the growing crops	• Durable enough to survive extreme temperature fluctuations and resist cracking and corrosion
		• **Polymer coatings** are used on some fertilizers	• Enables "slow release" of fertilizers and distributes their chemicals at a more metered pace
Harvesting, Processing and Packaging	Crops are collected and packaged for transportation and sale.	• **Plastic baskets and clamshells** are used to package and transport crops	• Prevents delicate produce such as berries from being crushed in transit • Enables efficient stacking in trucks
		• **Edible polymer coatings** protect and preserve food	• Reduces spoilage in transport • Intended to be eaten or to biodegrade, leaving minimal waste footprint
		• **Plastic gloves**	• Worn by workers to prevent contamination of crops
		• **Plastic netting** is used for harvesting olives and nuts	• Provides efficient, lightweight net to catch harvested items
Storage	Crops are prepared for storage.	• **Silage films and bale wraps** are used to protect and store forage, silage, hay and maize	• Protects crops from water damage and pests while they are being stored, often outdoors
		• **Bale twines** are used to tie up bales of hay or other crops	• Compacts materials and holds bales together for transport
Transportation and Shipping	Crops are moved from their growing site to the site where they will be sold to consumers.	• **Plastic crates, plastic packaging and bags, and plastic films** are used for packaging and transport of crops	• Protects crops during transport to their final destination • Provides consumer-facing packaging that will keep crops from contamination

Crop Archetypes for Plastic Usage

Current ways of categorizing food crops are not useful in describing the way that each crop may use agricultural plastic. For example, the Food and Agriculture Organization (FAO) organizes global agricultural production into the following categories: cereals, roots and tubers, sugar crops, pulses, nuts, oil-bearing crops, vegetables, fruit, fibers, spices, and all other crops (Leff, Ramankutty, and Foley 2004). This organizational schema distinguishes between the types of produce that each crop creates, but it does not specifically address the individual differences in means of production. For example, sugar beets and sugar cane are both classified as “sugar crops,” but they are very different plants with different modes of planting, growth, and harvest, and therefore – different needs for the use of plastic.

There are patterns in the ways that crops use agricultural plastics. In general, plastic use is more intensive with vegetables and small fruit crops, specifically high-value row crops such as tomatoes, peppers, melons, squash, and cucumbers, and others that are less price-sensitive. The cost of plastic mulching can be USD 500-1,000 per acre over bare ground production, which can be mitigated by the practice of double (or triple) cropping, where an additional crop is planted in the same plastic following the harvest of the initial crop in order to make the greatest use of the material before it is discarded (Maughan and Drost 2016). This practice requires a planned approach, for example using a short season crop before a long season crop to ensure that both may mature and be harvested before fall freezing occurs.

Other crops may also benefit from the plastic film mulch and other plastic applications, but the increased cost of production may make it a less viable option for lower value crops (Maughan and Drost 2016).

Crops grown using plasticulture are extremely varied, but include cucumbers, tomatoes, strawberries, peppers, squashes, gourds, melons, and cut flowers, amongst others (Wittwer 1993). Row crops such as cotton, wheat, maize and potato are also cultivated using plastic mulch film in some geographies, including China and the US (Wenqing et al. 2017). (See Figure 4)

Figure 4: Examples of crops grown with plastic film mulching in China

Source: Wenqing et al. 2017

Figures 5 and 6 provide estimates of the hectares covered globally by plastic greenhouses and plastic mulches and low tunnels (respectively) as of 1993. Given the significant growth observed in use of plastic in production since then, it should be assumed that these numbers may provide a sense of relative scale but do not represent current usage levels.

Figure 5: Estimates of plastic greenhouses and high tunnels with major crops

Country	Hectares	Crops (in approximate order of importance)
China	62,000	Cucumber, tomato, strawberry, pepper, eggplant, onion, chives, green bean, chinese cabbage, gourd.
Japan	30,000	Cucumber, tomato, cut flowers, strawberry, melon.
Spain	24,000	Watermelon, cut flowers, pepper, melon, strawberry, tomato, cucumber, squash.
Italy	21,000	Tomato, strawberry, pepper, melon, cucumber.
Greece	11,000	Tomato, cucumber, melon, pepper, eggplant, cut flowers.
Algeria	10,000	Tomato, cucumber, melon.
France	6,000	Tomato, cucumber, strawberry.
Egypt	6,000	Tomato, cucumber, melon, cut flowers.
Portugal	5,000	Melon, strawberry, tomato, pepper.
South Korea	4,000	Cucumber, tomato, green bean, cabbage.
Morocco	3,400	Tomato, cucumber, pepper, eggplant.
Turkey	3,000	Tomato, cucumber, melon, eggplant, pepper.
Russia	3,000	Cucumber, onion, tomato, strawberry.
United Kingdom, Holland, Belgium, Scandinavia, and Germany	6,000	Tomato, cucumber, cut flowers, grape, lettuce, strawberry.
United States	3,500	Bedding plants, potted plants, foliage plants, cut flowers, vegetables.
Canada	500	Bedding plants, potted plants, cut flowers, vegetables, cucumber, tomato.
Israel	300	Cut flowers (roses, carnations), tomato, strawberry.

Source: Wittwer 1993

Figure 6: Plastic row covers (low tunnels) and soil mulches (singly or in combination) and the crops grown

Country	Hectares	Crops in approximate order of importance
China	500,000	Watermelon, cucumber, tomato, strawberry, melon, squash.
Spain	70,000	Watermelon, pepper, melon, strawberry, green bean, eggplant, tomato, cucumber, squash.
Japan	25,000	Strawberry, tomato, cucumber, melon.
United States	25,000	Strawberry, melon, tomato, pepper, cucumber.
Italy	16,000	Strawberry, melon, tomato, watermelon, squash, cucumber, eggplant.
Greece	7,500	Watermelon, melon, squash, strawberry, tomato.
Israel	4,000	Strawberry, tomato, cucumber, flowers.
Turkey	4,000	Melon, strawberry, tomato.
South Korea	3,000	Cucumber, tomato, watermelon.
Egypt	3,000	Melon, tomato, strawberry, cucumber.
Tunisia	1,200	Tomato, watermelon, strawberry, cucumber

Source: Wittwer 1993

Based on research and observations about how plastic is used with different food crops, the report team developed a “crop archetype” organization to describe groups of crops based on their usage of plastic as a function of their growing needs, often correlated to the geography where they grow. (See Table 2)

Table 2: Overview of Crop Archetypes

Archetype
A. Ground-Bearing Crops • Includes strawberries, melons, gourds, cucumbers, cabbage • Plants typically touch the soil while growing
B. Bush-Bearing Crops • Includes peppers, eggplants, tomatoes • Plants grow upright or in bushes (and where the crop does not touch the ground)
C. Tree-Bearing Crops (Including Vineyards) • Includes nuts and tree fruits • Taller plants where the crop develops in a higher location, such as in orchards and vineyards
D. Foliage and Flowers • Includes flowers, leafy veggies, and potted plants
E. Row Crops • Includes Cotton, Wheat, Maize, Potato • Plants are grown in rows, sometimes in mounds • Cultivation is almost always mechanized

Plastic use appears to vary according to the structure, shape and needs of the plant. The basic groups, or archetypes, incorporating these characteristics are summarized below. (See Table 3)

Table 3. Summary of Plastic Usage Profile by Crop Archetypes

Phase	Type of plastic	Single-season product?	A. Ground-bearing Crops	B. Bush-bearing Crops	C. Tree-Bearing Crops	D. Foliage & Flowers	E. Row Crops
Pre-Planting	Fumigation film	Y	X				X
	Water reservoirs and channel lining	**Depends**	X				
	Drip tape, micro-irrigation, drippers	Y	X	X		X	X
	Pipes and drainage pipes for irrigation	N	X	X	X	X	X
	Starter trays	**Depends**	X			X	
	Nursery pots	Y	X			X	
Planting	Plastic mulch	Y	X	X			X
	Greenhouse covering	N				X	
	High or low tunnel covering	Y	X	X			
	Plastic netting	Y			X		
	Seed buckets	Y					X
Growing	Agrichemical buckets / tanks	Y	X	X	X	X	X
	Fertilizer bags	Y	X	X	X	X	X

	Polymer-coated fertilizers	**Y**	**X**	**X**		**X**	**X**
Harvest & Packaging	Plastic baskets	**N**	**X**	**X**	**X**		
	Clamshells, as appropriate	**Y**	**X**	**X**	**X**		
	Plastic bags, as appropriate	**Y**	**X**	**X**	**X**		
	Shrink wrap, as appropriate	**Y**	**X**	**X**	**X**		
	Plastic sleeves, as appropriate	**Y**			**X**		
	Edible polymer coatings	**Y**		**X**	**X**		
	Plastic gloves	**Y**	**X**	**X**	**X**		
	Tarps or netting	**N**			**X**		
Trans port	Reusable plastic crates	**N**	**X**		**X**		
	Plastic film wrap on palettes	**Y**	**X**		**X**		
Storag e	Silage films and bale wraps	**Y**	**X**				**X**
	Bale twine	**Y**					**X**

The archetypes show that the most plastic-intensive crops tend to be specialty crops. Specialty crops generally refers to fruits, vegetables, tree nuts, horticulture and nursery crops, however the precise definition, at least in the US, is all crops that do not receive direct income support under Title 1 of the Farm Bill from 2018.

Commodity crops such as corn, while not as plastic-intensive as specialty crops acre to acre, are grown on much greater acreage, so the total volume of plastic used may be greater.

Our analysis of these archetypes reveals that some of the most globally prolific crops include row crops, tomatoes, strawberries, and melons (Statista 2017), which are also plastic-intensive crops. Tomatoes fall into Archetype B, while strawberries and melons are within Archetype A. Both archetypes are examined in the case studies from this report. Future studies should explore Archetypes C and D.

Understanding the Impacts

While striking photos of plastic accumulations in the ocean have, unfortunately, become familiar to many people, plastic accumulations on land are not as common or well-known. Yet it is increasingly likely that there is far more plastic on land than there is in the ocean. Soil, especially agricultural land, has become a major sink for microplastics (Browne et al. 2011; Mahon et al. 2017; Nizzetto et al. 2016a; Nizzetto et al. 2016b; Rillig 2012; Zubris and Richards 2005).

This is confirmed through early reports from geographies where overuse of agricultural plastic has been reported, such as China, where the persistent nature of plastic fragments is discovered in the soil and air and their leakage into the watershed.

It is well documented that the amount of micro and macroplastics in agricultural soils is increasing. What is not yet well understood is what the implications of this increase will be on soil, ecosystem and human health.

While research to date has been limited, this report aims to marshal what is known and identify gaps to be addressed through future research. This report has identified these key questions for consideration in seeking to understand the impacts of agricultural plastics.

- Soil health and biota composition
  - What are the impacts of plasticulture on the soil's biological properties, and are there long-term concerns that should be considered despite the exhibited short-term benefits?
  - How does leaching of additives into the soil affect the composition of microflora, which is essential for soil fertility?
  - What is the impact of "biodegradable" plastics?
- Waste
  - What is the expected end of life for agricultural plastics, and what becomes of them when they reach this milestone?
- Human Health
  - Are there any public health concerns associated with plasticulture?

These questions address plastic's interaction with the environment, both terrestrial and human.

Soil Health

Soil is a "vital living ecosystem that sustains plants, animals and humans" (Sintim *et al.* 2018).

There is evidence to suggest that approximately "32% of all plastic produced is environmentally available in continental systems," and indeed, that it might be possible that soils could be a greater repository of microplastic litter than oceanic basins (Machado *et al.* 2018).

Sources of Microplastics Entering Soil

Microplastics enter soil from at least six specific sources. (See Figure 5 below.)

Plastic mulch film: Scientists have confirmed that plastic mulch does leave plastic behind in the soil after its useful life has ended (Brodhagen *et al.* 2017).

Plastic mulch film sheds microplastics into the soil during its useful life, which is estimated at only a few months, weather conditions permitting (Steinmetz *et al.* 2016). Microplastic residue is produced by the deterioration of plastic mulches as they are weakened by sun exposure, animal and bird interference, and a reduction in tensile strength due to weather.

Even as plastic residues break down into microplastics, they remain chemically intact and persist in the soil where they can continue to sorb agrochemicals.

While most growers in the US are required to remove plastic mulch from the soil, some plastics – particularly agricultural films—are extremely difficult to remove due to their low tensile strength, which makes them susceptible to tearing and shredding. Outside the US, some farmers simply plow the plastic into the soil rather than removing it. Globally, the rate of plastic film mulch recovery is relatively low, complicated by mechanized cultivation and the thinness of the film.

Plastic mulch that is not removed after its useful life will degrade into microplastics in the soil. Total degradation of a 60 µm thin low-density PE (LDPE) later can take approximately 300 years. In the degradation process, these plastics lose their integrity and become smaller and smaller, ultimately becoming tiny fragments, or "microplastics," in the soil's ecosystem (Steinmetz *et al.* 2016).

Meso- and microplastic PE film residues were identified in approximately 10% of surface soil samples collected by Ramos *et al.* (2015). The residues amounted to a concentration of approximately 3 g PE per m^2 and had a mean size of approximately 28 cm^2.

Each year, new plastic residue is added to the soil as mulch is laid and, in some cases, removed. Traditional tillage practices result in mega-, macro- and microplastic particles being added to agricultural soils (Changrong *et al.* 2014; Liu *et al.* 2014; Rillig *et al.* 2017a; Steinmetz *et al.* 2016).

Researchers in China report that residual mulch levels of 72–260 kg/ha have been detected in agricultural soils depending on the number of years of plastic film use (Changrong *et al.* 2014).

The large amounts of plastic mulch residue found in agricultural soils have come to be referred to as 'white pollution' in China. (See Figure 7)

Figure 7: Illustrations of plastic residue pollution in Inner Mongolia, China

Source: Wenqing et al. 2017; Photo by Changrong Yan

Sewage sludge: Microplastics also enter agricultural soil through fertilizer sludge, which is derived from sewage treatment systems (He *et al.* 2018). Microplastics have been identified in human waste from people around the world (Schwabl P, Köppel S, & Königshofer P, *et al.* 2019) and are frequently present in tap water at a broad range of concentrations (Koelmans, Albert A., *et al.* 2019). Studies of wastewater treatment in several European countries found that about 80% of microplastics were filtered out, suggesting that some proportion of these microplastics would be present in the sewage sludge, depending on the sequencing of filtration stages (Kole *et al.* 2017).

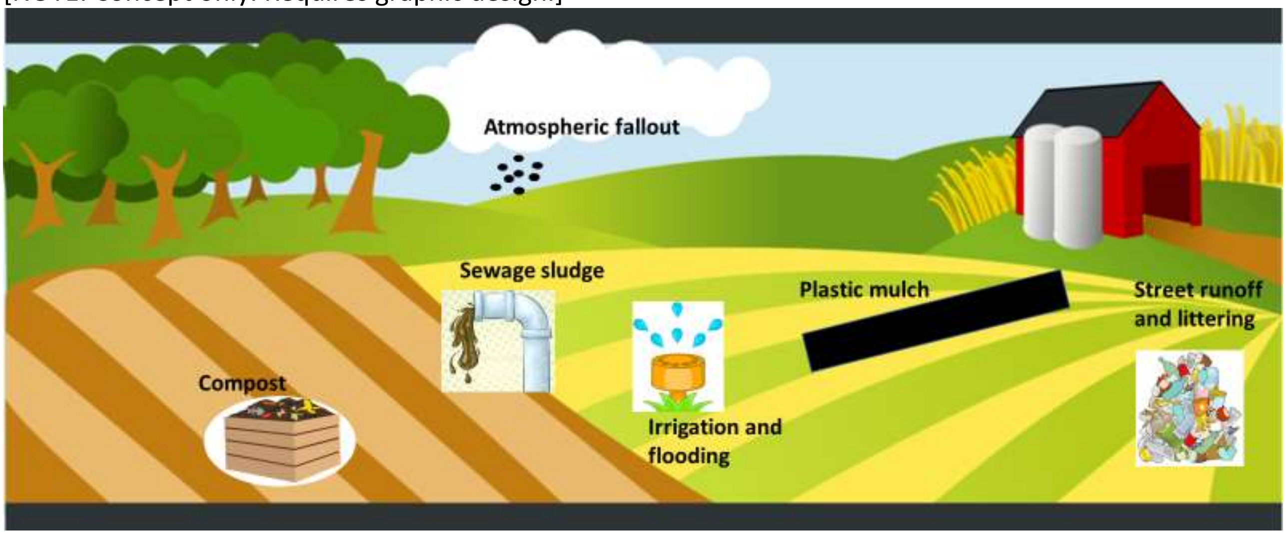
Irrigation: Treated wastewater used on farmlands for irrigation contains microplastics with observed concentrations of approximately 80-260 mg per m^3. It is estimated that approximately 430,000 and 300,000 tons of microplastics are incorporated into European and North American soils (respectively) per year (He *et al.* 2018).

Atmospheric fallout: Microplastics have been identified as ubiquitous in atmospheric deposition in metropolitan areas in Germany (Klein & Fischer, 2019), in Paris, France (Dris *et al.* 2015), and in Dongguan, China (Cai *et al.* 2017) as well as in the remote mountains in the French Pyrenees (Allen *et al.* 2019). While concentrations have been higher in urban areas than rural or remote areas in initial studies, it appears that atmospheric deposition is contributing some amount of microplastics to soil.

Street runoff and littering: Tire dust has been identified as on of the most significant sources of microplastics entering the environment as microplastics. Tire dust is carried through road runoff into surface waters, waterways and, depending on the type of sewer system, can be incorporated into municipal wastewater treatment. One study showed that 19.8% of microplastics >20 µm and 0.6% > 300 µm were not removed through wastewater treatment and would therefore be present in secondary uses of this water, such as through irrigation or through discharge to waterways then used as irrigation. (Kole *et al.* 2017). Studies are not available on the impacts of littering but by definition it is a potential source of microplastics in agricultural soils.

Compost: Multiple studies have confirmed that organic compost, including that from municipal solid waste compost programs, is a vehicle for microplastics to enter agricultural soils and the environment (Watteau 2018; Weithman 2018; Bläsing and Amelung 2018).

Figure 8. Potential Sources of Microplastics Entering Soil
[NOTE: Concept only. Requires graphic design.]



Source: Draws on data from Brodhagen *et al.* 2017; Steinmetz *et al.* 2016; Ramos *et al.* 2015; Changrong *et al.* 2014; Liu *et al.* 2014; Rillig *et al.* 2017a; He *et al.* 2018

It is still not known how many plastic pieces exist in the environment.

Once established in the soil, microplastic degradation is slow, and several studies show little to no weight change in polyethylene samples after lengthy periods of incubation in the soil. One study estimated 0.1-0.4% weight loss of polyethylene after 800 days exposed to soil, while another study found no degradation in polyvinyl chloride samples after 35 years (He *et al.* 2018).

Impacts on Microbes

Plastic in the soil, just as in the ocean, disintegrates into small fragments that are adsorbent and attract residual chemicals, potentially impacting multiple trophic levels such as plants, insects, microanthropods, earthworms, nematodes, and others. Microplastics are known vectors for the transfer of potentially harmful chemicals and pollutants such as plastic additives and other toxicants, which may then be transferred to soil organisms (He *et al.* 2018).

While plastic mulch is often seen as a benefit to agricultural practices due to its observed ability to elevate soil carbon content and establish better aggregate stability as compared to straw mulch (Munoz *et al.* 2017), it has also been observed to create stress and damage in soil bacterial and fungal colonies. (Note that in some cases, increasing microbial stress is not necessarily bad, depending on what is decomposing.)

Black plastic mulch heats the soil to the point that the soil organism shifts community towards a predominantly bacterial composition rather than a fungal composition, altering microbial functioning (Bandopadhyay et al, 2018). This can accelerate carbon and nitrogen metabolism, which results in less organic matter, less water absorbency and higher emissions of greenhouse gases.

Microplastics can be eaten or dragged through the earth by soil macro- and mesofauna. This behavior has been observed in earthworms, which are known to collect objects in the soil for use in their own burrows (Zhang *et al.* 2018). An increase in the presence of these microplastics in the soil has been correlated with higher mortality rates and reduced growth rates for earthworms (Lwanga *et al.* 2016).

Microplastics can also be ingested by other soil fauna including nematodes and mites. The impacts of the microplastics' toxicity on these organisms has been observed, including histopathological and immune system damage in earthworms (Rodriguez-Seijo *et al.* 2017*)* and adverse effects on nematodes such as intestinal damage and decreased survival rates, body length, and reproduction rates, amongst other concerns (He *et al.* 2018).

Impacts on Crops

Mulch film residues have been shown to reduce soil quality and crop production (Dong *et al*. 2015; Jiang *et al*. 2017; Zhang *et al.* 2016).

Microplastics' presence in the soil does correlate with variations in soil bulk density and a decrease in water stable aggregates—a trend often associated with the deterioration of soil quality (Machado *et al.* 2018).

In cotton crops, a residual amount of plastic film of 675 kg/ha resulted in a decrease in yield decreased due to a decrease in nitrogen utilization efficiency. The same researcher found in a meta-analysis that once plastic film residues exceeded 240 kg/ha, crop yield decreased significantly (Gao *et al.* 2018).

Plastic mulching practices can also accelerate soil processes, resulting in increased soil metabolism and mineralization, the rapid exhaustion of soil nutrients, and an overall degradation of soil quality (Steinmetz *et al.* 2016). These changes in soil colony composition may create a less favorable environment for crop growth long-term and warrant further study to truly understand the impacts on soil quality.

A further potential impact on crops is soil erosion. Plastic-covered fields minimize the amount of water that soil can absorb, resulting in higher rates of water runoff and soil erosion. Over time, erosion will reduce the amount of high-quality soil to use for growing crops.

Biodegradable Film

Most agricultural plastics will take centuries to degrade, assuming they are exposed to ultraviolet radiation or certain types of bacteria, otherwise it will take longer (Cassou 2018).

Biodegradable plastic films have been used as an alternative to conventional agricultural plastic films, and are designed to decompose into carbon dioxide, water, and microbial biomass (Sintim *et al.* 2018).

According to European standards, a polymer is biodegradable if after 6 months more than 90% of the compound has been broken down into biomass, water, and CO_2 (Steinmetz *et al.* 2016).

One motivation for developing biodegradable plastic films was to offer a solution to the problem of plastic mulch film residues in agricultural soil. However, it remains to be determined if they will be able to do so, and in the meantime the debate will rage on. (Changrong *et al.* 2014; Moreno *et al.* 2017; Ren 2003; Sintim and Flury 2017; Yang *et al.* 2014).

Biodegradable plastic mulch film designed to be broken down by the resident microbial colonies in the soil exhibits variable degradation rates, sometimes leaving fragments in the soil for long periods of time (Li, C.H., *et al.* 2014), creating soil contamination. Additionally, biodegradable plastic films have different gas permeability and thermal properties than non-biodegradable films, which alter the microbial life of the soil they cover (Bandopadhyay *et al.* 2018).

While biodegradable mulch film was designed to be plowed into the soil, there are still many questions yet unanswered about its long-term impacts on soil and soil ecosystems (Bandopadhyay *et al.* 2018).

Additional Research Needed

Findings to date demonstrate that the effects of microplastic contamination can cause ripples throughout the terrestrial ecosystem, with the potential to affect the germination and growth of crops. Key questions to address include:

- How might we balance the costs and benefits of plastic in agriculture over time? Is the long-term impairment of the soil worth the short-term boom in production?
- What are the levels of soil impairment and how are they characterized? What can farmers do? Can impaired soils be remediated? In what way and at what cost?
- What are the advantages and disadvantages of biodegradable films? Do they actually work?

Waste

The waste footprint of plastic's agriculture applications is another growing concern.

Plastic's lifespan is variable depending on the application, but in many cases, its inexpensive nature makes it more cost efficient to dispose of it after use. The volume of agricultural plastic that is categorized as a single-use material is difficult to precisely quantify, but it would be reasonable to say that most agricultural plastic falls into this category.

Each plastic application has its own waste profile and end of life options, as detailed here.

Film

Plastic mulch is only suitable for one growing season, although occasionally "double cropping" practices are employed to use the mulch for two different crops, one after another, to make the most of the material. In the case of agricultural films, re-use is not possible if the material is torn or damaged.

Black plastic costs farmer USD 250-300 per acre for the material and installation, not a trivial cost for farmers given their profit margins. It costs farmers another USD 20 per acre for the plastic to be hauled away for disposal (Feeser, Zinati and Moyer 2014).

Liu *et al.* (2014) estimated that every acre of land farmed using plastic mulch produces 45-54 kgs of waste that typically goes to landfills, while Cassou (2018) estimated that US farms with black plastic systems create approximately 18-22 kg of plastic waste per hectare. Grossman (2016) estimated US plastic mulch at 8 tons of plastic waste for every 100 acres of farmland, or 80 kg per acre, which is significantly higher than the other estimates.

There is a lack of efficient collection and disposal methods for agricultural film. Some manufacturers offer collection and recycling programs for the material after use to mitigate their waste footprint, but this is limited.

Most of the 454,000 metric tons of US agricultural film goes to landfills, with a less than 10% recycling rate (Grossman 2016). Due to the limitations of the recycling process, recycling of used agricultural films is only possible if contaminants such as soil, pesticide, and hay residue make up less than 5% of the mulch's total weight. Recycling of these materials has proven impractical and costly (Brodhagen *et al.* 2017; Kasirajan, Ngouajio 2012; Steinmetz *et al.* 2016).

As a result, approximately 90% of this waste is destined for landfill. However, sending used agricultural mulch off-farm can incur transportation costs which make this option undesirable and expensive. In some cases, incineration or pit burial are utilized to reduce the volume of plastic being sent to landfill. In-field burning of plastics is often illegal, as the high-temperature combustion required to incinerate plastic film mulches made of PE and PVC produces carbon monoxide and polycyclic aromatic hydrocarbons, which are both toxic atmospheric pollutants (see Human Health section below). Despite this, some states are willing to permit the burning of plastics due to the challenges that disposal of plastics often presents.

Irrigation

The industry's growing reliance on single-use irrigation systems has a yet-unknown plastic footprint and is likely to generate a substantial waste impact.

According to a 2017 study by Southern Waste Information Exchange, for every acre of land prepared for strawberry planting, there is approximately 21,849 feet of drip tape, 11,010 feet of oval hose, and approximately 58,720 square feet of plastic mulch. Based on averages provided by irrigation service providers, approximately 5,940 to 10,890 feet of plastic are used per acre. This equates to approximately 51.5 to 94.38 pounds of plastic per acre, and across the US, drip tape usage can be estimated to produce approximately 134,939 tons of plastic waste.

Other plastic sources such as PVC pipe mainlines and layflats are more challenging to estimate since they vary greatly from one ranch to another, but much of this plastic, particularly mulch films and drip tape, is single-use, designed to be collected and disposed of after a single growing season.

Single-use irrigation drip tape is challenging to dispose of because it becomes contaminated with soil, agricultural chemicals and organic matter like hay. For many years, used drip tape was placed in landfills or buried on farm. Recycling of drip tape has gained popularity in recent years, with some manufacturers offering programs which aid in the removal and recycling of this material.

Recycling and repurposing of irrigation drip tape is still a relatively recent development, and more data is needed to determine how effective this process is for handling the quantities of waste generated by the agricultural industry.

Packaging

In the US alone, packaging of fruits and vegetables accounts for one third of household waste, with about 80% of this plastic being single-use (Café Brands 2014).

The increased use of single use plastic packaging during harvesting, transportation and for marketing purposes[1] is likely present the same challenges facing the food and beverage industries – waste that is difficult to collect due to insufficient recycling capacities and chemicals leaching from the plastic material.

Disposable plastic products are extremely lightweight which makes them convenient and cheap packaging -- but also very prone to becoming litter.

Containers
Pesticide containers are a particularly difficult waste to deal with at the end of life because they are contaminated with pesticide. The Ag Container Recycling Council is an industry-funded non-profit that accepts contaminated containers and recycles them into items that will have minimal touch contact, minimizing the health risk. The ACRC claims that they have recycled over 86,000 metric tons of plastic since 1992.

Twine
Agricultural twine made from plastic can also be recycled, but it requires extension cleaning first, which can include having workers remove hay from it by hand. It is also rough on the machinery (Grossman 2015).

Additional Research Needed

- What is the economic impact of the waste footprint of plastic on farmers today? On rural communities? On society as a whole?
- How do agricultural plastics contribute to ocean plastics? At what order of magnitude are macro, meso and microplastics from agricultural plastics entering waterways?
- How can agricultural plastics become a loop rather than a line? What recycling technologies exist that could be tailored and scaled to address the unique challenges of used agricultural plastics?

Human Health

There are several potential human health risks that are associated with the use and disposal of plastics. Plastic contains chemicals with toxic potential, as well as the ability to transport contaminants. Disposal methods such as burning amplify the problem, as this releases chemicals into the atmosphere that have been demonstrated to pose health issues.

Toxicity via water

Black plastic-covered fields have the effect of raising the concentration of agricultural chemicals in the fields' runoff, as less is taken in by the soil. (Feeser, Zinati and Moyer 2014). Pesticides can be both acutely and chronically toxic to humans (World Health Organization and United Nations Environmental Programme, 1990) and are not always fully filtered out of drinking water.

Further, as elaborated in the section on Sources of Microplastics Entering Soil, microplastics from a range of sources, including agricultural, are present in drinking water as well as bodies of water. The health impacts on human ingestion of and exposure to these microplastics is not yet well understood, though the World

[1] Industry reports that customers like to inspect produce from all angles before purchase, which in turn drives the use of plastic clamshells and plastic bags.

Health Organization recently concluded that there is no evidence to conclude that microplastics in water pose a risk to human health (World Health Organization, 2019), yet did indicate that further research was needed.

Toxicity via air

In India, approximately 10-12% of all plastic waste is burned, releasing substances such as dioxins, furans, mercury, and polychlorinated biphenyls (Verma *et al.* 2016). Agricultural plastic is also burned, legally or illegally, in many other parts of the world. Burning plastic results in airborne particulate emission and ash, which can possess a high risk for human health implications as potential carcinogens (Verma *et al.* 2016).

As discussed in the prior section Source of Microplastics Entering Soil, atmospheric deposition is a source of microplastics to soil. Plastic dust settling out of indoor air onto food has been identified as another pathway through which microplastics enter the human body. Catarino et al (2018) determined that humans ingest approximately 114 plastic fibers with each meal from household dust settling onto food while it is on the table. While household dust is not likely to contain agricultural plastics, it is not yet well-known what proportions different plastics contribute to atmospheric plastic dust and fibers. As with microplastic ingestion through water, there is not yet evidence of human health impacts but further research is warranted.

Toxicity via soil

Some plastics are capable of leaching additives called phthalates, which are suspected of being carcinogenic and endocrine-disrupting. These chemicals not only harbor the potential to damage soil organisms and communities—their presence in the soil may serve as a gateway to entering the food chain, representing a potentially significant source of exposure to humans (Steinmetz *et al.* 2016).

Another example is the group of plasticizing agents known as phthalic esters (PAE), which are potentially carcinogenic and endocrine-disrupting (Steinmetz *et al.* 2016). In China, PAEs are often included in plastic mulches and are incorporated into the polymer structure without covalent bonding. This means that it is easier for these agents to leach from the mulches. This leaching was observed by Kong *et al.* (2012), who discovered concentrations of six of the major PAEs between 74 and 208% higher in croplands that had been mulched with plastic in China. These chemicals can be taken in by soil fauna and can also damage crop quality when absorbed by plants. This is a source of bioaccumulation and magnification that can create a threat of exposure for humans.

In addition to PAEs, several endocrine disrupting compounds are present in certain plastics which are of concern to developing organisms. Early developmental exposure to these compounds has been documented to lead to altered gene expression and phenotypic changes, as well as the potential development of cancer and early onset puberty in human females (Talsness *et al.* 2009).

Additional Research Needed

- Which additives are used in agriculture films and other popular agricultural plastics applications? What are the human health impacts of these additives?
- How might humans be exposed to potentially toxic substances in microplastics in agricultural soil and at what levels? What could be done to minimize this risk?
- Given that the cycling of nutrients and water is a key source of microplastics incorporation into agricultural soils, what can be learned about setting up circular systems that are effective at minimizing risks from persistent substances?

Next Steps

This report is intended to serve as a foundation for further studies and guidance for a portfolio of interventions: alternate materials, green chemistry, packaging design, redesign of existing materials, incentives to recycle, policy initiatives and economic tools.

As noted in prior sections, further research is needed in several areas in order to have better data and understanding of the impact of the use of plastic in agriculture on soil, waste streams and their economics, and human health.

But the data will merely point the way; it is the work of innovators and entrepreneurs, policy-makers, industry, farmers and others to do the work to identify or create solutions and facilitate their implementation.

Our recommendation is that the process follows the cascade of considerations, such as:

- What are the high-priority areas for intervention?
- What innovations might be readily available as an alternative?
- What is the role of public policy?
- Can circular economy principles be applied and how?
- What are some of the key gaps in knowledge that need to be addressed in order to better inform solutions in the future?

Appendix

Case Study: Strawberries in the Salinas Valley of California

Phase	Description	Use of plastic	Benefits
Pre-planting	Soil is prepared by one of two methods: (1) Flat fumigation; (2) In-bed fumigation Strawberry plants are transported to the fields.	Wrapping the soil for fumigation; plastic starter trays protect young plants.	Increases efficiency of fumigation; plastic trays protect young plants from damage or contamination prior to planting.
Planting	Layflat hoses connect main water sources to drip tape to irrigate the soil.	Drip irrigation delivers water directly to the root zone.	Very efficient use of water that minimizes waste.
Growing	Plastic mulch is laid over plant beds prior to planting; Pesticides and fertilizers are applied over the growing season.	Plastic mulch film is used; Pesticides and fertilizers come in plastic containers and can be polymer-coated.	Plastic mulch is laid over the beds to help them keep their shape, prevent mold and disease, suppress weeds, reduce water use and ensure that berries do not touch the ground to limit food waste; fertilizers and pesticide plastic containers are designed to be durable, resistant to cracking or corrosion, and safe to transport.
Harvesting *Transportation*	Plants are hand-picked in the fields and placed in clamshells for sale to the consumer.	Plastic clamshells are used to package the berries; Transport in reusable plastic bins.	Structural integrity of clamshell decreases bruising and food waste; improves shipping efficiencies by allowing stacking; and allows consumers to inspect the product prior to purchase
Processing/ *Packaging/* *Shipping*		Palettes are sometimes shrink-wrapped and gassed with CO_2.	Gasses applied to the berries are kept on the fruit via shrink-wrap, helping the berries stay fresh longer.

Strawberries were chosen as a case study for this report due to the high volume of plastic required for their cultivation. According to the most recent 2018 Tridge[2] data, the world's leading producer of strawberries is now China with almost 3 Million tons, followed by the US with approximately 1.38 Million tons. Other top strawberry producing countries in the world include Mexico, Turkey, Russia, Japan, South Korea, Poland, and Germany. Strawberries are the most extensively grown plasticulture crop (Wittwer 1993). After World War II, the Salinas Valley in California became America's foremost producer of strawberries, and between 1945 and 1957, strawberry acreage increased from 1,100 acres to more than 20,000 acres. Today, approximately 90% of the strawberries produced in the US are grown in California (Geisseler and Horwath 2014). Strawberry cultivation practices vary depending on location, and while they are grown across America, California's sunny days and cool, foggy nights make an ideal environment for optimal berry growth. Strawberries are a particularly remarkable case study in that despite an increase in cropland of only 11% between 1970 and 2012, total production is nearly six times greater (CropLife Foundation). This increase is due in part to the development of more productive cultivars and the optimization of pathogen- and pest-free planting stock, but one important element of this impressive growth is the extension of the growing season using plasticulture. Plasticulture's influence on strawberry growth is significant, and as such, it serves as an ideal case study for understanding the potential footprint of plastic in a crop that heavily relies on its presence.

Plastic Use and the Growing Process

Strawberries have a few sensitivities that make them prime candidates for plasticulture, and as such, plastic is used throughout the production lifecycle to extend the plants' productive capabilities. When necessary, some producers use plastic to cover their field to treat the soil to reduce the risk of soilborne diseases. This plastic film is then removed, disposed of, and replaced with a fresh sheet of plastic covering only the strawberry beds, which keeps berries clean, warms the soil, prevents the spread of disease, reduces water demand and further limits weed growth. Strawberries are also particularly susceptible to both over- and under-watering, and plastic drip tape can assist in the regulation of water delivery to the plants. Plastic mulch is used to separate the berries from the soil, preventing the spread of mold and strawberry mites, resulting in 20+% improvements in yield (KIvijarvi, Parikka, and Tuovinen 2002).

Considerations for Further Study

In order to create an accurate estimate of the plastic footprint of strawberry production, further study is recommended to gather and update the current data. There is very little information readily available on the quantities of irrigation piping and drip tubes used on farms, many of which are single-season use and recycled or disposed of following the harvest. Additionally, other sources of farm plastic such as starter trays and fertilizer containers and sacks are often overlooked when assessing quantities of plastic used on farms. A more in-depth study of plastics other than film mulches would greatly contribute to a clearer overall picture of the plastics used in strawberry cultivation.

[2] Global intelligence firm with data on agriculture and food

Case study: Tomatoes in the Salinas Valley of California

Tomatoes are one of the world's most consumed vegetables, and according to information from the FAO, approximately 340 billion pounds of fresh and processed tomatoes were produced in 2014 (Guan, Biswas, and Wu 2018). The tomato is one of the most widely grown vegetables in the US with an annual harvest of over 14 million tons across approximately 400,000 acres (Kelley and Boyhan 2017). California is a lead producer of tomatoes in the US for processing tomatoes, following just behind Florida, and in the fresh tomato market, Florida leads with California just behind it. Tomatoes are grown expansively throughout the USA, however, and other significant growing states include Georgia, the Carolinas, Tennessee, Alabama, New Jersey, and Michigan. In the Eastern US, tomatoes are frequently grown with the use of plastic mulch and drip irrigation. Tomato plants require a specific climate when being grown and are susceptible to periods of cold weather and frost. As a result, farmers employ plastic film mulch to warm the soil and keep plants at a temperature conducive to growth. Tomatoes may be grown in a variety of settings, including greenhouses, high tunnels, open shade structures, and outdoor hydroponic systems with no protected structure (Hochmuth 2012).

Plastic Use and the Growing Process

Within the state of California, tomato production is varied based on the type of tomato being grown. Some fresh-market tomatoes are grown on poles, while others are grown as bushes without support (Le Strange 2000). In Southern California, tomatoes being sold as fresh produce have traditionally been grown on poles—a practice that is costlier, but that results in an extended harvest and increased yields. In January and February, tomatoes are grown under plastic row covers for temperature control. Plantings made in mid-March are often protected by half tents, and plantings made April through August are left uncovered (Le Strange 2000). Once planted, tomatoes are watered via irrigation drip tape, which improves water efficiency, reduces weed germination, and reduces the risk of bacterial diseases (Le Strange 2000). When tomatoes are ripe and ready to be harvested, they are picked into buckets and emptied into bins or gondolas for processing in a packing shed (Le Strange 2000) where they are rinsed, sorted, and packed for shipment. They may remain in cold storage for up to two weeks and are treated with ethylene prior to shipment to ensure even ripening (Le Strange 2000).

Plastic use is common at almost every phase of the growing and shipping process, from the harvest buckets and bins used for transportation to the film used to wrap the tomatoes prior to ethylene treatment to ensure that the ethylene evenly treats the tomatoes. Despite its ubiquitous presence, little data is readily available on where, how and why plastic is used in the tomato growing process.

Since California is one of the largest producers of tomatoes in the US, it is likely that the plastic footprint of this industry is significant. This case study examines the reasons and benefits of plastic use, in order to understand its impacts and consider possible replacements or interventions.

Phase	Description	Use of plastic	Benefits
Pre-planting	Drip tape is installed, and the fields are prepared for plants.	Plastic drip tape is laid on the beds under the plastic mulch to provide water directly to the plant's root zone; Mainline transports water from the water source to the drip tape.	Drip tape is by far the most efficient form of irrigation, reducing water use significantly; plastic gloves prevent contamination and are inexpensive to replace after single-use.

		Mainline is primarily made from PVC, although metal piping does exist; workers use disposable gloves.	
Planting	Transplants are machine-planted into the prepared soil.	Transplants are moved to the planting site in Styrofoam planting trays; workers use disposable gloves.	Styrofoam is lightweight; vinyl gloves are chemical resistant and fit snugly on the worker's hands.
Growing	Plants mature for the duration of their growing season and are treated with pesticides and fertilizers to enhance growth and plant yield.	PET fertilizer and pesticide containers are used to transport and store chemicals prior to application.	Fertilizers and pesticide plastic containers are designed to be durable, resistant to cracking or corrosion, and safe to transport.
Harvesting	Tomatoes are picked from their plants and placed in buckets to be transported off the field.	Plastic harvest buckets; vinyl disposable gloves.	Plastic buckets are durable and can be tossed by workers without damage; vinyl gloves are chemical resistant and fit snugly on the worker's hands.
Transportation Processing	Tomatoes are packed into large plastic bins for shipment.	HDPE Plastic Bins.	Plastic bins must be durable enough to handle at least 1 ton of material per bin or 25 lbs/RPC.
Packaging	Tomatoes are packed for sale.	PET plastic shrink wrap.	Plastic shrink wrap is clear, which allows consumers to see the product they are purchasing, and it is also inexpensive.

Considerations for Further Study

In order to obtain a more accurate sense of the quantities of plastic used tomato growers, there are a few areas which would benefit from further study. One of these areas includes quantities of drip tape and irrigation piping typically used on farm. Specific numbers on this plastic application were difficult to locate, and it is recommended that interviews be conducted with individual farmers about the current needs of their operations. Additionally, plastic mulch in tomato production has altered in recent years, as tomatoes that are mulched are also generally grown on stakes. This is now becoming more infrequent in California although it is still practiced in the Eastern US, and as such, it is important to evaluate the amount of plastic used in California tomato production and how that usage compares to plastic usage in other states. These investigations might provide a clearer understanding of the trajectory that plastic use in tomato cultivation is currently progressing along.

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