Historic and Present-Day Environmental Issues Involving Tomato Plasticulture and Shellfish Aquaculture on Virginia's Eastern Shore

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Abstract

The Eastern Shore of Virginia, located on the Delmarva Peninsula, is known for its agricultural commodities, especially *Solanum lycopersicum*, *Crassostrea virginica,* and *Mercenaria mercenaria*. For decades, controversy has surrounded the two industries. Runoff from fields of tomatoes grown in plastic mulch was thought to have caused mass casualties of shellfish in hatcheries in the tidal creeks and bays of the Eastern Shore. The impervious surface of the plastic mulch decreases infiltration of rainfall and increases runoff velocity and volume. Several studies have sought to determine the effect of plasticulture systems on water quality, which in turn affects aquaculture production. Many chemicals, including pesticides and copper, are applied to tomatoes grown in a plasticulture system to reduce disease, weed, and pest pressure. When applied after plastic mulch has been laid, these chemicals can wash off of the plants and the plastic mulch during a rain event. Unfortunately, studies have shown that copper, as well as other chemicals used in tomato production, have a detrimental effect on shellfish growth and survival. Increased amounts of sediment in runoff waters due to erosion of fields also have negative effects on shellfish production. After the threat of regulation in the late 1990s, the tomato industry on the Eastern Shore has been working closely with several agencies to implement best management practices (BMPs) for the reduction of erosion and runoff. These conservation practices have been proven effective in reducing impacts on water quality. Water quality monitoring should be continued to determine whether the implementation of these BMPs is indeed decreasing tomato production's negative impact on the aquaculture industry on the Eastern Shore of Virginia.

Key terms: Crassostrea virginica, Eastern oyster, Mercenaria mercenaria, Northern Quahog, copper, best management practices

Introduction

The Eastern Shore of Virginia is comprised of two counties: Accomack County to the north and Northampton County to the south. Virginia's Eastern Shore is a 70-mile stretch of land that is the southernmost part of the Delmarva Peninsula. The Chesapeake Bay, which separates the Eastern Shore from the rest of Virginia, lies to the west, while the Atlantic Ocean, lined with barrier islands, is to the east. Maryland borders Accomack County to the north, and the Chesapeake Bay Bridge Tunnel, a 23-mile-long system, connects the southern tip of Northampton County with the Hampton Roads area and the rest of the state (Eastern Shore of Virginia Community Needs Assessment 2011; Figure 1). The year-round population in 2012 was 45,567, with 73% of the population living in Accomack County (US Census Bureau 2012).

Figure 1- The Eastern Shore of Virginia

The Eastern Shore of Virginia is very rural and its strong history of agriculture, fishing, and tourism is evident today, as its economy continues to be dependent on farming and seafood. Being one of the few places on the East Coast that has preserved its pristine marine environment and shoreline ecosystem, the tourism and eco-tourism industries flourish. Agriculture, aquaculture, tourism, new and existing businesses, education, and water quality are the focus of the shore's economic development strategy (Eastern Shore of Virginia Comprehensive Economic Development Strategy 2011).

Well-drained, deep, sandy loam soils comprise most of the agricultural land on the Eastern Shore. These soils, along with average rainfall amounts around 50 inches/year and the flat terrain, are very conducive to agricultural production.

Vegetable Production

According to the most recent USDA Census of Agriculture (conducted in 2007), Northampton County is contains 151 farms with a combined acreage of 63,760 acres. Northampton County ranks number one in the state for sales of vegetables with a total annual value equaling $32,012,000. Accomack County is contains 248 farms with a combined total of 93,764 acres. Accomack County ranks number two in the state for sales of vegetables with a total value equaling $22,660,000. In 2012, 572.6 acres in Accomack County were used for tomato (*Solanum lycopersicum*) production, while 892.6 acres of tomatoes were grown in Northampton County (Farm Service Agency, personal correspondence).

Aquaculture

Historically, oysters and clams were harvested from their natural habitats. Due to disease, predation, and poor water quality, shellfish aquaculture has shifted from natural harvesting to a more farmed approach. Northampton County ranks number one in the state of Virginia in aquaculture sales with a total value of sales equaling $30,731,000, while Accomack County ranks number three in aquaculture sales with a total value of sales equaling $4,016,000 (USDA 2009). The same report shows a total of $9.5 million of market oysters sold by Virginia growers in 2012, with about 25-30% coming from Accomack and Northampton counties. The Virginia Shellfish Aquaculture Situation and Outlook Report shows the value of Virginia market clams sold in 2012 as $26.8 million, with almost 100% grown in Accomack and Northampton counties (Virginia Marine Resources Commission [VMRC], personal correspondence). According to economic assessments compiled by the VMRC, Virginia leads the U.S. in the culture of hard clams (Murray & Hudson 2013).

Historical and present-day social and economic issues related to plasticulture and aquaculture

During John Smith's travels to the Chesapeake Bay in the 17th century, he described oysters that "lay as thick as stones." Along with disease and predation, severe harvesting practices and over-harvesting of the eastern oyster has led to drastic declines in its population in the Chesapeake Bay. Oyster bed dredging, a common harvesting technique in the mid-19th century, destroyed centuries-old oyster reefs (Rothschild et al. 1994). Today, because of the market demand for and the realized water quality benefit of oysters, oyster reef restoration is popular and practiced throughout the Chesapeake Bay and its tributaries.

In the past several decades, as both plasticulture and shellfish aquaculture production have increased on the Eastern Shore of Virginia, there has been controversy surrounding the relationship between the two agricultural practices. Since the early 1900s, mortality of shellfish larvae at hatcheries was common; however, in 1996, clam hatcheries began to experience mass mortalities of larvae. The cause was thought to have originated from chemicals and sediments washing off of plasticulture fields into tidal creeks; this water was then used in the hatchery systems (Petrocci 2001). Concern from members of the aquaculture industry about plasticulture and its relationship to clam mortality on the Eastern Shore of Virginia, as well as concerns regarding water quality issues, protection of aquatic life in estuarine environments, economic development and prosperity in commercial and recreational fisheries, and tourism with regard plasticulture on the Eastern Shore, led to action from the state of Virginia (House Document No. 44 1998).

In response to House Resolution No. 44, in which the 1997 General Assembly of Virginia requested that an interagency task force be established to review the water quality management measures utilized in the practice of plasticulture, studies were conducted to determine (1) whether existing programs and policies are sufficient to ensure adequate water quality management when the practice of plasticulture is utilized; (2) whether additional research and development of best management practices relating to plasticulture should be undertaken by the Commonwealth; and (3) whether existing state programs are consistently applied and coordinated between agencies with regard to the practice of plasticulture (House Document No. 44 1998).

The task force, led by the Virginia Department of Agricultural and Consumer Services (VDACS), reviewed conservation and best management practices, existing scientific research, and existing programs and policies related to water quality management and plasticulture practices, and solicited public comments. The task force made several recommendations to the Governor and the General Assembly concerning conservation practices, water quality monitoring, and funding for further research. Their findings suggested that the current regulations were adequate in protecting water quality in the bay. Arguably, the most important outcome of this task force was to open channels of communications between the agriculture and aquaculture industries and the environmental communities on the shore.

Accordingly, the objectives of this paper are to detail the tomato plasticulture system and the aquaculture systems used on the Shore, discuss effects of plasticulture practices on aquaculture, describe conservation practices studied to reduce negative effects from plasticulture, and discuss the present-day status of plasticulture issues on Virginia's Eastern Shore.

Agricultural Systems

Plasticulture

Plasticulture, as defined by the University of California's Division of Agriculture and Natural Resources (Schrader 2000), is "the art of using plastic materials to modify the production environment in vegetable crop production.." The concept of plasticulture is often taken beyond this basic definition and is described as a management tool which includes many components, such as plastic mulches, raised beds, drip irrigation, soil fumigation, fertigation, windbreaks, disease prevention, weed and pest management, and cropping strategies and rotations (Lamont 1996).

Overview

As a management tool, plasticulture can offer many benefits to vegetable producers, enabling them to realize greater returns per unit of land. These benefits include extended growing seasons by enabling earlier crop establishment, higher yields per acre, more efficient use of water and fertilizers, and better management of and decrease in diseases, pests, and weeds (Lamont 1994, Lamont 1996).

One of the main uses of plastic mulch is to manage the soil temperature. The color of the mulch determines the amount of solar radiation that is reflected and therefore the effect on soil temperature. Clear, white, silver, and black mulch dominate the vegetable market. White or silver plastic is used most frequently on tomatoes planted in the spring on the Eastern Shore of Virginia. The plastic is typically 1.25 millimeters thick, 3-6 feet wide, and comes in rolls of 2,000 to 3,000 feet (North Carolina Cooperative Extension Service 1996). Both white and silver plastic reflects the sun’s radiation away from the soil and back into the plant canopy, lowering the soil temperature. Compared to bare soil, soil temperatures under a white or silver plastic mulch are generally 0.7-2°F lower, depending on the depth (Lamont 1994, Lamont 1996). White plastics are used to establish a crop when soil temperatures are high. Depending on the opacity of the white plastic, fumigants or herbicides may be required to reduce the risk of weed growth under the mulch (Lamont 1996). In contrast, black plastics, which reflect the sun’s radiation, are used to lower soil temperatures, and their opacity blocks light and prevents weed growth under the mulch.

Other options of mulch are available on the market. Wave-length-selective mulches, usually blue-green or brown, provide a compromise between the soil-warming characteristic of clear mulch and the weed–control opacity of black mulch by absorbing photosynthetically active radiation and transmitting solar infrared radiation (Lamont 1996). Other colors of mulch, such as orange, red, gray, and yellow, reflect different radiation patterns that can affect plant growth and development. Different colored mulches have also been studied for their effect on pest populations; for example, yellow, red, and blue mulches have been shown to increase aphid populations (Lamont 1996).

Plastic mulch used in conjunction with drip irrigation is preferable for a number of reasons. Drip irrigation tape (commonly called “drip tape”) or tubing is laid in the vegetable row, under plastic, and will continuously wet the soil (Figure 2). Water is provided slowly through the tape or tube and is generally applied daily (North Carolina Cooperative Extension Service 1996). Water use can be decreased by as much as 80% by using drip irrigation versus other methods (Lamont 1996). The source of irrigation water can include wells, ponds, municipal lines, or pits. A sand, screen, or disc filter may be necessary to filter debris and contaminants from water before irrigation occurs (Lamont 1996; North Carolina Cooperative Extension Service 1996).

Figure 2--Drip irrigation tubing visible under plastic mulch; photo courtesy of Eastern Shore Soil & Water Conservation District.

Fertilization of the crops can be done through the irrigation lines, a practice called fertigation. Water-soluble fertilizers are added to the water source by injectors and then distributed throughout the system. This practice allows for a more precise, uniform, and efficient use of fertilizers and may prevent excess leaching of nutrients through the soil profile (Lamont 1996). If fertigation is used, the grower must coordinate irrigation with crop nutrient needs.

Soluble fertilizer forms such as nitrogen, phosphorus, and potassium can also be added to the soil before the beds are laid (Figure 3).

Figure 3- Fertilizer being placed on bare beds; photo courtesy of Eastern Shore Soil & Water Conservation District.

The crops that have shown the most benefit (earliness of development, yield, and/or fruit quality) from the use of a plasticulture system include tomato (*Solanum lycopersicum*), squash (genus *Cucurbita*), eggplant (*Solanum melongena*), muskmelon (*Cucumis melo*), bellvpepper (*Capsicum annuum*), watermelon (*Citrullus lanatus* (Thunb.), and okra (*Abelmoschus esculentus*). Similar responses have been shown in other crops such as sweet corn, herbs, pumpkins, and snap beans (Lamont 1996; Virginia Cooperative Extension 2013). The focus of this paper will be solely on tomato production on the Eastern Shore of Virginia, where tomatoes are grown in two overlapping seasons, with the first planting occurring in March or April and the second in June.

A tight, firm, well-formed raised bed must be formed before the plastic is laid. Care must be taken to ensure that no debris is in the soil that may puncture the plastic (North Carolina Cooperative Extension Service 1996). The raised bed is crowned in the middle and the sides tapered away from the row center, allowing water to shed between rows (Figures 4, 5). Stretching plastic tightly on top of the raised bed and tucking the ends of the plastic under the soil allows for even greater water runoff (Figure 6). Bedding machines are available and can make the beds and lay the plastic in one operation. Raised beds in conjunction with plastic mulch are beneficial to producers who want to reduce drowning of crops by excess rainfall and/or irrigation and to generate a cleaner crop by eliminating soil splashing up onto the produce (Lamont 1994). In tomato production using plastic mulch, approximately 55 percent of the field is covered in plastic (Dietrich et al. 2001).

Figure 4- Formation of raised beds; photo courtesy of Eastern Shore Soil & Water Conservation District.

Figure 5- Formation of raised beds; photo courtesy of Eastern Shore Soil & Water Conservation District.

Figure 6- White plastic mulch; photo courtesy of Eastern Shore Soil & Water Conservation District.

Soil fumigation for control of nematodes

Nematodes are microscopic worms that live in soil; many are parasites to plants, insects, and animals. Nematodes inhibit a plant's ability to absorb water and nutrients, generally reducing productivity. Root knot *(Meloidogyne hapla)* and root lesion *(Pratylenchus penetrans*) are the two most common nematode species found in tomato fields in Virginia (Pest Management Strategic Plan for Tomato 2007).

In the southeastern United States, fumigating the soil is common. Chemical fumigants are mainly used to control nematodes, but there are multi-purpose fumigants that provide good control of soil-borne diseases, insects, and weeds as well (Lamont 1996; North Carolina Extension 1996). Fumigants can be used to control active nematodes after harvest and/or to treat preventively for the next growing year (Gatton 2007). A fumigant can also be applied to the soil immediately before plastic is laid; the impervious nature of the plastic mulch acts as a barrier and aides in retaining the fumigant in the soil, increasing its effectiveness (North Carolina Cooperative Extension 1996). The soil should be well-worked, have adequate moisture for seed germination, and be at least 50°F (10°C). Both warm soil and warm air will allow the fumigant to escape through the plastic mulch in 12-14 days (Lamont 1996, North Carolina Cooperative Extension 1996).

Historically, the broad-spectrum fumigant methyl bromide was widely used as the main chemical for nematode, fungus, insect, and weed control. Methyl bromide effectively controls crop nuisances, relatively inexpensively, without causing a loss of yield. However, the US Environmental Protection Agency (EPA) is concerned with potential developmental and neurological human health risks associated with methyl bromide inhalation, as well as with the human health risks associated with methyl bromide's role in the depletion of the stratospheric ozone (US EPA 2008b). Under the Clean Air Act and the Montreal Protocol on Substances that Deplete the Ozone Layer, as of January 1, 2008, US production of methyl bromide was banned. A critical-use exemption allows for the use of methyl bromide as a soil fumigant in the US for tomatoes through 2013 (US EPA 2008b). Because of methyl bromide's wide use and effectiveness, research has been done to find the best alternative for tomato growers needing a broad-spectrum fumigant after 2013.

The current primary alternatives of methyl bromide include chloropicrin, 1,3 dichloropropene (1,3-D), and methyldithiocarbamate salts (metam-sodium and metam-potassium) (US EPA 2008b; US EPA 2011b).

Chloropicrin has shown promising results as a feasible alternative of methyl bromide (US EPA 2011b). When used as a pre-plant fumigant, the chemical controls soil-borne fungi, diseases, and nematodes (Extension Toxicology Network Pesticide Information Profile 1993). It can either be incorporated into the soil before plastic is laid or run through the drip irrigation system. Chloropicrin is not listed under the federal Clean Air Act, so it does not raise the same concerns over ozone depletion as methyl bromide. However, chloropicrin is highly toxic to humans when ingested and can potentially leach into groundwater or reach surface water during heavy rain events due to its high solubility. In a plasticulture system, the plastic mulch inhibits excess rainfall from reaching the soil, therefore limiting the potential for leaching of chloropicrin (US EPA 2008a).

1,3-D is another broad-spectrum soil fumigant used for its nematicidal, fungicidal, insecticidal, and herbicidal properties (Extension Toxicology Network 1986). It too can either be incorporated into the soil before plastic is laid or run through a drip irrigation system. 1,3-D is of moderate acute toxicity to humans; exposure can occur through inhalation of volatilized 1,3-D and/or drinking contaminated drinking water. Studies have shown that high rates of 1,3-D in groundwater can occur where soils are permeable and water tables are shallow (US EPA 1998b). The EPA states that 1,3-D is "highly toxic to invertebrate species, moderately toxic to birds and mammals and moderately toxic to fish" and expects the same toxicity patters for estuarine and marine organisms (US EPA 1998b).

Metam sodium and metam potassium are broad-spectrum, non-selective soil fumigants that control nematodes, insects, weeds, and soil-borne fungi. These dithiocarbamate salts break down quickly in the environment to methyl isothiocyanate (MITC), which is highly volatile and the responsible agent in the fumigant properties of metam sodium and metam potassium (US EPA 2008c). Both of these chemicals offer superior pest control in tomato production, and, unlike methyl bromide, have no effect of the stratospheric ozone layer. Because of the high potential of MITC to volatilize and degrade rapidly, its potential for exposure to terrestrial and aquatic organisms is somewhat limited (US EPA 2008c).

Post-plant control of diseases, weeds, and/or pests

Post-plant chemicals are used if a broad-spectrum fumigant was not used pre-plant, or was found to be ineffective at controlling diseases, weeds, and/or pests. Good spray penetration and coverage beneath leaves are necessary for the chemicals to reach the plants and the soil, thus it is important that the sprayer used has sufficient pressure. The application of post-plant chemicals may lead to chemical build-up on the plastic mulch; these chemicals may wash off during a rain event and run off into surface water. Chemicals should be used efficiently to control the disease or pest so as to not negatively affect the environment (Lamont 1996).

Disease prevention

Tomato production in Virginia is challenged by the large number of diseases that affect tomatoes and the limited availability of control options (Nessler 2007). The most common problems in Virginia are early blight, Septoria leaf spot, bacterial leaf spot, and bacterial wilt.

Early blight and Septoria leaf spot are caused by the fungi *Alternaria solani* and *Septoria lycopersici*, respectively. Early blight is by far the most injurious leaf spot disease in Virginia, especially in fields with continuous tomato production. It can occur at any time of the growing season, despite its name. Lesions of blotches will appear on lower, older, plant leaves and stems; as the disease progresses, the lesions will develop up the plant. Affected fruit bear dark, sunken lesions on the stem end; these lesions can reach considerable size and the rot can extend deep into the flesh. *A. solani* will survive year-to-year on old, infected plants left in the field; spreading of the disease occurs by splashing rain, running water, and moving machinery (Hansen 2009a). Septoria leaf spot will appear on infected plants as lesions on lower, older leaves. If severely infected, the leaves die and drop off, causing potential of sun-scalding of fruit and failure of the fruit to mature properly. The fungi that cause leaf spot are seed borne but can establish on tomato stakes and crop debris as well. Septoria leaf spot is often confused with early blight; the small, uniform lesions and presence of fungi fruiting bodies, which appear as black specks, confirm septoria leaf spot (Hansen 2009b). Preventative fungicide applications, applied as multi-purpose fumigants (see above), are the best way to control leaf spot diseases, including early blight. The chemicals chlorothalonil, an organochloride, mancozeb, an ethylene bisdithiocarbamate (EBDC), and copper are effective post-plant foliar protectants against these fungal diseases. Chlorothalonil can also act as a curative treatment if low levels of disease pressure occur post-emergence (Nessler 2007, Gullino et al. 2010).

In general, bacterial diseases are difficult to control due to the limited chemicals available. Bacterial spot (*Xanthomonas campestris* pv. *vesicatoria*) is a seed-borne disease, making obtaining pathogen-free seeds and transplants very important. Once bacterial spot is present, it is devastating and hard to control. Spots on leaves and tomatoes caused by the disease render the products unmarketable. Bacterial spot also causes extreme blighting and defoliation under moist weather conditions. In Virginia, acibenzolar-S-methyl, applied as a post-emergent foliar spray, has proved to be the most effective chemical for preventing bacterial spot on tomatoes. To avoid fruit rot problems, it should be used in conjunction with copper hydroxide (Nessler 2007). If disease is already present, a curative agent such as chlorothalonil should be applied in conjunction to provide disease control, while the acibenzolar-S-methyl will further prevent the disease from spreading (Syngenta Crop Production LLC, Actigard 50WG label). Applications should begin within one week of transplanting, and can be in 7- to 10-day intervals for a maximum of 6 applications (Kemble 2013). Other chemicals known to be effective against bacterial spot in tomatoes in Virginia are maneb, a manganese ethylene bisdithiocarbamate (EBCD), fixed copper formulations, famoxadone + cymoxanil + fixed copper, and mancozeb plus copper hydroxide. When used with copper, mancozeb allows for better absorption of copper by bacteria, increasing its efficacy (United Agri Products Canada 2010). Reapplication of copper is common after rain events, which wash the copper from the plants.

Bacterial wilt (*Ralstonia solanacearum*) is a soil-borne disease that affects plant roots. It favors warm, moist soil conditions and results in wilting and eventual collapse of tomato plants. Other than methyl bromide, chloropicrin (pre-plant) and maneb (foliar post-plant) are viable chemical options for tomato growers in Virginia (Nessler 2007).

According to the Southeastern US 2013 Vegetable Crop Handbook (Nessler 2007), foliar disease control in fresh-market tomato production may necessitate weekly spraying before and during harvest.

Toxicities of Chemicals Used for Disease Prevention

Chlorothalonil is a broad-spectrum organochloride fungicide that has been found to be highly toxic to fish, aquatic invertebrates, and marine organisms. One Canadian study shows reduced shell growth in oysters from minimal exposure to the chemical (Caux 1996). There is a possibility of leaching into groundwater in the sandy soils of Virginia's Eastern shore due to the chemical's moderate mobility and low binding in sand (Extension Toxicology Network 1994a).

Mancozeb and maneb belong to the ethylene bisdithiocarbamates (EBDC) class of chemicals. Several types of fungicides belong to this class, and mancozeb arose by the repeated enhancing of several of these. Nabam and zineb, two early EBDCs, were used extensively in the 1940s and 1950s. Maneb, another of these, was found to be more active as a fungicide than nabam and zineb and was patented in the 1950s; Mancozeb, discovered in the 1960s, is the zinc ion complex of maneb, and has proved to be the most important and economically significant of all of the EBDCs. An EBDC itself is not fungicidal; when exposed to water, it breaks down to release ethylene bisisothiocyanate sulfide (EBIS), which is then converted into ethylene bisisothiocyanate (EBI) by UV light. EBIS and EBI are considered to the active toxicants and interfere with enzymatic processes within the fungal cell (Gullino et al. 2010). Maneb is moderately soluble in water, while mancozeb is essentially insoluble. Of the EBDCs in production today as fungicides, mancozeb and maneb are two of the least toxic to humans and animals (Fishel 2005a).

The chemical acibenzolar, belonging to the chemical class benzothiadiazole, induces host plant resistance to disease with no direct effect on the target. According to the EPA, acibenzolar-S-methyl is highly toxic to several estuarine animals, including the Eastern oyster (US EPA 2000).

Copper compounds are registered as foliar sprays for control of numerous fungal and bacterial diseases (Extension Toxicology Network 1992). There are several formulations of copper used for disease control, including copper sulfate, fixed copper oxychloride, and copper hydroxide. All copper formulations start with the same metallic copper, and are processed, reacted, and formulated to make different products for different crop uses and disease controls (United Agri Products Canada 2010). Copper formulations are protective, meaning they do not cure disease but only protect the plant from the onset of disease, and are only effective if they are applied before the onset of disease.

High copper levels can be very damaging to aquatic organisms, reducing survival, reproduction, and growth. Copper sulfate is very toxic to fish and its presence in water may cause a significant decrease in aquatic invertebrate, plant, and fish populations (Extension Toxicology Network 1994b; Fishel 2005b). Copper hydroxide has proven to be lethally toxic to many aquatic organisms, including crustaceans, mollusks, and macroinvertebrates (Pesticide Action Network 2010).

Famoxadone, an oxazolidinedione, is highly active against spore growth and germination of fungi by inhibiting the fungal mitochondrial respiratory chain. Famoxadone has shown little toxicity and carcinogenic effects mammals, but can be toxic to estuarine organisms; spray drift and runoff of famoxadone in its dissolved phase present the greatest risk for toxicity to aquatic organisms (US EPA 2003).

Cymoxanil, an acetimide, is used for suppression of several fungal diseases on tomatoes. It has low acute and chronic toxicity to mammals and has only slightly toxic effects of estuarine organisms (US EPA 1998a).

Management of Weeds

Common weeds of tomato fields in Virginia include broadleaves such as yellow nutsedge (*Cypercus esculentus*), nightshade (*Solanum spp*.), pigweed (*Amaranthus spp*.), common lambsquarters (*Chenopodium album*), jimsonweed (*Datura stramonium*), and bindweed (*Convolvulus spp*.), and grasses such as johnsongrass (*Sorghum halepense*), crabgrass (*Digitaria spp*.), bermudagrass (*Cynodon dactylon*), and barnyardgrass (*Echinochloa crus-galli*). Nightshade is in the same taxonomic class as tomatoes, and is therefore especially hard to control (Davis et al. 1998).

When weeds are present in a tomato field, they compete with the tomato plants for essential nutrients, light, and water. The white plastic mulch commonly used in a plasticulture system on the Eastern Shore reflects most of the sun's rays, but light will still reach the soil, and weed growth may be a problem. Weeds can also flourish around the planting hole and in between the rows of tomatoes, where no plastic is applied. Methyl bromide, the chemical discussed early, is an excellent pre-plant weed control method. However, some weeds may not be effectively controlled by methyl bromide and other soil fumigants. The weed nutsedge (*Cyperus sp*.) in particular can escape soil fumigation because their tubers are dormant in early spring, when many fumigants are applied (Bonanno 1996).

Due to the eventual phase-out of methyl bromide, other alternatives for weed management pre- and post-plant are being explored (Virginia Cooperative Extension 2013). Sodium methyldithiocarbamate (metam sodium) is often used as a methyl bromide substitute, but is not as effective as methyl bromide at controlling weeds (Bonanno 1996). Pre-plant incorporation of a herbicide immediately before laying the plastic can help prevent emergence of broad-leaf weeds and/or annual grasses under the plastic mulch or in the planting holes if severe weed pressure is known to exist. Care should be taken to abide by crop planting recommendations for specific herbicides; for example, when applied under plastic, the halosulfuron label requires a 7-day period between application and transplant of the tomato crop (Masabni & Arboleya 2007). If a multi-purpose soil fumigant is applied, an additional application and incorporation of a pre-plant herbicide is rarely needed (Bonnano 1996).

Trifluralin is a dinitroaniline chemical used as an herbicide to control broadleaf weeds. It can be applied as a pre-plant incorporated treatment, but is primarily used as a layby herbicide, applied in the early stages of crop growth to provide soil residual to control weeds later in the growing season (Davis et al. 1998).

Metribuzin can be incorporated into the soil as a pre-plant, pre-emergence control. It has also shown effectiveness at controlling weeds post-emergence. Napropamide can be incorporated pre-plant or applied at planting (Davis et al. 1998).

Directed shield spraying of soil strips between plastic mulch rows will help control weeds post-emergence while avoiding contact with and harm to the tomato plants (Virginia Cooperative Extension 2013). Broadcast spraying of herbicides directly over the plastic mulch is not recommended at any time (Virginia Cooperative Extension 2013).

Paraquat is a successful control for post-emergent control of weeds between rows of plastic mulch. However, paraquat can burn and injure tomato plants, and improper application of the chemical between rows may negatively affect tomato growth and production (Nessler 2007).

Pest management

Insecticides can be used at planting to prevent infestations or for control when pests are cited in the field (Nessler 2007).

In Virginia, stink bugs and thrips are the most common pests of early-season tomatoes, while tomato fruitworms and aphids can damage late-season crops. Both the green stink bug (*Acrosternum hilare*) and brown stink bug (*Euschistus servus*) feed on developing fruit in the spring. Their feeding causes puncture marks surrounded by a yellow halo on the fruit, reducing the fruit's market value. Stink bugs can move and hide quickly, making them hard to monitor and treat (Nessler 2007). Pyrethroids such as cyfluthrin and lambda-cyhalothrin are most commonly used to treat stink bugs. Endosulfan, an organochlorine, and methamidophos, an organophosphate, have also proven successful in controlling stink bug populations in tomato fields in Virginia (Nessler 2007). These chemical classes target the insect's nervous system, causing overstimulation and eventual death.

The two species of thrips common in Virginia, tobacco thrips (*Frankliniella fusca*) and western flower thrips (*Franklinella occidentalis*), feed on the leaves, blossoms, and developing fruit of seedling tomato plants. The damage to the plants reduces their photosynthetic potential and stunts their growth. Thrips can leave scars on and reduce marketability of tomatoes by laying their eggs in the small developing fruit. These thrips species can also transmit the devastating disease tomato spotted wilt virus; the virus moves from their bodies into the plant as they feed. Under favorable conditions, thrips can complete several generations per season in Virginia, but cold winters will kill them (Nessler 2007).

In fields or areas with a history of thrips infestations, insecticides should be applied at planting. Along with planting resistant tomato varieties, applying a neonicotinoid or other insecticide through the canopy can control thrips when first observed in the field. The neonicotinoid imidacloprid can be used to control thrips as well as aphids. Other chemicals used in Virginia to control thrips are pyrethroids cyfluthrin, lambda-cyhalothrin, and fenpropathrin, methamidophos, an organophosphate, and spinosad, a spinosyn (Nessler 2007).

Tomato fruitworm (*Helicoverpa zea*), also known as corn earworm, soybean podworm, or cotton bollworm, is a major pest on fall tomato crops on the Eastern Shore of Virginia. Fruitworms feed directly on the fruit, rendering the produce unmarketable, and on leaf tissue, causing plants to look ragged (Nessler 2007).

Several insecticides are available to Virginia tomato growers to control tomato fruitworm infestation. It is recommended that the chosen insecticide be applied every 5-7 days following the initial treatment (which is applied when pests are detected or the specified economic threshold has been reached). Pyrethroids such as cyfluthrin, lambda-cyhalothrin, esfenvalerate, and fenpropathrin are frequently used to control tomato fruitworm. Because of the wide use and heavy reliance on pyrethroids, however, insecticide resistance has become an issue. Other chemicals such as methamidophos and spinosad, and methomyl, a carbamate, are commonly used in Virginia for tomato fruitworm control (Nessler 2007).

The green peach aphid (*Myzus persicae*) and potato aphid (*Macrosiphum euphorbiae*) are both common pests of tomatoes in Virginia, with the potato aphid being more prevalent. Aphids typically feed on the underside of a tomato plant's leaves, causing curling of the leaves and reduce photosynthetic potential. Aphids may also be vectors of certain viral diseases of tomato. Large aphid populations lead to the excretion of large amounts of honeydew (a sugar-rich, sticky liquid), which can support the growth of fungal diseases. Pesticides used to treat thrips populations (see above) will also control aphids. In addition, endosulfan, an organochloride, and thiamethoxam, a neonicotinoid, are chemicals often used on tomato plants in Virginia to control aphids (Nessler 2007).

Toxicities of Chemicals Used in for Disease Prevention

Pyrethroids are synthetic chemicals specifically designed to be stable in the environment, providing long-lasting insect control (Brown 2006). Organochlorines, a group of chemicals that includes the banned pesticide DDT (dichlorodiphenyl-trichloroethane) and endosulfan, tend to be very persistent in the environment and can move long distances in surface and groundwater. These chemicals have been known to cause severe illness in humans and have been linked to hormone disruption and reproductive problems in aquatic invertebrates, fish, birds, and mammals (Colborn et al. 1993). Because of this, in 2010, the EPA has introduced a phase-out of endosulfan use in the US. The EPA requires all endosulfan use on tomatoes to cease on or before July 31, 2015 (US EPA 2010).

Organophosphates inhibit enzymes in insects that affect nerve impulse transmission. They can be very poisonous to humans and were used in World War II as nerve agents (US EPA 2012). Many organophosphates are highly toxic to aquatic organisms. In terms of mode of action, the carbamate class of chemicals is very similar to organophosphates. Methomyl, the carbamate pesticide successful in controlling tomato fruitworm, is moderately toxic to aquatic organisms (Fishel 2005c). Spinosad is a broad-spectrum microbial insecticide that is derived from the *Saccharopolyspora spinosa* bacteria. It is considered to be eco-friendly and its toxicity to aquatic organisms is low (Kollmon 2002). Neonicitinoids affect the nervous system of insects, causing paralysis and death. The mode of action of neonicitinoids is specific to insects, causing less of a chance for non-target injury or poisoning (Brown 2006). The EPA classifies these chemicals as practically non-toxic to aquatic species; however, they can persist in the soil for years and potentially leach into groundwater (National Pesticide Information Center 2010).

Environmental and water quality issues related to plasticulture systems

Runoff, chemicals, and sediment

Because of the impervious surface created by covering soil with plastic, runoff during rain events begins sooner than on a pervious surface (McCall et al. 1988). The amount of runoff will also be greater from a plasticulture system versus bare or planted soil; Rice et al. (2001) observed a significantly greater volume of runoff water from plots containing plastic mulch versus vegetated plots. Along with rainwater, chemicals that have been sprayed on the plastic-covered rows (and that haven't bonded to the plastic through chemical processes) will run off, as well as any sediment, to which chemicals can bind. Some of the runoff may infiltrate the soil between rows of plastic, and the remaining runoff will eventually drain to the nearest creek or directly to the bay. Depending on the toxicity of the chemical(s) used, the increased runoff from a plasticulture system can severely affect downstream aquatic life.

Removal and disposal of plastic

Because most of the white plastic mulch used as row covers isn't biodegradable, and it should never be disked or incorporated into the soil, it must be removed from the field and disposed of after each planting season, along with the irrigation drip tape (Moreno et al. 2009). The labor and cost of removing the plastic can be time-consuming and expensive. In the past, plastics were disposed of by burning, burying, or dumping in landfills; the obvious environmental concerns associated with these disposal methods has led to restrictions in some regions (Lament 1993). However, tomato growers on the shore dispose of most of their plastic in the landfill. A company they used to recycle plastic mulch went out of business in 2012, and while there have been inquiries from recycling companies, it is difficult to recycle dirty plastic because of all of the resources it takes to get it clean (Virginia Department of Agricultural and Consumer Services, personal communication, 2013).

Photodegradable and biodegradable mulches have become popular in the vegetable growing community, but they are not used on the Eastern Shore. Photodegradable plastic mulches eventually break down into small flakes over time when exposed to sunlight.

Biodegradable plastic mulches are degraded in the soil by microorganisms and are eventually decomposed. However, these mulches usually cost more than conventional plastics, which has precluded their use on the Eastern Shore (Kemble 2013; North Carolina Cooperative Extension Service 1996; Lament 1993).

Aquaculture

Common shellfish grown on Virginia's Eastern Shore

Eastern Oyster (*Crassostrea virginica*)

Other common names of the eastern oyster include American Oyster, Atlantic Oyster, Common Oyster, and Virginia Oyster (Figure 7). The eastern oyster is commonly found in estuaries on the eastern coast of North and South America. These oysters occur naturally in dense aggregations, commonly called reefs or beds. They thrive in estuarine waters with salinities from 10 to 25 parts per thousand (ppt). In the spring, when water temperatures rise, oysters are stimulated to spawn; this release of sperm and eggs into the water further stimulates other oysters to spawn, resulting in a massive release of reproductive product (Wallace et al. 2008).

Figure 7- Crassostrea virginica; photo courtesy of Ballard Fish & Oyster Company

Fertilized eggs develop into free-swimming larva over a period of 12-20 hours. Toward the end of the larval cycle, the oyster larva develops a foot, which eventually helps it find a hard surface on which to attach. At this point, it may be referred to as an “eyed larva” due to the development of a pigmented eye spot. After 14-20 days from fertilization, larvae settle out of the water column and attach (set) to suitable substrate, also called clutch, where they transform into small oysters called spat. The spat are soon able to feed on algae and other particulate matter by filtering water through their gills (Wallace et al. 2008).

The eastern oyster plays a key role in the function of estuary systems. Their natural large oyster beds provide habitat for numerous fish and invertebrate species. Oysters are filter-feeders, removing nutrients and both organic and inorganic particulate matter from the water column (Puglisi 2008). Research shows that establishment and maintenance of oyster reefs improve water quality due to the oysters' ability to reduce suspended sediment and nutrient concentrations (Nelson et al. 2004).

Northern Quahog (*Mercenaria mercenaria*)

The common names of the *M. mercenaria*, aside from hard clam, are based on standardized commercial conventions, the most popular being littleneck (25 mm thick, shell length 45-50 mm), cherrystone (32-38 mm thick, shell length 65-79 mm), and chowder (>38 mm thick, shell length >79 mm) (Hadley & Whetstone 2007) (Figure 8). Generally called hard clams, they are found along the eastern coast of the United States, Florida, and the Gulf coast of Texas. They prefer intertidal and subtidal waters where they burrow into the substrate, whether sand, mud, shell, or a mixture of these (Hadley & Whetstone 2007). Similar to the eastern oyster, hard clams are filter-feeders, feeding on suspended particulate organic matter, primarily single-celled algae (Hill 2004). On average, adult hard clams filter 2 gallons of water per hour (Hadley & Whetstone 2007).

2007).

Figure 8- *Mercenaria mercenaria*; photo courtesy of Ballard Fish & Oyster Company

Sexually-mature clams are stimulated by environmental conditions, normally high water temperatures, to release sperm or gametes into the water. This release of sexual products stimulates further spawning of other clams in the vicinity. Spawning typically occurs from May to October (Hadley & Whetstone 2007). Within 12 hours, fertilized eggs develop into free-swimming larvae. Within 24 hours of fertilization, bivalve shells form and the larvae are referred to as “D” larvae because the shape of their shells resembles the letter “D.” The larvae feed on small phytoplankton, bacteria, and dissolved organic matter. The larval period can last anywhere from 7 to 21 days, depending on available food and water temperature. Soon after developing a foot (similar to the eastern oyster’s), the clam loses its swimming organ and develops siphons, which allows the clam to settle out of the water column and attach (set) to suitable substrate. At this time, the set clams assume the sedentary lifestyle of the adult clam (Hadley & Whetstone 2007).

According to the Southern Regional Aquaculture Center, hard clam aquaculture "is the largest and most valuable of the shellfish aquaculture industries on the East Coast" (Whetstone et al. 2005).

Growing shellfish

Oysters

Hatchery & nursery

Oyster hatcheries produce juvenile oysters for commercial production, restoration, or research. The two hatcheries on the Eastern Shore of Virginia are private hatcheries, meaning they spawn oysters for their own use (Flimlin 2012). The location of an oyster hatchery is dependent upon water supply. Hatcheries require large volumes of clean water with adequate salinity. Low salinity may reduce spawning, larval development, and early growth of young oysters. Before the water supply reaches the young oysters, it is usually pumped into settling tanks, which helps reduce suspended sediment concentrations. The water is also filtered and treated using a combination of sand or cartridge filters, activated carbon, ultraviolet sterilization or pasteurization (Wallace et al. 2008).

An oyster hatchery essentially provides a controlled environment for the early stages of the oyster life cycle. Oysters selected for breeding that are reproductively mature are placed in tanks where spawning is stimulated by warm water. Once the eggs are fertilized they are placed in larval-rearing tanks which have been cleaned, disinfected, and filled with treated water. The larvae are fed algae and the tanks are drained, cleaned, and refilled at least every other day. The larvae are monitored for size and the development of an eye spot, which indicates their readiness to set. Setting is the stage in a larval oyster's life cycle when the larva develops a "foot" and can move short distances to settle and cement itself to hard substrate, usually oyster shells (Wallace 2001). Larvae (Figure 9) are sieved through a fine screen; the larvae that pass through are restocked into the tanks and the larvae that are retained, commonly called eyed larvae or free-swimming larvae, are transferred to setting tanks (Wallace et al. 2008, Flimlin 2000).

Figure 9- Oyster larvae; photo courtesy of H.M. Terry Co., Inc.

Setting tanks, commonly called wellers, are containers with a thin layer of microclutch (finely-ground oyster shell) over a fine mesh bottom. The wellers are immersed in shallow tanks containing source water from the nearby Bay or creek. This configuration allows for two techniques that are used in the setting process: upwelling, where water is drawn upwards through the container, and downwelling, where water flows down through the mesh bottom. Upon stocking the tanks with eyed larvae, the tanks are configured for downwelling for setting and metamorphosis to seed oysters, which usually takes place within 48 hours (Flimlin 2000). Downwelling is used at this stage so as to not draw early post-set oysters through the water drainage system; they instead are drawn downward and stopped at the mesh screen (Hadley & Whetstone 2007). The tanks are then configured for upwelling to maximize the growth of the spat (Wallace et al. 2008).

Growth of the spat into mature oysters, which is dependent on stocking density, water flow, and food, is monitored daily. The upwelling culture is continued until the seed oysters have grown to a size where they can be placed in the smallest mesh size nursery bag (typically 1 mm bag mesh). The filled bags are either kept in the nursery under high water flow or placed into the off-bottom oyster cage system in natural waters for the grow-out stage (Wallace et al. 2008). If growers don't produce their own oyster seed, they purchase the seed from commercial hatcheries. Care must be taken to ensure that good quality, disease-free seed is purchased.

Grow-out

There are several techniques for growing oysters. The historically common "extensive" approach involves a process called "spat-on-shell," where oyster seeds are allowed to settle onto old oyster shells and grow freely on creek or bay bottoms. On the Eastern Shore of Virginia, oysters are mostly grown for the half-shell market, requiring a more intensive "single shell" culture of oysters. Disease and predation of cultured oysters in an extensive growing system have also contributed to the shift to intensive culture. For this technique, oysters are suspended above the bottom in bags or floats. This allows for easier access to the oysters, less fouling of the equipment when in tidal waters, predator protection, minimal flow obstruction, and less suspended sediment. The reduced suspended sediment allows oysters to experience higher growth rates because less energy is used towards filtering the sediment (Luckenbach et al. 1999; Murray & Hudson 2012).

There are many types of off-bottom growing systems, but growers on the shore mostly rely on oyster floats, cages, and bags, which are relatively inexpensive and sturdy and provide the important features listed above. Oyster cages are typically made of vinyl coated wire in 1" x 1" squares. The cage is attached to a float, typically constructed of PVC pipe, and moored to the bottom on the other end. The seed oysters are then placed in mesh bags and placed in the float (Luckenbach et al. 1999; Figure 10).

Figure 10- Oyster bags; photo courtesy of Ballard Fish & Oyster Company

The mesh size of the bags depends on the size of seed oysters cultivated or purchased. Small seed oyster will require bags with small mesh openings. As the size of the oysters increase, the mesh opening size of the bags should be increased and the density of the oysters within the bags decreased (Wallace et al. 2008). The intent is to allow the greatest volume of water possible to reach the growing oysters, which allows the largest amount of food to reach them. Cultured oysters will typically reach harvestable size in 18-24 months (Luckenbach et al. 1999; Murray & Hudson 2012).

Clams

Hatchery and nursery

Before spawning, sexually-mature adult clams are brought into the hatchery for conditioning (ripening of the gonads). This entails providing ample food and simulating cool, early spring water temperatures. To induce spawning, conditioned clams are subjected to a water bath with alternately warm and cool water temperatures. Fertilization takes place from the eggs and sperm released into the water (Hadley & Whetstone 2007).

The fertilized eggs are maintained in fiberglass or plastic larval culture tanks filled with filtered source water until the larval stage is reached, usually within 24 hours (Figure 11). At this time, the larvae are fed algae and thinned. The water, which is filtered and treated, is changed frequently, and food is added daily. The larvae are kept in the tanks until they set, or settle and cement themselves to hard substrate (Hadley & Whetstone 2007).

Figure 11- Culture tanks; photo courtesy of Cherrystone Aqua Farms

Upweller and downweller systems, almost identical to those in the oyster hatcheries and nurseries discussed above, are most often used to culture hard clams (Hadley & Whetstone 2007). When the post-set clams grow to a shell length of 1 mm, they are transferred to a nursery system, usually an upweller system, which provides a protected environment for small clam seed until they are large enough to be transferred to a field grow-out system (Hadley & Whetstone 2007). Some nurseries also use a raceway system, where clams are placed in shallow, rectangular trays. Water is pumped to one end, flows over the clams placed in the raceway, and drains off the other end (Flimlin 2000, Hadley & Whetstone 2007; Figures 12, 13). Both nursery systems allow for rapid growth and good survival. Clam seed, similar to oyster seed, can be purchased from hatcheries if the field operation does not grow its own.

Figure 12- Outdoor raceway system; photo courtesy of Eastern Shore Soil & Water Conservation District

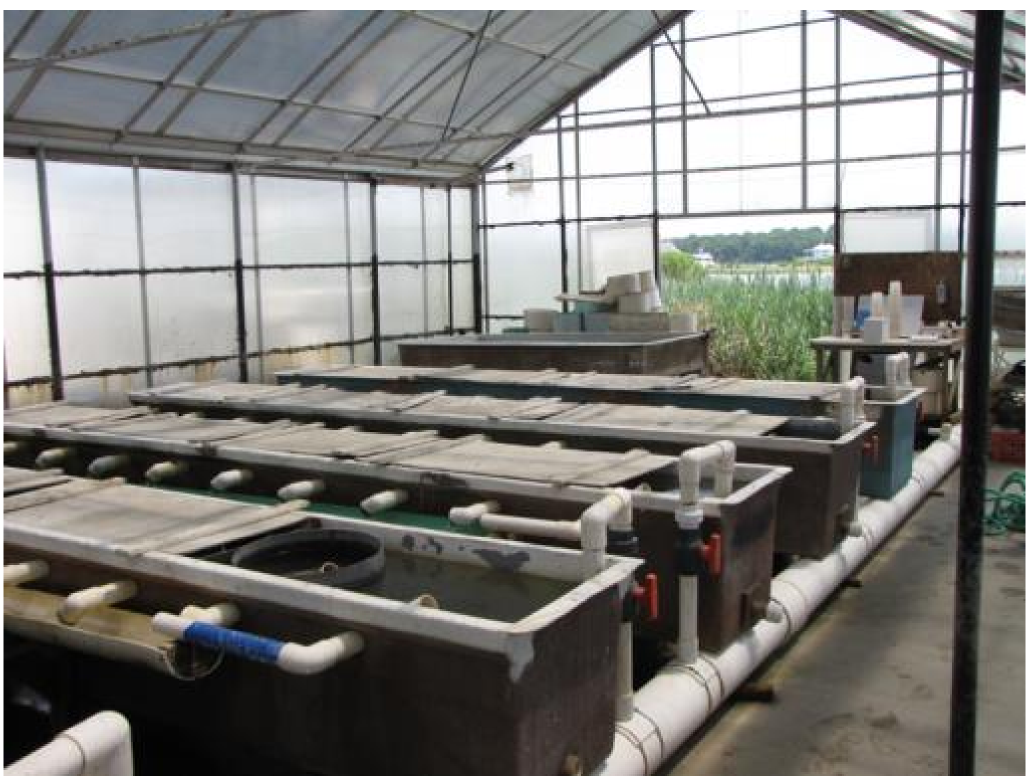

Figure 13- Indoor raceway system; photo courtesy of Eastern Shore Soil & Water Conservation District

Grow-out

The clam seed, for which shell lengths range from 0.3 to 0.5 millimeters, are placed in mesh bags. Unlike oysters, hard clams do well when placed on the creek or bay bottom, allowing the clam seed to burrow in the bottom sediment and sand. Some growers place the clam bags directly on the creek or bay bottom. Others use trays where the clam seed are added to 76-100 mm of sand, then covered with plastic mesh (to prevent predation) and placed in the water (Flimlin 2000). When clams reach 20mm shell size, they are usually taken from the bags and placed in small beds on the bottom. The clams are planted in the bottom substrate then covered with plastic mesh, again to prevent predation. Clams are harvested when they reach desired size, the time frame ranging from 2 years for littlenecks to 8 years for chowders, from seed to harvest (Whetstone et al. 2005).

Common problems, including pollutants and contaminants, for aquaculture production on Virginia's Eastern Shore

Water Pollution

Shellfish production in hatcheries and nurseries and natural growth of shellfish in the estuarine environment depend on the local watershed for water and food. Naturally-occurring shellfish grown in the estuarine environment are susceptible to pollutants that enter the system. In commercial operations, oysters and clams are grown in same estuarine water and are fed algae that are cultured in that water as well. A discussion of pollutants to aquaculture facilities will continue later in this paper.

Disease

The two most common and mortal endemic diseases to oysters are multinucleated sphere X (MSX) and Dermo. MSX is caused by the protozoan parasite *Haplosporidium nelson* and, when the disease was found in the lower Chesapeake Bay in 1959, was given the acronym MSX for multinucleated sphere X (Virginia Institute of Marine Science 2013b). Dermo results from infections by the protozoan parasite *Perkinsus marinus*. The disease was originally thought to be caused by the fungus *Dermocystidium marinum*; the organism was reclassified based on structural characteristics as *Labyrinthomyxa marina* in 1966, and again as *P. marinus* in 1988 (Virginia Institute of Marine Science 2013a). The name Dermo stems from its original classification. Over the past few decades, Virginia's oyster populations have been severely affected by sustained disease presence. The levels of the parasites that cause these diseases have been at record highs due to warm temperatures, drought, and high salinity of tidal waters. Both parasites become more prevalent and their infections intensify at warm temperatures. Warmer winters allow for the over-wintering of the parasites. Droughty conditions cause an increase in salinity of tidal waters, which intensifies the diseases caused by these parasites (Elston 1990; Virginia Institute of Marine Science 2013a; Virginia Institute of Marine Science 2013b; Luckenbach et al. 1999).

Much care is taken to prevent the onset of these diseases. Infected oysters should not be moved into areas with uninfected oysters and subjecting oysters to waters with low salinity will retard disease development and restrict mortality (Virginia Institute of Marine Science 2013a; Virginia Institute of Marine Science 2013b). The intensive culture of oysters allows growers to be selective when purchasing oyster seed, therefore reducing the risk of disease by using disease-free stock.

Hard clams have few diseases compared to other aquaculture systems; the only significant pathogen is the protist QPX, short for Quahog Parasite Unknown. Disease caused by this parasite can result in slower growth, lower-quality meat, and mortality. Detection of QPX in clam seed has not been observed, suggesting that the parasite is found at the areas of planting (Baker & Mann 2006). While this disease has been known to cause mortality along the East Coast, it does not pose a significant problem for hard clam aquaculture on Virginia's Eastern Shore.

Predation

The oyster leech or oyster flatworm (*Stylocus ellipticus*) and blue crab are among the most significant predators to cultured oysters on the Eastern Shore of Virginia. Dipping infected oyster bags in a brine dip is the preferred treatment for flatworm infestation, while close monitoring of the bags for crabs is crucial to protect the oysters from crab predation (Luckenbach et al. 1999). The intensive culture of oysters lends itself to be convenient and manageable way for growers to manage possible predation on their oysters.

Predators of hard clams include blue, stone, mud and horseshoe crabs, conch and whelk, sting rays, and snails (Flimlin 2000, Whetstone et al. 2005). Clams burrow into bottom substrate when disturbed to avoid predators (Whetstone et al. 2005). Screens as described above are used in the grow-out phase of oyster aquaculture to prevent losses from predators.

Effects of plasticulture on aquaculture

Pollution of estuaries and water bodies where oysters and clams are grown is of great concern to shellfish growers. The Chesapeake Bay is a particularly sensitive estuary. Over 100,000 rivers, creeks, and streams, covering over 165,779 square kilometers of land in Virginia, Delaware, New York, West Virginia, Maryland, Pennsylvania, and the District of Columbia, make up the watershed that drains into the bay. The Chesapeake Bay itself and its tidal tributaries cover only 11,603 square kilometers, and the bay has an average depth of 6 meters (US EPA 2011a). Because of the large watershed, there is great potential for polluted water to flow into the bay, causing distress to its aquatic life. Estuaries like the bay are considered among the most sensitive areas for the accumulation of toxic chemicals (Sericano et al. 1990).

When shellfish are in their larval stage, they are free-swimming and without a hard protective shell, causing them to be particularly sensitive to poor water quality (Dietrich et al. 2001). Filter feeders such as oysters and clams can easily take up these pollutants from biota, contaminated bottom sediments, or suspended solids (Dietrich et al. 2001).

Chemicals

Copper-based crop protectants for disease control

Copper has been shown to have a detrimental effect on respiration of gill mitochondria of *Crassostrea virginica*. Mitochondria are the major sites of oxygen utilization and are extremely sensitive to oxidative stress. The presence of copper can overwhelm cellular defense mechanisms, compromise respiratory function, and impair cellular health and survival. In one study, basal oxygen consumption of *C. virginica* gill mitochondria was reduced up to 90% (Collins et al. 2010). Any decrease in oxygen consumption can be detrimental to an oyster's growth rate and health; a decrease of 90% will most likely be fatal.

All registered chemicals for use in agriculture are tested to determine their effect on humans and other organisms. Toxic effects on organisms are often reported as the lethal concentration of a chemical at which 50 percent of the organisms die (LC50). According to a study by Calabrese et al. (1973), the 12-day LC50 value for copper on *C. virginica* larvae is 32.8 µg/L. A study by Calabrese et al. (1977) shows the 8-10 day LC50 for copper on larval *M. mercenaria* to be 16.4 µg/L.

Several studies (Calabrese et al. 1977, MacInnes & Calabrese 1979) suggest that the embryos of clam and oyster are less susceptible to copper toxicity than their larvae, but can still be affected. A study by Arnold et al. (2001) predicted the LC50 for *M. mercenaria* embryos as 20 µg Cu/L, while a study by Calabrese et al. (1973) determined the LC50 value of copper for embryos of *C. virginica* is approximately 103 µg/L. Virginia's water quality criteria for copper in saltwater is 2.9 µg/L dissolved copper for both the one-hour concentration, not to be exceeded more than once every three years, and the four-day average, not to be exceeded more than once every three years (Virginia Department of Environmental Quality 2002).

There have been several studies conducted on the Eastern Shore of Virginia to determine whether the presence of tomato plasticulture has any effects on aquatic organisms. Dietrich et al. (1997) measured copper concentrations in runoff from several watersheds on the shore with varying acreages of agriculture. In one particular watershed, which contained plasticulture tomato fields, copper concentrations ranged from 1-700 µg/L. In runoff draining directly from plasticulture fields, copper concentrations varied between 400-1450 μg/L. The higher copper concentrations occurred immediately after rainfall; because of this, the researchers hypothesized a possible association between high copper concentrations and storm water runoff from agriculture and plasticulture. Another study by Brady et al. (1999) measured copper concentrations runoff from plasticulture fields on the shore. After rain events, they measured dissolved copper concentrations from 20-238 μg/L.

Sublethal concentrations of pollutants/metals may not cause death but can severely limit growth rate of organisms, leaving them more susceptible to disease and predation and causing a decrease in production. LaBreche et al. (2002) found that larval *M. mercenaria* suffer from deformation, reduced activity, delayed metamorphosis, and death when exposed to copper concentrations between 4 and 8 μg/L for one to three days. Calabrese et al. (1977) observed percent growth of *C. virginica* and *M. mercenaria* at the above LC50 for copper as 67.1% and 51.7% of their normal growth rate, respectively.

As filter feeders, oysters and clams can take up copper from the algae that they feed on or from contaminated bottom sediments or suspended solids (Greer & Terlizzi 1995, Al-Sabri et al. 1993). A study by LaBreche et al. (2002) found that the algae *Isochrysis galbana* was a source of copper toxicity to larval clams that fed on it, due to the algae's sorption and accumulation of copper from the surrounding water. This same study also predicted that, for adult shellfish, 94% of copper intake is accumulated via food ingestion.

Numerous studies have sought to show the source of copper runoff. A study by Gallagher et al. (2001) demonstrated that only 1% of copper applied to a simulated plasticulture system was lost from the fields, and, of that, only 0.82% in runoff. However, copper concentrations of that 0.82% in runoff ranged from 2100 μg/L total copper and 189 μg/L dissolved copper. Of that copper, 74% of the 1% lost was sorbed to soil suspended in the runoff, which eroded from in between the plastic mulched rows.

A study by Dietrich et al. (2001) compared dissolved copper concentrations in water runoff from several different land-use types: active plasticulture, previous plasticulture, conventional agriculture, and grasslands and woodlands. The highest dissolved copper concentrations were found in runoff from active plasticulture fields, where concentrations from 7 to 238 µg/L were measured. In contrast, copper concentrations ranging from 1 to 5 µg/L were measured on non-plasticulture runoff. Another study by Dietrich and Gallagher (2002) measured dissolved copper concentrations of 22 µg/L in a tidal creek on the Eastern Shore of Virginia whose watershed included plasticulture in 1998.

A study by Snyder et al. (1999) was done to not only determine the source of the copper runoff but determine how much of that copper was available to aquatic organisms. Total copper is the sum of copper dissolved in solution, particulate copper, and copper bound to sediment and organic matter; bioavailable copper was defined as the portion of the total copper concentration, usually in the form of cupric copper, which interacts with a given organism and causes toxicity (Dietrich et al. 1997, Rice et al. 2004). They found that every simulated rain event yielded high amounts of copper in runoff from the plasticulture fields. Of that runoff, they determined that approximately 15% of copper-based crop protectants applied to plasticulture fields may be available to aquatic organisms. They measured bioavailable copper levels in runoff from approximately 0 µg/L to 30 µg/L.

Luckenbach et al. (1996) evaluated water quality in tidal creeks of Virginia's Eastern Shore in relation to vegetable cultivation. One particular water testing site was adjacent to a tomato field that drained directly into the creek by a series of ditches and channels. Another water testing site where plasticulture was utilized had wide vegetated buffer strips around the fields, and runoff fed into a retention pond. From their comparison and evaluation of the two different testing sites, Luckenbach et al. (1996) were able to suggest that toxic inputs of pesticides and metals into tidal creeks on the Eastern Shore could be correlated to vegetable (particularly tomato) farming. They also found that management practices, such as vegetated buffers, can dramatically decrease the likelihood of impacts on aquatic organisms in tidal creeks resulting from toxic runoff.

Pesticides

The mode of action for many of the herbicides in use is to target photosynthetic pathways, while many insecticides disrupt nervous system function (DeLorenzo et al. 2001). DeLorenzo et al. (2001) studied the effects of several pesticides on aquatic algae, which are the primary source of food for oysters and clams. They found that endosulfan, carbamate and organophosphate insecticides, and the fungicide maneb, all had detrimental effects on several algae species. While some chemicals may not be directly toxic to oysters and clams, they can indirectly affect them by reducing the growth and survival of microorganisms, their primary food source. The pesticide endosulfan caused toxicity to C. virginica embryos at high levels in a study by Wessel et al. (2007).

In a study using *Palaemonetes pugio* (grass shrimp) as an indicator of toxicity, Luckenbach et al. (1996) found that lethal inputs of organic pesticides and metals into creeks on the Eastern Shore of Virginia occurred after rain events in runoff from vegetable farming (particularly tomato cultivation). Rice et al. (2001) compared plots of tomatoes grown on plastic mulch versus plots grown on a vegetated mulch. Runoff from plots with plastic mulch contained 19 and 9 times greater amounts of cholorothalonil and endosulfan (respectively) than runoff from vegetated plots, due to greater concentrations of these chemicals and larger runoff volumes. Rice et al. (2002) observed a loss of up to 36% of copper hydroxide applied to a plastic mulch field in runoff versus a loss of just 6% of applied copper hydroxide in a field with vegetative mulch. The vegetated mulch surface is much more pervious than the plastic surface, allowing both rainwater and chemicals to infiltrate the soil profile. The impervious surface created by the plastic mulch does not allow for this infiltration, therefore increasing both the runoff and chemical amounts that leave the field.

It is interesting to note that a study conducted in South Carolina by Scott et al. (1990) showed that runoff from plasticulture fields contained a lower concentration of pesticides than runoff from fields that did not use plastic covers. However, this study also concluded that, in a plasticulture system, toxic runoff events were more frequent and occurred after smaller rain events.

Sediment

Increased amounts of sediments in estuarine waters where clams and oysters live can have several detrimental effects. Because they are filter feeders, oysters and clams rely on the filtration of water for their food. If there is a high amount of sediment or suspended solids in the water column, they may find it difficult to filter water. Loosanoff and Tommers (1948) subjected *C. virginica* (then *Ostrea virginica*) to varying levels of sediment; they found that in water with a high volume of sediment, the rate of pumping water through the gills decreased more than 80%.

In a study by Davis (1960) the percentage of normally-developing *M. mercenaria* eggs decreased significantly as suspended sediment concentrations rose. While growth of clam larvae also decreased as suspended sediment concentrations rose, there was no appreciable mortality within 12 days. Pratt and Campbell (1956) observed lower growth rates of *M. mercenaria* in sediments, and suggest that the additional energy required for frequent cleaning of the feeding apparatus is the cause.

A study of sediment transportation from different agricultural land uses showed that a significant increase in sediment and nutrient transport occurred when land was transitioned to plasticulture (Lowrance et al. 2007).

The Rice et al. (2001) study mentioned previously, which compared plots of tomatoes grown on plastic mulch versus plots grown on a vegetated mulch, observed losses of two to four times more runoff and at least three times as much sediment on the plots with plastic mulch versus the plots with tomatoes grown in vegetation. The vegetated mulch reduced both the sediment-bound and dissolved chemical loads, decreasing the amount removed with runoff after rain events.

The sediment that leaves the field usually contains chemicals that were applied to the plants and the soil. In a study on runoff-reducing practices, Rice et al. (2004) found that more than 88% of the total copper loads in runoff was adsorbed onto suspended particulates. Copper easily adsorbs to sediments; the combination of heavy use of copper fungicides and the increased amount of sediment erosion on plasticulture fields increases off-site movement of total copper into the aquatic ecosystem, some of which may be bioavailable to aquatic organisms.

However, results of some studies show no association between plasticulture and shellfish health and mortality Arnold et al. (2001) deployed juvenile *C. virginica* in several tidal creeks on the Eastern Shore of Virginia for one year to determine whether oyster growth and mortality were affected by proximity to plasticulture fields. In this study, mortality was lowest and growth was fastest in two sites that had a history of plasticulture in the watershed. Oysters with the highest levels of growth were found in a creek with over 30 acres of its watershed in plasticulture, while oysters located in creeks whose watersheds contained no crops grown on plastic mulch were among the smallest (mean shell length in mm) measured. Their results indicate that the use of plasticulture in these specific watersheds had no negative effect on oyster growth and mortality. This study also showed no correlation between plasticulture and shellfish mortality; the control creek, which had a relatively small amount of plasticulture in its watershed, had the highest levels of cumulative mortality.

A study by McCall et al. (1988), in which conventional and plasticulture tomato fields were compared for loss of the insecticides endosulfan and fenvalerate after rain events, found that, while the plots with plastic mulch caused a greater volume of runoff after rain events, there was no significant increase in the mass or concentration of those two chemicals lost from the fields. In the aforementioned study by Luckenbach et al. (1996), a metal toxicity assay was used to test waters for toxic levels of metals. The test showed that some of the runoff from plasticulture fields carried amounts of copper over 500 µg/L, which is much higher than toxic concentrations of copper on certain shellfish. The limitations of the study do not allow for results implicating plasticulture for poor water quality due to toxic chemicals.

Best management practices

Best management practices (BMPs) for a plasticulture operation are crucial for reducing the volume and velocity of runoff, filtering sediment from runoff, and promoting infiltration of rain water. High volumes of runoff can cause flooding issues; coupled with high velocities, it can cause massive erosion between rows. Runoff control practices not only prevent soil loss but also reduce pollution in surface waters. The eroded soil from the operation may also contain toxic agricultural chemicals used on the plants. Any residual chemicals remaining on the plastic mulch will also run off during rain events.

Between-row furrows

Water erosion can be prevented if bare soil is covered with vegetation or other protective cover. Establishing grass on bare soil is the first line of defense against erosion. Grass planted in between rows of plastic can help prevent erosion as well as reduce the volume of runoff from the field during and after rain events (Figure 14). For example, the calculated volume of runoff for bare soil between rows of plastic is 610,000 cubic feet/24 hours, while the calculated volume of runoff for rye cover between rows of plastic is 381,000 cubic feet/24 hours (Virginia Department of Conservation and Recreation 1993).

Figure 14- Between-row furrows; photo courtesy of Eastern Shore Soil & Water Conservation District

Sterrett et al. (2009) observed that establishing annual rye at bed establishment greatly reduced the total sediment movement from the field. Rice et al. (2004) observed that rye planted in between rows of plastic mulch reduced the amount of soil loss during rain events by 80% compared to bare soil and reduced runoff volume by more than 40%. Mixing rye with a legume such as *Vicia* offers even better erosion control because of the legume's deep root system. Certain grasses, such as Kentucky bluegrass, can tolerate higher flow velocity better than others, such as small grains (other than rye) and redtop (Virginia Department of Conservation and Recreation et al. 2007). Grasses provide the most economical and most effective prevention of erosion and runoff and can prevent the need for other, more expensive erosion control measures (Virginia Department of Conservation and Recreation et al. 2007).

A cover crop that will survive during the colder months, such as rye, should be planted after the plastic is removed from the fields to prevent erosion of bare land between growing seasons (Figure 15).

Figure 15- Cover crop; photo courtesy of Eastern Shore Soil & Water Conservation District

Vegetated perimeter buffers

In addition to planting grasses between rows of plastic, planting the outermost perimeter of the field in grasses can further prevent erosion, filter sediment from runoff, reduce runoff velocity, and promote infiltration (Figure 16). These grass buffers are relatively inexpensive to establish and can also serve as a visual screen and windbreak.

Figure 16- Vegetated buffer; photo courtesy of Eastern Shore Soil & Water Conservation District

Both cool season grasses, such as fescue, and warm season grasses, such as switchgrass and big bluestem, can be planted. Compared to cool season grasses, warm season grasses have greater root biomass, which help stabilize the soil and promote infiltration of runoff, and support a less-diverse population of insects. However, they can take 2-3 years to establish, may appear weedy, and need to be protected from vehicle traffic, especially during establishment (Virginia Department of Conservation and Recreation et al. 2007).

Planting a buffer of both warm- and cool-season grasses can also be beneficial. Buffers of tall fescue and switchgrass were proven by Mersie et al. (2003) to be effective of removing 60-80% of the pesticide endosulfan and at a slow runoff rate and by 27-39% at a faster runoff rate.

The width of the buffer is important; the wider the buffer, the more contact the vegetation has with the runoff, providing greater resistance to slow the flow of runoff and allow it to infiltrate into the soil. According to the United Stated Department of Agriculture Natural

Resources Conservation Service (2004), the minimum buffer width for a crop field with 1-3% slope is about 8 meters.

Establishing or utilizing a perimeter of trees around the fields will also reduce runoff amounts, velocities, and sediment load (Figure 17). Arnold et al. (2004) found that copper levels in runoff were reduced after filtering through a natural forest floor, which slows the flow of runoff and allows some of the runoff and its associated chemicals and sediments to infiltrate into the forest floor and possibly adsorb to the soil and organic matter.

Figure 17- Newly established perimeter of trees; photo courtesy of Eastern Shore Soil & Water Conservation District

Swales and ditches

Swales or ditches can also be installed to carry runoff from plasticulture fields (Figure 18). Swales are usually grassed depressions that collect runoff and allow it to infiltrate. Ditches are designed to carry larger volumes of runoff with higher velocities. Coir rolls, straw rolls, or large rocks can be used as check dams in ditches to reduce runoff velocity and prevent erosion of the ditches themselves. Ditches should be engineered to ensure their size will be able to handle the volume of runoff from plasticulture fields (Virginia Department of Conservation and Recreation et al. 2007).

Figure 18- Vegetated ditch; photo courtesy of Eastern Shore Soil & Water Conservation District

Coir and straw rolls

Coir rolls, made out of fibrous coconut husks, and/or straw rolls can be used in conjunction with a warm-season grass perimeter or in ditches. These rolls are biodegradable, come in a variety of sizes, and are used to filter runoff, protect perimeter buffers from high velocity water flow, as check dams in shallow ditches, or at the tops of ditches. In field trials, particles and debris filtered from runoff were observed in coir rolls placed in ditches (Virginia Department of Conservation and Recreation et al. 2007).

Ponds/Sediment basins

Ponds are often used in plasticulture systems for both irrigation and to manage runoff. These ponds, also called sediment basins, trap sediment and detain runoff (Figures 19, 20, 21). They must be designed in order to be able to hold the amount of runoff that is capable of leaving the field(s) draining to the pond (Wolfe et al. 2002). Because the runoff carries chemicals remaining on the plastic mulch and sorbed to the soil, sediment basins also reduce the potential for toxic chemicals reaching surface waters by allowing the sediment to settle out. A study by Snyder et al. (1999) showed a three-fold decrease in copper concentrations in runoff draining from a sediment pond in a tomato field with plastic mulch versus runoff directly from plasticulture tomato fields. In contrast, Arnold et al. (2004) observed copper levels at the outlet of a sediment pond equal or higher to levels measured at the inlet to the pond, 11 days later. There is also the concern of increased inputs of chemicals to groundwater if contaminated runoff is diverted to a sediment pond.

Figure 19- Empty runoff pond; photo courtesy of Eastern Shore Soil & Water Conservation District

Figure 20- Sediment pond; photo courtesy of Eastern Shore Soil & Water Conservation District

Figure 21- Vegetated sediment basin; photo courtesy of Eastern Shore Soil & Water Conservation District

Alternative mulch

Because of issues concerning pollution, disposal, and rising production costs that go along with using plastic mulches, studies have been done of the effectiveness of vegetative mulches. A study by Abdul-Baki et al. (2002) compared yield and soil health of tomatoes grown in traditional plastic mulch versus tomatoes grown in a hairy vetch mulch. Their results indicate that tomato yields using the vegetated mulch were greater than or equal to yields of tomatoes grown in plastic mulch. They also observed less soil compaction due to less machinery traffic, and less nitrogen inputs due to the natural nitrogen fixation of the hairy vetch legume. A study by Rice et al. (2002) compared copper levels in runoff from tomato fields planted in plastic mulch versus tomatoes planted in a hairy vetch mulch. They found that the hairy vetch mulch increased rain infiltration, decreasing erosion and runoff amounts, and significantly decreased copper loads from runoff compared to the plastic mulch.

Status of plasticulture issues on the Eastern Shore of Virginia

Overall, tomato growers on the Eastern Shore of Virginia are utilizing one or more of these best management practices to reduce soil and chemical runoff into its waters (Eastern Shore Soil & Water Conservation District, personal correspondence). In 2008, Virginia's Water Control Board, comprised of Virginia citizens and whose regulations are carried out by the Department of Environmental Quality (DEQ), initiated a Notice of Intended Regulatory Action (NOIRA) for adoption of regulation for the management of runoff from plasticulture operations. Because of the community's desire to keep management solutions voluntary and locally-led rather than regulated, the tomato growers on the shore formed a committee with the Eastern Shore Soil & Water Conservation District (ESSWCD), which falls under the Department of Conservation and Recreation's Storm Water Management Division, to discuss existing and planned best management practices. The resulting Memorandum of Agreement (MOA) between the tomato growers and the ESSWCD outlines guidelines and goals for addressing water quality issues; from this, a Plasticulture Technical Water Quality Committee was formed. This committee, which includes representatives from ESSWCD, the tomato growers industry, the Virginia Department of Agricultural and Consumer Services, Virginia Tech, the Department of Environmental Quality, the Department of Conservation and Recreation, Virginia Cooperative Extension, and various other agencies and individuals, was tasked in part to write and evaluate

Plasticulture Water Quality Plans. These plans are written for each field in tomato plasticulture production on the shore; acreage reports and field sites are done each year to ensure all productive fields have a plan and are following that plan. The committee has been successful in implementing and documenting best management practices on tomato fields on the shore. Because of the actions of this committee, the knowledge and understanding from the tomato industry of their environmental obligations, and the declining acreage planted in plasticulture tomatoes each year, there have been few incidents of mass mortality of shellfish at nurseries such as those experienced in 1996 and 1997. While it is obvious that plasticulture can have severe detrimental effects on the aquaculture industry, tomato producers today have been using resources and practices to reduce or mitigate those effects (personal correspondence with ESSWCD, 2013).

Summary

In the past, there has been controversy surrounding the tomato plasticulture industry and the aquaculture industry on Virginia's Eastern Shore. Both industries are important social and economic assets to the communities, and it is important to keep both viable and productive. Several shellfish operations suggested their mass mortalities were caused by the plasticulture industry on the shore, which initiated research on the effects of growing tomatoes in plastic, and the chemicals used, on shellfish in estuarine environments. While many studies have determined the potential for several chemicals and practices used in the plasticulture industry to be detrimental to shellfish and estuarine environments, some studies have also failed to correlate tomato plasticulture with shellfish mortality. Therefore, it has not been proven that the practices and chemicals used in tomato plasticulture on Virginia's Eastern Shore have caused detrimental effects to shellfish in adjacent waters. In response to the controversy and the potential for regulatory actions, tomato growers have begun to increase their use of best management practices to reduce and mitigate potential negative effects on water quality. From studies done on these practices, and the resulting water quality, it seems that they are succeeding in reducing impacts to the estuarine environment.

Although many of the chemicals used in plasticulture have proven to be toxic to mammals and aquatic organisms, it was difficult to find research and studies to their specific effects on *M. mercenaria* and *C. virginica.* Few recent studies have been done to assess current water quality or to compare results to studies done in the past. Further research on the current water quality of tidal creeks and estuaries on the Eastern Shore would allow us to know whether the conservation practices being implemented are successful in reducing erosion and pollution. Continued communication, partnership, and support and implementation of conservation practices among communities, businesses, and agencies are important and will allow both industries to survive and thrive on the Shore.

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