

SUSTAINABLE VEGETABLE PRODUCTION

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1. Introduction

Farming is the number one industrial enterprise both in the United States and the world. Like any other industry stakeholder, farmers strive for maximum profit from their investment. The most obvious way to increase profit is by obtaining maximum output from per unit land area while keeping the production cost to a minimum. Similar to other industries, sustaining farm profitability requires continuous investment in the upkeep of its underlying foundation, soil and water being the most important. Continuous cropping the same land is not sustainable without inputs. Early civilizations, which were unaware of this, were only able to develop along alluvial flood plains of rivers where the land was renewed annually with fresh deposits from rich flood water. Sustainability in this context then refers not to the lack of input, but the sources of inputs and how they are managed.

In the decade starting in 1930, crop yields in the United States, England, India, and Argentina were alike ¹⁶⁰. However, before the decade was over, farmers in the United States outpaced other countries in farm productivity. Crop specialization, mechanization, and use of chemicals for supplying nutrients, controlling weeds, insects and diseases were, to a large extent, responsible for this transformation. These adaptations enabled American farmers to obtain ample harvests at reasonable costs.

By early 1980s, viability issues pertaining to agriculture started drawing the attention of policy makers, industry, and researchers. As a result, research was set in motion to find out the long-term effects of high input agriculture on economy, ecology, rural society, and public health. A number of studies came to the conclusion that high input agricultural practices were responsible for rendering farming enterprise unstable with inputs and their costs continuing to spiral upward, yields fluctuating widely year to year due to exacting climatic requirements, and losses increasing from pathogens and pests as they became resistant to chemicals ^{65, 162}. Thus it became clear that time had come to revisit farming philosophy and to select and preserve practices that had long-term viability while substituting the rest with suitable alternatives. Replacements could be in the form of sound old practices, which were discarded unwisely, or new discoveries tested for their environmental compatibility. However, while making adjustments in the existing farming systems caution ought to be exercised not to regress in productivity or profitability otherwise these methods would not be adopted by the farmers.

Sustainable agriculture places great emphasis on incorporating innovative farming practices that help safeguard the soil and water quality on a long-term basis. Thus, some of the reinvented or new technologies in conservation tillage, pest and predator management, nutrient conservation, soil and water conservation, land rehabilitation, green manuring, and water management are integral parts of sustainable agricultural systems.

There is general agreement on the goals of sustainable agriculture: 1) to make better use of farm based resources, 2) to minimize the need of external inputs, 3) to prevent loss and degradation of farm resources, and 4) to maintain quality of farm life.

To put sustainable agriculture in proper perspective, it can be stated that while the aim of farming changes made in the 1930s was to boost farm productivity, the aim of changes started in the 1980s under the umbrella of sustainable agriculture is to make sure that the gains made in 1930s are preserved in perpetuity. This can only happen if the soil and water resources are wisely used and rejuvenated and soundness of farm ecology is maintained. Thus, while sustainable farmers continue to use tractors, they use new ploughs that disturb the soil to a minimum, thereby preventing erosion. The emphasis on the control of weeds, insects, and diseases on crop plants remains unchanged, but new methods consist of a combination of chemicals, pest-predator control, crop rotation, increased plant resistance, and other innovative means to prevent toxic contamination of soil, water, and crop. Farmers continue supplementing nutrients to increase crop yield, but they use not

only chemical fertilizers, but also rely on leguminous nitrogen fixation, increased availability of bound soil nutrients through enhanced microbial activity, etc. Thus, sustainable agriculture is not a movement against industrialized agriculture but an economically and environmentally viable option for all farmers.

2. Cover Crops

Cover crops play an important role in sustainable agriculture because of their influence in increasing crop production, improving soil and water quality, and suppressing weeds, insects, and diseases^{124, 125, 179, 209}. Generally cover crops use residual nutrients, such as N, P, K, left in the soil after crop harvest, thereby reducing the potential of nutrient loss through erosion and leaching,^{143, 183}. When cover crop residues are incorporated into the soil, the increased biomass compared with weeds in the bare soil not only recycle greater amounts of residual nutrients, but also improve soil quality by increasing organic matter concentration, thereby influencing the physical, chemical, and biological properties of the soil^{141, 208, 209}. While nonlegume cover crops are effective in removing soil residual N and reducing N leaching, legume cover crops are effective in supplying N to the crop, increasing its yield, and reducing the amount of N fertilizer^{95, 123, 205}.

Abundant literature is available on the effects of legume and nonlegume cover crops on the growth and yield of field crops^{143, 205}, but little is known about their impact on vegetable production. Vegetable production differs from field crops production in management intensity and amount of input required. While field crops are managed mostly during planting and harvesting seasons, vegetables require intensive management throughout their growth. Incidences of insects and diseases are also more likely in vegetables than in field crops. As a result, cultural practices, such as weeding or applications of herbicides, pesticides, or irrigation, are required more frequently throughout vegetable production to reduce the competition of weeds, incidences of insects and diseases, and to maintain vigorous growth. Furthermore, vegetables require a greater degree of inputs, such as N, P, and K fertilizers than field crops¹⁸⁴. This is because nutrient uptake and recovery in the plant biomass is lower in vegetables than in field crops where most of nutrients are used for the production of fruits, tubers, or bulbs^{134, 184}.

2.1. Cover crop establishment and biomass yield

Cover crop is planted after harvesting the summer crop in mild winter climates. While nonlegume cover crops, such as rye (*Secale cereale* L.) establish rapidly in the early fall, legume cover crops, such as hairy vetch (*Vicia villosa* Roth) and crimson clover (*Trifolium incarnatum* L.), grow slowly in the fall with most biomass gain occurring in the spring when temperatures increase²⁰⁸.

The establishment of cover crops in regions with cold winters is more problematic. The short growing season in these areas warrants that cover crops be planted early in the fall. As a result, cover crops are often established in late summer-early fall by overseeding under the standing canopy of the summer crop before it is harvested. In small areas, this can be achieved by spreading seeds with a hand-crank seeder²¹⁵. In large areas, cover crops can be established under the standing canopy of the summer crop by broadcasting seeds with aerial crop dusters or tractor-mounted seeders¹⁵². The cost of seeding by this method, however, is a major shortcoming, which discourages the producers to grow the cover crop. In areas with cold winters where cover crops are grown in the summer, seeds are broadcast in the frozen soil under the standing canopy of the winter cereal crops, such as wheat (*Triticum aestivum*, L.)²¹⁵. As freezing and thawing occur, seeds fall into crevices of the soil and start to germinate. After winter crop harvest in late spring, the previously seeded cover crops become established. In regions with hot weather, such as in the tropics, cover crops, such as cowpea (*Vigna unguiculata* L.), can be grown in the summer when high temperatures prevent the growth of other crops²¹⁵.

Cover crops can also be established by reseeding from the plant itself. Once a cover crop is planted in the fall, it is allowed to grow until full maturity in the spring at which time it reseeds. A cash crop is grown and harvested in the summer prior to the germination of reseeded cover crop in the fall. This method saves on cost and time; however, it may delay planting in the summer because the grower has to wait until the cover crop matures. In such cases, growers may have to choose a crop, which can be planted late with a short growing period. For example, if barley (*Hordeum vulgare* L.) is grown as a cover crop in the winter with the expectation it will be allowed to reseed, then soybean (*Glycine max* L.) can be grown as the summer crop because planting of soybean in late summer generally does not affect its yield. Another example is crimson clover which has been successfully established by reseeding in cotton (*Gossypium hirsutum* L.) production¹⁷⁹.

Because of varying soil and climatic conditions, a cover crop growing well in one region may not do so in another. In such cases, various species of cover crops are grown within a region and the best species are chosen based on growth potential and biomass yield in that area. For example, a cold-tolerant species is needed for regions with cold winters while a heat-tolerant species may be needed for regions with warm summers. Legume cover crops, such as hairy vetch and crimson clover, and cereals, such as rye, have been found to be well adapted to both sub-tropical^{208, 221} and temperate regions^{201, 215}.

Biomass yield of cover crops and their N accumulation vary between legumes and nonlegumes and from one region to another²⁰⁵. Nonlegume cover crops with small grains, such as rye, have biomass yields and N accumulations of 6.7 Mg·ha⁻¹ and 137 kg·ha⁻¹, respectively, in Georgia²¹⁰, 5.0 Mg·ha⁻¹ and 74 kg·ha⁻¹, respectively, in Maryland⁴¹ and 5.3 Mg·ha⁻¹ and 60 kg·ha⁻¹, respectively, in Washington¹²⁵. In comparison, legume cover crops, such as hairy vetch, have biomass yields and N accumulations of 4.8 Mg·ha⁻¹ and 188 kg·ha⁻¹, respectively, in Georgia^{209, 211}, 3.0 Mg·ha⁻¹ and 100 kg·ha⁻¹, respectively, in Maryland⁴¹ and 3.9 Mg·ha⁻¹ and 120 kg·ha⁻¹, respectively, in Washington¹²⁵. Both legumes and nonlegumes have similar C concentration, but legumes have greater N concentration because of their ability to fix atmospheric N²⁰⁸. Nonlegumes accumulate more C because of their greater biomass, while N accumulation is greater in legumes because of higher N concentration^{124, 125, 211}.

2.2. Vegetable production

Fresh-market yields of several summer vegetables have been known to increase substantially with winter legume cover crops compared with nonlegume or no cover crops. When planted after legumes, increases in yields of tomato (*Lycopersicon esculentum* L.)^{2, 206, 221}, brassica (*Brassica spp.*)²²⁰, lettuce (*Lactuca sativa* L.)²²⁷, and eggplant (*Solanum melongena* L.)²¹¹ have been reported. Tomato yields were greater with hairy vetch than with polyethylene mulch or bareground even during the late season with adverse climatic condition, thereby increasing monetary returns¹¹⁹. Similarly, Sainju et al.²¹¹ observed that tomato and eggplant yields with hairy vetch and crimson clover cover crops were comparable to synthetic nitrogen fertilization. As a result, legume cover cropping can substitute or reduce the amount of nitrogen fertilizer applied to summer vegetables. However, yields of snap bean (*Phaseolus vulgaris* L.) and pea (*Pisum sativum* L.) did not increase significantly with legume cover crops compared with bare soil^{153, 154, 241}.

The increased vegetable yield with legumes compared with nonlegumes or no cover crop results from their increased N supply^{1, 3, 209}. Because of their higher N concentration and lower C/N ratio, legumes decompose rapidly in the soil and release N earlier than do nonlegumes^{123, 125, 209, 246}. Half of the N supplied by legume cover crops is available for uptake by the succeeding crop within two to four week of their incorporation into the soil^{125, 229, 258}. As a result, N supplied by legume cover crops is synchronized with N needs of tomato during its growth²⁶³. Nitrogen supplied by winter legume cover crops usually increases yields of nonlegume summer vegetables, such as tomato, eggplant, and lettuce. Yields of legume summer vegetables, such as snap bean and pea, however, may not increase with increased N supplied by legume cover crops because these vegetables, being legumes, fix N from the atmosphere.

Cover crop residue can increase soil water content, especially with no-till practices, thereby improving tomato⁴³ and corn (*Zea mays* L.)⁴² yields. Cover crops can also influence yield of vegetables through promotion of root growth. Sainju et al.²¹⁰ reported that legume cover crops, such as hairy vetch and crimson clover, increased root growth of tomato by increasing N supply to the soil but nonlegume cover crops, such as rye, increased root growth due to its higher biomass yield and increased organic matter concentration. The increase in root growth produced by hairy vetch and crimson clover was similar to that produced by N fertilization rates of 90 and 180 kg·ha⁻¹. When cover crop residue was placed at the soil surface in no-till systems, it further increased root growth and yield of tomato^{119, 207}.

2.3. Soil Properties

Besides enriching soil N by legumes, cover crops can improve soil quality by conserving and increasing organic matter concentration, especially when compared to weeds on fallow soils^{124, 125, 143, 209}. Organic matter is the key component of soil quality that helps to sustain its fertility and productivity by influencing its physical, chemical, and biological properties^{13, 58}. While tillage increases mineralization of organic matter by incorporating plant residues, disrupting soil aggregates, and altering its temperature, moisture, and aeration^{33, 55, 260}, cover crops maintain or improve soil organic matter by replacing organic matter lost by tillage through plant residue addition and by reducing soil erosion^{95, 124, 143}. Sainju et al.²¹¹ observed that cover crops increased soil organic C and N concentrations by 9 to 19% compared with bare soil after seven year

when residues were incorporated into the soil. They also observed that organic C concentrations was increased by 17 to 23% after six year when cover crop residues were placed at the soil surface with no-till systems as opposed to the residues incorporated into the soil in mouldboard tillage. No-till practices reduced mineralization of cover crop residues due to its decreased contact with soil microorganisms^{79, 212}.

The amount and type of cover crop residue added to the soil and its rate of decomposition determines the amount of organic C and N concentrations in the soil^{124, 125, 207}. Larson et al.¹²⁸ and Rasmussen et al.¹⁸⁸ observed that changes in organic C were linearly related with the amount of plant residue applied to the soil and were independent of the type of residue. Kuo et al.^{124, 125} and Sainju et al.^{209, 211} observed greater concentrations of soil organic C and N with nonlegume cover crops than with legume cover crops because nonlegume cover crops had greater biomass accumulation and higher C:N ratios that may have slowed their rate of decomposition. By contrast, several researchers reported greater soil organic C and N concentrations with legume than with nonlegume cover crops^{95, 141, 144}. The difference in soil and climatic conditions among regions probably reflect cover crop growth and its influence on soil organic C and N concentrations. The growth stage of cover crop at the time of incorporation also influences its rate of decomposition in the soil because of variation in C:N ratio of its biomass during growth⁷⁸. Based on the soil N enriching ability of legumes and organic C increasing ability of nonlegumes, a mixture of legume and non-legume cover crops may be needed to achieve the twin objectives of supplying N and improving organic matter concentration in the soil.

Cover crops also improve soil physical properties, such as water content, temperature, aggregation, bulk density, infiltration capacity, and hydraulic conductivity. The water content and temperature of the soil is altered by the mulch effect of the cover crop residue²²³. It also can improve soil aggregation, hydraulic conductivity¹⁹⁶, and water infiltration capacity^{141, 257}. Frye et al.⁸² observed that cover crops reduced soil erosion from 18 to 2 Mg ha⁻¹ per year. Langdale et al.¹²⁶ obtained reductions in erosion of 62% in Ultisols and 72% in Alisols by using cover crops.

2.4. Water quality

Cover crops can improve the water quality of runoff by absorbing nutrients, such as NO₃⁻ N, from the soil and reduce its potential for leaching in the groundwater^{143, 205}. After the fall crop harvest, some portion of N fertilizer applied to the summer crop is left as residual N in the soil because plants do not absorb 100% of applied N⁹³. The potential for NO₃⁻ N leaching under vegetables is often greater because vegetable production needs greater input of N and N uptake efficiency by vegetables is often lower than by field crops^{134, 184}. The mineralization of N from soil and plant residue also contributes to the leaching potential. In humid regions, N leaching occurs mostly during fall, winter, and spring seasons when evapotranspiration is low and precipitation exceeds water-holding capacity of the soil^{40, 143}. Winter cover crops use residual N and moisture after crop harvest in the fall, thereby reducing the amount of NO₃⁻ N and water available for leaching^{143, 183}.

Cover crop species vary in their ability to absorb residual N from the soil and reduce N leaching. Nonlegume cover crops are more effective in reducing N leaching than legumes^{122, 143, 205}. This is because nonlegume cover crops, such as rye, grow and establish rapidly in the fall²⁰⁸, thereby absorbing greater amount of the residual N and reducing its amount available for leaching¹⁴³. By contrast, legume cover crops, such as hairy vetch and crimson clover, produce most of its biomass during spring when temperatures increase^{143, 208}. As a result, soil residual N in the fall is not effectively removed by legume cover crop²⁰⁸. The N fixing characteristic of legumes also interferes with their ability to reduce N leaching²⁰⁸. In a review of literature, Sainju and Singh²⁰⁵ observed that nonlegumes reduced NO₃⁻ N leaching from 29 to 94% compared with 6 to 48% by legumes. Similarly, McCracken et al.¹³⁸ reported that rye reduced NO₃⁻ N leaching by 94% compared with 48% by hairy vetch. Besides grasses, several brassica species, such as mustard [*Brassica juncea* (L.) Czerniak], canola (*B. napus*, L.), radish (*Raphanus sativus* L.), and turnip (*B. rapa* L.) can also effectively remove residual N from the soil thereby reducing N leaching^{109, 143, 228}.

2.5. Weed, insect and disease control

The effect of cover crops on weeds, insects, and diseases are dealt in respective sections dedicated to their control.

2.6. Economic evaluation of cover crops

Although cover crops have many benefits in increasing crop production, improving soil and water quality, and suppressing weeds, insects and diseases, their economic benefits as a result of these improvements have not been fully studied. For a farmer or producer to grow cover crops, its economic benefit should outweigh the cost of growing it. Although cover crops also improve soil and water quality by increasing organic matter concentration and reducing soil erosion and nutrient loss, the returns in terms of these benefits are often ignored during economic evaluation of the cover crop. Unlike crop yields, it takes a long time to measure these improvements and their economic benefits are often hard to measure. In such cases, the benefits provided by cover crops in improving soil and water quality averaged across the years should be used to calculate the annual return. The total return from crop production systems should include returns from crop yields as well as due to improvements in soil and water quality. The decrease in the costs of purchasing herbicides and pesticides due to the suppression of weeds, insects, and diseases from growing cover crop and/or in the amount of N fertilizer used for optimum crop production when growing a legume cover crop should also be used in calculating costs and returns.

Frye et al.⁸² observed substantial economic return in corn production using hairy vetch compared to rye, crimson clover, and big flower vetch (*Vicia grandiflora* Koch) or no cover crop in Kentucky. A net return of \$199 per ha over no cover crop was observed for hairy vetch compared with \$35 per ha for rye, \$4 per ha for crimson clover, and \$64 per ha for big flower vetch. When 100 kg-ha⁻¹ fertilizer N was added with cover crop residue, the net return of corn production over no cover crop was \$157 per ha for hairy vetch, \$18 per ha for rye, \$6 per ha for crimson clover, and \$138 per ha for big flower vetch. Similarly, Kelly et al.¹¹⁹ found that hairy vetch mulch system was more profitable under all market and yield adjustment scenarios than polyethylene mulch or bare soil in tomato production.

3. Fertilizers and Compost

3.1. Fertilizers

Sustainable Vegetable crop production mandates efficient use of all resources including fertilizers. Excessive fertilization not only does contribute to groundwater and runoff pollution, but also can lead to biological imbalances in the soil. High rates of nitrogen fertilization can impair the ability of nitrogen-fixing bacteria to colonize roots of legumes. In addition, mycorrhizal activity can be reduced in soils with heavy fertilization⁷.

3.1.1. Soil pH

Plants can best utilize added fertilizers if the soil pH is within the optimum range. Plant nutrients are usually most available when the soil pH is between 6 and 7. N, P, K, S, Ca, and Mg become less available as the pH drops below 6. As the pH rises above 7, micronutrients such as Fe, Mn, B, Cu, and Zn become less available. NH₄⁺-N is best absorbed at pH 7 and will generally reduce soil pH. As soil pH increases above 7.2, ammonia gas is lost from the soil when either ammonium nitrate or urea is applied.

3.1.2. Soil testing

Soil testing particularly over a period of years is critical for maintaining, improving, and determining crop nutrient requirements. Expert systems have been developed to aid in managing soil fertility. Some of these systems take into account not only residual soil nutrients, but also previous crop history²⁴⁵. Global position systems are also being used to assist in soil fertility management thereby increasing the efficiency of inorganic fertilizer use and reducing the amount of application. Image analysis of crop cover is another method of assessing crop status and thus managing crop fertility and soil condition¹⁷. Using tissue testing also increases fertilizer-use-efficiency as crop nutrient status can be evaluated and fertilization adjusted accordingly.

3.1.3. Fertilizer sources, time and method of application

Fertilizers come in both liquid and solid formulations. Liquid fertilizers are rapid source of plant nutrients. However, some slow release liquid formulations marketed recently should increase the availability period of these products to crops. Dry fertilizers can be broadly grouped into readily available and slow release. Timing and placement are critical to efficient use of readily available fertilizers. Splitting applications, particularly with N and K, are a more efficient use of these readily leached nutrients. Application timing gives more nutrients to the plant when needed and reduces loss due to runoff and leaching. Placement can also be critical in reducing the use of fertilizers. Banding, where fertilizer is placed just to the side and below the crop row, is a more efficient use of fertilizer compared to broadcasting. Sidedressing is a more efficient method of placement for timed applications compared to broadcast applications. Slow release formulations offer another alternative that is also efficient in fertilizer use with the added benefit of reducing the number of applications and time spent in applications. Various formulations of slow release fertilizer are available, including urea, urea-formaldehyde, and resin-coated technologies. There is lot of research currently underway evaluating the performance of these slow release products. In one such experiment, rock-phosphate-coated urea and gypsum-coated urea worked better and were presumably more efficient than urea formaldehyde in tomato and okra (*Abelmoschus esculentus Moench*) production²¹⁴. Irrigation water is often used as the carrier for fertilizer. This practice is particularly useful in drip or trickle irrigation where the fertilizer is metered out on a daily or weekly basis. As a result, fertilizer-use-efficiency is increased and total fertilizer need is decreased.

3.2. Compost

Compost is the amorphous remains of formerly living organisms with C to N ratio of 25:1 to 40:1. Generally the starting material will have a C: N ratio on the high side of this range and aerobic respiration with a loss of CO₂ reduces this ratio in the finished product. A variety of organic materials can be used to generate compost. Large scale composting uses such sources as farm waste, municipal yard waste, groundnut (*Apios americana Medic.*) hull, cotton gin trash, poultry litter, packing-shed culls and even casting of earthworms (vermicompost)¹³⁷. Composting requires aeration and develops a temperature in the range of 54 to 68°C for six to 12 weeks. Large quantities of compost for agricultural needs are just now becoming available. The most important and measurable difference this has entailed is the reduction of water requirements on mineral soils.

4. Tillage Operations

4.1. Types of conservation tillage

Conservation tillage practices are divided into four categories depending on the amount and type of tillage performed.

In no-till, the soil is left undisturbed from harvest to seeding and from seeding to harvest. The only tillage is the soil disturbance in a narrow slot created by coulters, disk or runner seed furrow openers, or hoe openers attached to the planter, transplanter or drill to plant the seed. No-till planters or transplanters and drills must be able to cut residue and penetrate undisturbed soil.

In ridge-till, except for fertilizer injection soil is undisturbed from harvesting to planting. Crops are planted and grown on ridges formed in the previous growing season. A planter equipped with sweeps, disk row cleaners, coulters or horizontal disks is used in most ridge-till systems. These row-cleaning attachments remove 2.5 to 5 cm of soil, surface residue and weed seeds from the row area. Ideally, this process leaves a residue-free strip of moist soil on top of a ridge into which the seed is planted.

Mulch-till includes any conservation tillage system other than no-till and ridge-till. Tillage is performed by a chisel plough, blade plough, rod weeder, disk or field cultivator. Herbicides and/or crop cultivation control weeds. The number of operations must be limited to assure that adequate residue cover remains for erosion control.

Recently, strip-till has drawn much attention as a conservation tillage practice. In this method, the soil is left undisturbed prior to planting. Tillage in the row is performed at or before planting using tools such as coulters, an in row subsoiler, or other row cleaners. The implements used in strip tillage are continuing to evolve. Many producers and companies are making modifications to their current equipment to meet the special needs of different crops. All strip-till implements are composed of parts in line that perform a specific operation. The first part is usually a large coulters, which is used to slice through soil residue. This allows other operations to occur without plugging due to thrash build up.

The most commonly used strip-till system follows the coulter with a sub-soiler shank to fracture a hard pan, if it exists. The sub-soiler makes a slot in the soil profile which needs to be closed. If it is not closed adequately, seeds may wash down the slot. Fluted coulters placed on both sides of the ripper foot are most commonly used to close the slot and to perform some tillage. Small pneumatic tires or spiders are used in some row-till systems to close the slot. The next operation performed is to flatten and firm the soil for good soil/seed contact. One way this is performed is by using a rolling basket which in some cases is followed by a flat drag. An alternative way is to use spring loaded drags to fatten and firm the soil. New systems are being developed to incorporate herbicides. Some current systems provide linked, shallow herbicide incorporation. However, the systems using spring loaded drags push treated soil down into the slot which may cause damage to plant root systems depending on the crop.

Other strip-till systems are being developed that do not incorporate a sub-soiler shank. These are applicable to crops that do not respond to subsoiling. They, also, may be suitable for cropping systems that use controlled traffic, referring to the practice in which the crop is planted in or near the previous crop row using the same traffic pattern, especially if the previous crop was under row sub-soiled. This system still uses fluted coulters to till the soil and may use a row cleaner to remove residue from the seedbed. This type of system may be used in conjunction with a paraplough in some crops. The paraplough leaves a small elevated bed which can be planted on.

Strip-tilling and planting can either be done in the same pass or in a separate operation. The advantages of performing both operations in the same pass are fewer trips made over the field and the ability to accurately plant in the tilled strip. As with any system, there are disadvantages. One is the size and weight of the combined unit. Another is timing which is critical when both operations are performed at once.

Options are available to clean crops which have high weed pressure. No-till cultivators are available from various manufactures which can handle the residue without clogging. There are several different designs of cultivators. However, two major types are being used. One type resembles a heavy duty conventional cultivator with fenders but is equipped with disk hillers or sweeps, or a combination of each. The other type is equipped with a coulter to cut through residue which is followed by a small chisel shank with flat peanut type blades mounted on each side of the shank. The blades run horizontally through the soil to under cut the existing weeds. Depth of operation can be adjusted depending on the crop being cultivated.

Another option that is available is a hooded sprayer. The nozzles in this type of sprayer are mounted inside a closed box to protect the crop being sprayed from contact with the chemical. The box has a flexible curtain in front and in the rear to allow weeds to flow through and be treated.

As conservation tillage systems evolve, the systems adopted will probably be a combination of the systems listed above. Some conventional tillage may be included in the total system to maintain soil fertility and weed control.

4.2. Conservation tillage and vegetable production

Research results of limited number of studies on the suitability of conservation tillage in vegetable production have been mixed. For example minimum till (chisel plow) with lower nitrogen rates can result in similar yields as with conventional tillage and higher nitrogen applications in tomato production²⁶³. Research with squash (*Cucurbita pepo* L.) has shown, however, that planting into a previous cover crop can delay and reduce yields if the previous cover crop is not adequately killed²⁴⁷. Phatak¹⁷⁶ suggested of using conservation tillage for vegetables only where it had been proven consistently successful.

Tillage systems that minimize or eliminate soil operations must be carefully managed to eliminate competition from previous cover crops and weeds which appear to be the major source of reduced yields and particularly reduced early yields^{43, 108, 247}. The importance of preventing weed competition in these systems is illustrated with English peas where crop nitrogen uptake was 34% greater without weed competition than where weed competition was present¹²¹. Hatfield and Keeney⁹⁸ expressed concerns in the area of nutrient and pest management strategies with conservation tillage.

Alleopathic effects from previous crops and green manures can be a problem in limited till and no till systems. This is particularly true when rye or wheat are used as green manures or are the previous crop. Using transplants may overcome alleopathic effects compared to direct seeding.

4.3. Research needs

Most research on conservation tillage in vegetable crops has been on individual aspects of vegetable production. For example, research on specific aspects of fertility, weeds, insects, diseases, and nematodes etc. have been made, but not on total systems^{1, 3, 25, 28, 29, 86, 108, 176, 177, 178, 186, 231, 233, 235}. Some research has been done on comparisons of conventional and sustainable vegetable production^{26, 27}. Phatak and Reed¹⁷⁹ discussed the opportunities for conservation tillage in vegetable production and also outlined small plot research and on-farm research conducted since 1985. Overall, most research on conservation tillage on vegetables conducted in recent years has been encouraging. However, more practically oriented research is needed to integrate conservation tillage in sustainable vegetable production systems.

5. Weed Management

Webster²⁵³ reported the result of a survey carried out in Georgia, USA to identify problem weed species in vegetables. For this survey, vegetable crops were divided into the same four broad categories as used by the Environmental Protection Agency when considering the registration of a new herbicide. Purple nutsedge (*Cyperus rotundus* L.) and yellow nutsedge (*Cyperus esculentus* L.) were the most troublesome weeds of cucurbits (e.g. watermelon and squash), fruiting vegetables (e.g. tomato and pepper), and other vegetables (e.g. legumes), while these weeds trailed only wild radish in importance in cole crops and greens (e.g. cabbage and turnip greens) (Table 1). Cole crops and greens had more winter annual weeds (e.g. wild radish, cutleaf evening primrose, henbit, and chickweed spp.) than other vegetable categories. Eight of ten most troublesome species were common among the cucurbits, fruiting vegetables and other vegetable categories. Differences (and similarities) in important weeds among the crops were often a reflection of the cultural practices (e.g. planting dates) and weed control practices employed (e.g. plastic mulch or no mulch).

5.1. Crop losses due to weeds

5.1.1. Crop yield reduction and critical weed-free periods

Weed interference studies often take one of two forms, both of which provide vital information on weed-crop interactions. The objective of the first type of study is to quantify yield losses based on weed density (Table 2). This is useful when considering whether weed control is economically justified based on weed populations. The objective of the second type of study is to evaluate the critical period of interference in which weeds must be controlled (Table 3). The critical period is composed of: 1) the minimum duration after seeding/transplanting in which a crop must be kept free of weeds to avoid a reduction in crop yield and 2) the maximum duration that weeds which emerged with the crop can remain in the field before they begin to reduce crop yield²⁵².

Table 1. Most troublesome weeds in four vegetable categories (Georgia, USA).

Rank	Cole crop and greens	Cucurbit	Fruiting vegetables	Other vegetables
1	Wild radish	Yellow nutsedge	Yellow nutsedge	Yellow nutsedge
2	Yellow nutsedge	Purple nutsedge	Purple nutsedge	Purple nutsedge
3	Purple nutsedge	Pigweed spp.	Morningglory spp.	Pigweed spp.
4	Pink purslane	Morningglory spp.	Sicklepod	Morningglory spp.
5	Cutleaf eveningprimrose	Sicklepod	Smallflower, morningglory	Sicklepod
6	Pigweed spp.	Smallflower, morningglory	Pigweed spp.	Smallflower, morningglory
7	Swinecress	Florida pusley	Goosegrass	Florida pusley
8	Henbit	Texas panicum	Texas panicum	Texas panicum
9	Chickweed spp.	Coffee senna	Florida pusley	Pink purslane
10	Morningglory spp.	Bermudagrass	Pink purslane	Wild radish

Table 2. Effect of weed density on crop yield reduction for various vegetable crops.

Crop	Weed	Density	Yield loss	Reference
Bell pepper	Purple nutsedge	200/m ²	32%	151
Broccoli	Common lambsquarters	1/m ²	22-37%	20
Broccoli	Common lambsquarters	15/m ²	73%	20
Broccoli	Italian ryegrass	4.9/m of row	3.6%	14
Broccoli	Italian ryegrass	600/m of row	100%	14
Cabbage	Wild radish	16/m of row	Not detectable	225
Cucumber	Mix of weeds ¹	11/m ²	46%	80
Cucumber	Yellow nutsedge	15/m ²	5%	113
Tomato	Mix of weeds ¹	9/m ²	27-62%	81
Tomato	Barnyardgrass	16/m of row	26%	18
Tomato	Barnyardgrass	64/m of row	84%	18
Tomato	Common lambsquarters	16/m of row	17%	19
Tomato	Common lambsquarters	64/m of row	36%	19
Tomato	Purple nutsedge	80/m ²	14%	115
Tomato	Purple nutsedge	160/m ²	68%	115
Tomato	Purple nutsedge	320/m ²	70%	115
Tomato	Purple nutsedge	200/m ²	44%	151

¹ Weed mixture included common lambsquarters, common ragweed, and longspine sandbur

Table 3. Critical period of weed interference for various vegetable crops

Crop	Weed	Critical period	Reference
Cabbage	Mix of weeds ¹	3 rd and 4 th week after planting	250
Cucumber	Mix of weeds ¹	3 rd and 4 th week after planting	250
Cucumber	Mix of weeds ²	12 to 36 days after emergence	80
Onion	Mix of weeds	5 to 7 weeks after 50% emergence	197
Onion	Mix of weeds	First crop yield loss: 90 TTU (Thermal Time Units)	60
Onion	Common sunflower	2 to 12 weeks after planting	145
Tomato (seeded)	Mix of weeds ¹	5 to 8 weeks after planting	250
Tomato (transplanted)	Mix of weeds ^{1,2}	4 to 5 weeks after transplant	251
Tomato (transplanted)	Mix of weeds ²	12 to 36 days after transplant	81
Tomato (transplanted)	Palmer amaranth	30 to 35 days after transplant	84
Yellow squash	Mix of weeds ³	First 4 weeks	135

¹ Weed mixture included common lambsquarters, powell amaranth, large crabgrass, and ladythumb.

² Weed mixture included common lambsquarters, common ragweed, and longspine sandbur.

³ Weed mixture included quackgrass, common lambsquarters, common ragweed, and groundnut.

5.1.2. Cole crops and greens

High populations (15 plants/m²) of common lambsquarters (*Chenopodium album* L.) reduced broccoli (*Brassica oleracea* L. var. *botrytis*) plant biomass up to 73% at 58 days after planting and resulted in yield reductions primarily due to smaller broccoli head weights ²⁰.

Bell ¹⁴ determined that 4.9 Italian ryegrass (*Lolium multiflorum* L.) plants/m² of crop row caused 3.6% broccoli yield loss corresponding to the cost of control. Broccoli competed relatively well with Italian ryegrass, and a total loss of yield only occurred at weed population densities of 600 to 1000 plants/m of crop row.

Weaver ²⁵⁰ studied the effect of high densities (>80 weeds/m²) of annual weeds [mixture of common lambsquarters, Powell amaranth (*Amaranthus powellii* (S.) Wats.), large crabgrass (*Digitaria sanguinalis* (L.) Scop.), green foxtail (*Setaria viridis* (L.) Beauv.), and ladythumb (*Polygonum persicaria* L.)] on growth of cabbage (*Brassica oleracea* L. var. capitata). A single weed control operation between three and four weeks after planting averted crop yield loss from weed interference in spring-seeded cabbage.

Weed competitiveness with a crop can be affected by crop planting method. Healthy crop transplants can have an appreciable advantage over weeds that emerge from the soil seedbank. Steed et al. ²²⁵ found that seedling wild radish (*Raphanus raphanistrum* L.) plants were poor competitors with transplanted cabbage. Densities of 16 wild radish/m of cabbage row did not reduce cabbage yield relative to the nontreated control.

5.1.3. Cucurbits

Friesen ⁸⁰ found a critical weed-free period for seeded cucumber (*Cucumis sativus* L.) of 12 to 36 days after crop emergence. When weeds [common lambsquarters, common ragweed (*Ambrosia artemisiifolia* L.), and longspine sandbur (*Cenchrus longispinus* (Hack.) Fern.)] were removed past this interval, cucumber plants were unable to compensate with increased plant growth and crop yields were similar to the weedy control. This suggests that effective pre-emergence herbicide applications to target these weeds should provide residual activity for five weeks.

Cucumber was not very tolerant of the presence of common lambsquarters, common ragweed, and longspine sandbur. A mixture of these species at a density of 9 weeds/m² reduced cucumber yields 42 to 46%, relative to those in the weed-free control ⁸⁰. The relative competitiveness of a crop to a weed will also affect the amount of yield reduction incurred. A uniform stand of cucumber was shown to be relatively competitive with yellow nutsedge (*Cyperus esculentus* L.), a weed often regarded as a weakly competitive species. Johnson and Mullinix ¹¹³ observed that high densities of yellow nutsedge (>900 shoots/m²) reduced cucumber yields much more when cucumber densities were 4 to 6 plants/m² compared to when cucumber densities were 14 plants/m². At a cucumber population density of 14 plants/m², yellow nutsedge at 15 plants/m² reduced cucumber yield by 15%.

Mallet and Ashley ¹³⁵ reported the critical period for seeded yellow squash in a field infested with a mixture of quackgrass [*Elytrigia repens* (L.) Nevski], common lambsquarters, common ragweed, and groundnut (*Apios americana* Medik) were between four and six weeks after planting. This period coincided with squash flower bud formation (four weeks) and continued through flowering opening (six weeks). When squash was maintained free of weeds during the critical period, crop yields were higher and fruit maturation earlier than those in which weeds interfered during this period.

5.1.4. Fruiting vegetables

Tomato yields were reduced if weeds were allowed to infest plots longer than five weeks or if plots were not kept free of weeds for at least eight weeks after seeding ²⁵⁰. A single weed control treatment (initiated between four and eight weeks after seeding) was not sufficient to avoid crop yield loss due to weed interference. Therefore, the critical period of weed interference for seeded tomato is between five and eight weeks after planting ^{250, 252}. Tomato tolerance to weed presence was influenced by planting method. Weaver and Tan ²⁵¹ found that a single weed removal at four to five weeks after transplanting was sufficient to prevent crop yield loss in transplanted tomatoes.

According to Friesen ⁸¹, transplanted tomatoes should be kept free of weeds (common lambsquarters, common ragweed, and longspine sandbur) for 12 to 36 days after transplant to avoid a yield reduction, relative to the weed-free control. The end of this critical period coincided with the full bloom stage of the crop, indicating that shading of the crop at this stage may be critical in affecting fruit set. Allowing weeds to compete with tomatoes for 48 days (12 days beyond the critical period) reduced crop yield 50%. Season-long interference from 9 weeds/m² reduced tomato yields 27 to 62%, relative to the weed-free control.

Bhowmik and Reddy ¹⁸ found that season-long interference of barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.] at densities of 16 and 64 plants/m of crop row reduced marketable tomato yields 26 and 84%, respectively. A similar study determined that season-long interference from common lambsquarters at densities of 16 and 64 plants/m of crop row reduced marketable tomato yields 17 and 36%, respectively ¹⁹.

While plasticulture systems have been an effective means of suppressing most weeds, the opportunity for weed survival still exists in the crop hole of the polyethylene mulch. Garvey and Monks⁸⁴ found that transplanted tomatoes in a plasticulture system required a six-week weed-free period for in-row Palmer amaranth [*Amaranthus palmeri* (S.) Wats] and that established weed must be removed by four weeks after transplanting to avoid reduction in tomato vegetative dry weight. Non-linear regression indicated that the critical weed-free period to avoid loss in marketable yield was between 30 and 35 days for Palmer amaranth in tomato.

Purple nutsedge (*Cyperus rotundus*) has been shown to interfere with tomato growth and yield^{114, 151, 213}. Kadir¹¹⁵ found that purple nutsedge planted at densities of 80, 160, and 320 tubers/m² reduced tomato yields 14, 68, and 70%, respectively. Other studies have shown that a purple nutsedge density of 200 plants/m² reduced tomato and pepper (*Capsicum annuum* L.) fruit yields 44 and 32%, respectively¹⁵¹. Disparity of crop yield losses among studies may be due to a number of elements, including differences in cultural practices (e.g. fertilization management, irrigation schemes, and planting dates), crop varieties, or site characteristics (e.g. soil type and soil temperatures). Other studies have shown that tomato was more competitive than both yellow and purple nutsedge and of the two species, yellow nutsedge, was more competitive with tomato than was purple nutsedge²¹³.

Black nightshade (*Solanum nigrum* L.) interference with tomato was lessened if weed emergence was delayed. When black nightshade emerged simultaneously with tomato, crop yield was reduced 37%. However, delaying black nightshade emergence to the 2-, 4-, and 6-leaf of tomato resulted in crop yield losses of 15, 9, and 0%, respectively¹⁸². In contrast, pepper was much more sensitive to interference from black nightshade. Pepper yields were reduced 93% when black nightshade emerged with the crop, while yield reduction was 62, 44, and 29% when black nightshade emerged at the 2-, 4-, and 6-leaf stages of tomato, respectively¹⁸². Thus it can be inferred that if weed emergence could be delayed in the fruiting vegetables, reduction in yield due to weeds could be lessened.

5.1.5. Other Vegetables

Onions (*Allium cepa* L.) are often in the field for six months or longer. Roberts¹⁹⁷ found spring-seeded onions capable of tolerating weed presence for about five weeks after 50% crop emergence. However, weeds must then be removed and field kept weed-free for the remainder of the season to avoid yield loss. During the sixth and seventh weeks of weed interference, if weeds are not controlled, losses approach 4% of final yield for each day the weeds are present (across densities of 150 to 850 weeds/m²). In addition, it was necessary to prevent establishment of weeds for about seven weeks after 50% crop emergence to avoid yield losses. Therefore, the narrowest critical period of weed control in onion is between five and seven weeks after 50% crop emergence.

A model of duration of weed competition in spring-seeded onions in Colorado indicates that crop yield loss can be predicted using thermal time units (TTU)⁶⁰. The first significant crop yield loss occurs at approximately 90 TTU [using the following equation: $TTU = \sum (\text{Tempmax} - \text{Tempmin})/2 - 7.2^{\circ}\text{C}$]. These researchers found that onion yield was more sensitive to duration of competition than it was to weed density.

Menges and Tamez¹⁴⁵ reported that spring-seeded onions that were kept free of common sunflower (*Helianthus annuus* L.) for two to 12 weeks had yields similar to the weed-free control. The shortest weed-free periods occurred under conditions that favored fast onion germination, emergence, and growth (e.g. high light irradiance, high soil temperature, and intermediate soil moisture). High densities of common sunflower (360 plants/m²) reduced onion yield after six weeks of interference, while lower densities (50 and 5 plants/m²) were tolerated for longer durations (12 and 15 weeks after crop emergence, respectively).

5.2. Weed control methods

Pest management for vegetable growers is very complicated. Growers are often in the precarious position of balancing the concern over protection of the environment and the production of pesticide residue-free produce while growing the crop economically and efficiently with a limited selection of herbicides¹⁸⁶. One of the primary reasons for the wide scale adoption of herbicides for weed control was that they were replacing an expensive and often difficult to find labour force that was previously required for weed control. While herbicides may serve as the basis for weed management in many crops, their use may be limited by the number of herbicides available, lack of crop tolerance, or the shift to weed species less sensitive to herbicides currently utilized. To effectively manage weeds, a combination of cultural practices, physical weed control and biological weed control must be utilized to minimize the number of weeds competing with the crop,

suppress competition by surviving weeds, and reduce weed seed production³⁴. Growers will need to integrate these strategies with herbicides into a practical and economically viable weed management system that can be sustainable¹¹².

5.2.1. Prevention

One of the most important means of managing weeds is to grow a healthy crop using best management practices. Healthy and vigorously growing crops are less susceptible to invasion by weeds³⁴. Best management practices call for the use of adapted, disease-resistant cultivars (diseased plants will not be very competitive with weeds), appropriate crop row spacing patterns, plant densities that assure rapid canopy closure, and optimum fertilization and irrigation management.

Prevention also requires utmost care to minimize the risk of introducing new weeds to the cropping system. Some common avenues of introduction for new weeds include: field margins, crop seeds/transplants, irrigation water, and farm equipment from weed-infested fields. Field margins should be maintained in a dense grass cover that provides a barrier against weed invasion. Weeds that do exist in the field margins should be mowed or treated with herbicides before seeding.

Weed propagules (i.e. seeds, tubers, rhizomes, and creeping roots) should be excluded from all material being introduced into cropping areas by using crop transplants, crop seeds, greenhouse media, and soil amendments that are certified to be free of weeds and weed seeds. When moving from an infested field to a non-infested field, proper cleaning of farm equipment can prevent the import of weed seed with soil. In the event of a new weed species finding its way on to the farm, the avenue of introduction should be identified promptly and corrective measures taken to avoid future weed introduction.

A crucial step in managing a weed problem is correct weed identification. Weeds in the field should be properly identified and awareness should be developed of some of the characteristics of difficult to control species in the area.

5.2.2. Eradication

The adage, “one year’s seeding, seven years’ weeding” accurately conveys the difficulty in eliminating weed species from a field once they become established. Weed seed longevity in the soil is variable, depending upon species, environmental conditions, cropping history, and amount of disturbance.

The best means of preventing wide-scale dispersal of a new weed species in a field is to destroy patches of the new species before it becomes established. Eradication may involve spot spraying, hand-weeding, or increased mechanical control (i.e. cultivation, mowing) in areas in which these weeds are becoming established. Removal of weeds should be carried out before they had an opportunity to seed. Once a seedbank becomes established, eliminating a particular weed from the field is not easy. The area of infestation should be marked on a map so that these sites could be monitored regularly over time and subsequently emerging weeds eliminated promptly.

5.2.3. Matching crop competitiveness with level of weed infestation

A general recommendation is to plant the least competitive crops on fields with the lowest weed pressure. Some crops have the natural ability to suppress weed growth because of their growth habit, which may out-compete weeds for common limited resources (e.g. light, water, and nutrients). While the level of susceptibility to this suppression by the crop varies among weed species, there are some crops that are naturally more competitive under good growing conditions. Examples of competitive crops are beans, cucumber, Irish potato (*Solanum tuberosum* L.), pumpkin (*Cucurbita maxima* Duch.), southernpea [*Vigna unguiculata* (L.) Walp.], sweet corn, sweet potato [*Ipomoea batatas* (L.) Lam.], and tomato¹⁴⁹. Similarly, there are several crops including broccoli, cabbage, carrot (*Daucus carota* L.), English pea, greens [e.g. spinach (*Spinacia oleracea* L.), collard (*Brassica oleracea* L.), turnip green], lettuce, onion, pepper, and radish¹⁴⁹ that are not very good at suppressing weeds. However, these lists are largely dependent upon cultural practices and weather conditions. A review of weed tolerance among various crop cultivars revealed that high amounts of early-season leaf area were strongly correlated with relative competitiveness with weeds³². One example of this principle was cited by Barker and Bhowmik¹² in a squash and tomato weed control study. Weed control was superior in squash relative to tomato due to the aggressive low growth of the squash plants allowed the crop canopy to close at six weeks, while tomato required an additional two weeks for full canopy. The earlier canopy closure allowed squash plants to shade

out small weeds and to inhibit growth of established weeds.

Development of cultivars that are more capable of tolerating the presence of weed species may improve weed management systems^{34, 146}. Investigation of the ability of different potato cultivars to tolerate the presence of common lambsquarters and redroot pigweed revealed that the highest yielding cultivar under weed-free conditions was not well suited to tolerate weed presence. The potato cultivar 'Katahdin' out-yielded a standard cultivar, 'Green Mountain' by 20% under weed-free conditions^{130, 146}. However, in the presence of common lambsquarters and redroot pigweed (*Amaranthus retroflexus*) 'Green Mountain' tuber yields were not affected, but 'Katahdin' tuber yields were reduced 40%^{130, 146}.

While weeds are most often regarded as interfering with crop growth, weed growth can also be negatively impacted by crop interference. In some instances, crops employ a type of noncompetitive interference called allelopathy. While competitive interference refers to the competition for resources (e.g. light, water, nutrients), allelopathy refers to the exudation of chemicals by one plant to hinder the growth of a competing plant species. Field studies demonstrated that 'Regal' sweet potato greatly reduced the growth of yellow nutsedge. Coupled with the aggressive growth habit of sweet potato, allelopathy was suspected as contributing the advantage of sweet potato over yellow nutsedge^{97, 175}.

5.2.4. Crop rotation

Crop rotation was the cornerstone for weed management systems prior to the introduction of herbicides. Monocultures (continuous growth of a single crop or crop type) maximize the opportunity for the best-adapted weed species to thrive and dominate the cropping system⁹¹. In contrast, a crop rotation that introduces crops with different planting and harvesting dates, various competitive characteristics, and differing weed control options will tend to minimize these opportunities^{91, 131}. Due to the lack of herbicide options, crop rotation has remained an important component of weed management in vegetable crops.

5.2.5. Prediction of weed emergence

Prior knowledge of the timing and pattern of weed emergence relative to the crop under particular environmental condition can be very helpful for effective weed control²¹. For instance, the ability to predict weed emergence will help determine the optimum timing for: 1) pre-emergence herbicides, 2) mechanical control, 3) scouting weed populations, and 4) application of post-emergence herbicides. The timing of post-emergence spray is especially important with herbicides without soil activity, such as glyphosate and paraquat⁷⁷. Oriade and Forcella¹⁶³ reported that mechanical operations were optimized when a weed emergence model was used to indicate the appropriate timing. Instead of relying on calendar dates to guide mechanical weed control operations, consistent weed control across sites was achieved when a rotary hoe was used at the predicted 30% emergence of green foxtail followed by field cultivation at 60% emergence. This can go a long way in reducing weeds, improving herbicide-use efficiency and increasing sustainability.

A model used to estimate the date of the first emergence of yellow nutsedge was accurate to within two days of actual emergence²⁵⁶. Due to the limited number of herbicide options for yellow nutsedge control in vegetable, this knowledge can be utilized to effectively time cultivation treatments. Cultivation of the initial flush of yellow nutsedge reduced the number of resprouting shoots 50% at two weeks after cultivation, though 90% of the shoots resprouted by eight weeks²³⁹. However, this may be enough of a headstart for some of the more competitive vegetable crops to establish a height differential over yellow nutsedge in an effort to shade out the weed. Different weed emergence models will be needed for the different regions taking into account the climate, soil, and prevalent weed species.

5.2.6. Crop-need-based fertilization

Fertilizers, particularly nitrogen, should be used prudently so as not to promote weed growth at the expense of the crop. Di Tomaso⁵⁶ observed that crop competitiveness relative to weed could be improved through manipulation of fertilization strategies. Applications of high rates of inorganic nitrogen that is readily available for use tended to increase weed soil seedbank density in a multi-year rotation⁵⁹. Dieleman et al.⁵⁷ noted that patches of high weed populations in a field were associated with high fertility spots.

5.2.7. Stale seedbed

By definition, a stale seedbed involves preparing the seedbed for planting several weeks or months prior to crop planting/transplanting¹¹². Under moist soil conditions, many weed seedlings emerged within six weeks of cultivation²¹. However, under dry conditions this period of emergence extended to 13 weeks after cultivation, with emergence peaks correlated with rainfall events. It is apparent that the level of soil moisture coupled with soil temperature will be the two most important factors in determining when weeds will emerge following cultivation. When employing stale seedbed weed control, it is critical to encourage germination and emergence of the maximum number of seedlings and then apply some type of control measure, such as cultivation or an appropriate herbicide, to eliminate the weeds prior to crop planting^{21, 112}.

A stale seedbed that was power tilled twice (two weeks prior to planting and again just prior to planting) had fewer weeds and greater cucumber yields than a stale seedbed that was treated with an application of glyphosate¹¹². The lack of control of Florida pusley (*Richardia scabra* L.) by glyphosate resulted in reduced cucumber yield. Relative to other shallow tillage implements, the power tiller was recommended as the best implement because it pulverized the soil and provided a seedbed that promoted weed seed germination due to increased soil-seed contact¹⁹⁸.

Caldwell and Mohler³¹ reported that while stale seedbed treatments did not eliminate weed presence, it was effective in reducing the density and biomass of the principal broadleaf weeds- common purslane (*Portulaca oleracea* L.) and common chickweed [*Stellaria media* (L.) Vill.]. Single application of glyphosate or a flame weeding in the stale seedbed reduced weed densities relative to the nontreated control. Controlling weeds with single or multiple spring tine harrow treatments or a single treatment with the rotary tiller were not as effective and neither treatment reduced weed density relative to the nontreated control. None of the stale seedbed techniques were effective at reducing yellow nutsedge densities.

5.2.8. Cover crops and biodegradable mulches

For cover crops to be successful in weed control, sufficient plant residue is needed to cover the ground surface for impeding weed seed germination and/or emergence. A review of literature by Teasdale²³⁶ indicated that weed control increased with increasing biomass of the cover crop residue. The efficacy of cover crops in suppressing weeds was weed specific, being most effective in suppressing emergence of small seeded annual weed species with a light requirement for germination (e.g. redroot pigweed).

While cover crops can provide suppression of some weed species, they will often be a component of a weed management system, not a stand-alone weed management treatment. Residue levels of 4,372 to 6,390 kg ha⁻¹ was needed to reduce annual grass populations by 90% and 11,210 to 12,892 kg ha⁻¹ to reduce other species [e.g. redroot pigweed, common lambsquarters, common chickweed, curly dock (*Rumex crispus* L.)]^{148, 236}. Cover crop mulches that included fall planted mixtures of hairy vetch, rye, crimson clover, and barley suppressed weeds as well as herbicide plots⁵³. In a reduced tillage transplant tomato cropping system, a rye cover crop killed with glyphosate suppressed weed emergence for four to eight weeks at a level similar to an herbicide-treated conventional tillage system. However, all treatments required additional weed management to achieve commercially acceptable levels of control. Smeda and Weller²²² found high levels of weed control (80%) from rye residues for four to five weeks in transplanted tomatoes, with crop yields similar to bare ground weed-free controls. Zasada et al.²⁶⁵ observed that successful weed suppression was related to weed density. Low densities of common lambsquarters (20-40 weeds/m²) were suppressed by a rye cover crop, while high densities of common lambsquarters (150-170 weeds/m²) were not suppressed.

In pumpkin, the lowest weed populations and weed biomass accumulation occurred in plots with a ladino clover (*Trifolium repens* L.) cover crop, however re-growth of the ladino clover interfered with crop growth⁸³. A study in Arkansas evaluating several cover crop mixtures for their effectiveness in suppressing weeds in sweet corn concluded that those most effective in reducing weed growth (wheat, rye, and rye + hairy vetch), also reduced sweet corn emergence, height, and yield³⁰. By contrast, Dyck and Liebman⁶² observed crimson clover cover crop in sweet corn effectively suppressed common lambsquarters emergence and growth without affecting sweet corn. Relative to the non-residue control, biomass of common lambsquarters was reduced 46% and 26%, respectively, at 23 and 53 days after planting.

Living mulches are another type of cover crop in which the objective is to suppress weed germination and growth through competition with an established living cover crop that coexists with the cash crop²³⁶. Usually this type of system will require some means of preventing the living mulch from interfering with the growth of the crop (e.g. herbicide application or mechanical cultivation)^{70, 236}. Cabbage and broccoli have been grown successfully in strip-tilled areas in living clover mulch^{52, 156}. Broccoli yields and crop quality were equivalent when the crop was grown in common purslane living mulch and in a conventional, herbicide-intensive system⁷⁰.

Natural biodegradable mulches have also been used for suppressing weed population in vegetable crops. Monks et al.¹⁵⁰ observed that chopped newspaper applied to a depth of 7.6 cm controlled grass weeds at least 90% (large crabgrass and barnyardgrass) and broadleaf weeds 94% [common lambsquarters and Virginia copperleaf (*Acalypha virginica* L.)]. Wheat straw was not as effective as chopped newspaper in controlling weeds. Newspaper mulch applied to a tomato cropping system two to four weeks after crop transplanting resulted in weed control and crop yields similar to conventional herbicide treatments. Schonbeck²¹⁹ found that hay mulches applied several weeks after tomato transplant to a depth of 10 cm, corresponding to rates of 15 to 24 Mg·ha⁻¹, reduced weeds and labour costs relative to the non-mulched control. Another study indicated that weed control increased as the weight of imported plant residue increased from 6 to 24 Mg·ha⁻¹ and these mulches generally provided better weed control than did frequent tillage in a conventional system¹². However, one of the largest drawbacks to using imported plant mulches is that they can be difficult to apply over large acreages.

5.2.9. Soil solarization

Solarization is a technique that uses solar energy to raise soil temperatures in an effort to control pests. The effectiveness of solarization will depend upon many factors, including soil moisture, cloud cover, surface residues, and will usually require some type of polyethylene mulch. The efficacy of solarization for controlling weeds is a function of two factors: temperature and duration of exposure, when combined are referred to as thermal time. High temperatures will require a shorter duration of exposure than will low temperatures. The knowledge of thermal time on weed propagules (e.g. seeds, tubers, rhizomes, bulbs) for a given species will be needed to successfully utilize solarization¹⁰⁷. Clear polyethylene mulch has been found to be most effective in increasing soil temperatures. Soil temperature under clear polyethylene mulch is elevated because light will penetrate the mulch, but heat cannot be dissipated by evaporation. Clear plastic mulches have been documented to raise maximum soil temperatures up 8°C higher than black opaque mulches, to a maximum temperature of 40°C at a depth of 4 cm¹⁷⁰. A similar study found that clear plastic mulch and a heat retentive mulch raised soil temperatures at 10 cm depth to greater than 45°C, while black opaque mulch could not³⁷. Solarization is often most effective during the hottest part of the summer, with clear and sunny days.

The relative susceptibility of many weed species to soil solarization has been reviewed in detail⁷¹. Egley⁶⁶ found that the numbers of viable common cocklebur (*Xanthium strumarium* L.) and prickly sida (*Sida spinosa* L.) seeds were reduced 91% and 94%, respectively, from a one-week solarization in the mid-summer in Mississippi. On a typical day, soil temperatures in this study exceeded 60°C at 1.3 cm depth and 55°C at 5.1 cm depth for 4 hours, beginning at noon. Seed viability of johnsongrass, (*Sorghum halepense*), common purslane, and pitted morningglory (*Ipomoea lacunose* L.) was not reduced by soil solarization relative to the nontreated control. Weed emergence following solarization for 14 weeks was reduced 77% with a 90% or greater reduction in the emergence of redroot pigweed, prickly sida, and pitted morningglory.

Weed species have been shown to have differential tolerances to heat treatments. Viability of prickly sida and common cocklebur seeds was eliminated by a heat treatment of 60°C for 12 hours in moist soil⁶⁸. Similarly, a treatment of 50°C for 72 hours eliminated common cocklebur seed viability in moist soil. Seed viability of common purslane, redroot pigweed, johnsongrass, and spurred anoda (*Anoda cristata*) was reduced at least 88% from a treatment of 70°C for 72 hours in moist soil. Lethal temperatures for dried seeds of redroot pigweed wild mustard (*Brassica kaber*), and common lambsquarters were 85°C, 95°C, and 95°C, respectively¹⁰⁶. Weed seeds in moist soil were more sensitive to the lethal effects of temperature than those in dry soil⁶⁷. As some seeds were capable of surviving in moist soil at temperatures of 60°C and 70°C, it is unlikely that solarization will eliminate all weed seeds.

Rhizomes of johnsongrass and common bermudagrass (*Cynodon dactylon*) were very sensitive to heat treatments. Heating treatments of 40°C for 30 minutes reduced bermudagrass and johnsongrass emergence at least 90%, relative to the nontreated control²⁰⁴. Emergence of these two weeds was eliminated by a 50°C treatment for 30 minutes. By contrast, purple nutsedge tubers were reduced only 20% from a 60°C treatment for 30 minutes and required a treatment of 90°C for 30 minutes to eliminate emergence²⁰⁴.

Clear polyethylene mulches have been shown to reduce the number of nutsedge spp. shoots relative to white (black mulch painted white) polyethylene mulch³⁹. Chase et al.³⁷ found that purple nutsedge shoot densities were reduced at least 78% by clear polyethylene mulch (30 micrometer or 1.2 mil) and exceeded 95% reduction with thermal-infrared-retentive films after six weeks of solarization. Laboratory studies indicated that diurnal maximum temperatures of 50°C for six hours, followed by a gradual temperature reduction to 26°C, eliminated purple nutsedge tuber viability after two weeks³⁸. A 200-day solarization reduced purple nutsedge populations 59% and increased yields of carrot, cabbage, beet (*Beta vulgaris*), and green bean at least 28%¹⁹⁰. While high temperatures will be needed to completely eliminate weed

propagules (i.e. seeds, tubers, rhizomes, creeping roots) of many species from the soil, integration of solarization as a component in a larger weed management system may be an option to reduce populations of heat-susceptible weeds ⁶⁷.

5.2.10. Field cultivation

Timing is critical for cultivation to be effective in weed control. Weeds are easy to control with cultivation when they are small. Cultivation efficiency is maximized if conducted after weed germination, but prior to weed emergence (often referred to as the white thread stage), approximately three to seven days after crop planting ⁹¹.

The flex-tine cultivator (spring-loaded, finger-like tines that vibrate in the soil) was not an effective stand-alone program for weed control in broccoli and snap beans ⁴⁴. While this implement was effective at controlling small weeds (cotyledon stage), it was unable to manage larger weeds. By contrast, the brush hoe was more effective than a flex-tine cultivator under a variety of conditions in controlling weeds that were larger than cotyledon stage. The brush hoe is a PTO-driven rotating cylindrical brush that rubs weeds from the surface of the soil with shields that protect the crop from the action of the bristles ⁴⁴. The brush hoe also is capable of providing significant control of in-row weeds, in addition to the between-row weeds that are targeted by most cultivators. Researchers have found that a single cultivation was capable of controlling weeds such that a reduction in crop yield was averted in cabbage and broccoli ^{44, 250}. Combining these two implements was ideal; using the flex-tine cultivator to target small weeds followed by brush hoe cultivations as the crop grows larger was very effective ⁴⁴. Timely cultivation of snap beans and sweet corn may need to be supplemented with herbicides in order to prevent a yield loss due to the slow growth rates of these species in the early season ⁴⁴.

Parish et al. ¹⁶⁸ recommend the use of a rotary tiller cultivator with smooth guide wheels without the addition of the rolling cultivator for the first cultivation when both the vegetable crop and weeds are small. For subsequent cultivations, when the vegetable crop is large enough to allow for higher cultivation speeds without crop damage, a sweep cultivator with smooth guide wheels and rolling cultivator gangs is preferable. In addition, using crop transplants allows for uniformity in crop stand and creates a height differential between weeds and the crop, allowing for increased selectivity during cultivation ⁴⁴.

Effective weed control with cultivation is as much an art as it is science. Science can define the principles needed for effective weed control and predict an outcome. However the knowledge of how to accomplish the task under a given set of conditions (soil type and moisture, weed type and size) is required ⁹¹.

5.2.11. Flame cultivation

Flame cultivation can be an effective, non-herbicidal option for controlling weeds in many crops. The most common use of flame cultivation in vegetables is to target emerged weed species prior to crop planting ¹⁶⁹. One flame cultivation four days after irrigation and just prior to transplanting lettuce reduced weed seedling densities 86% when average weed height was 0.4 cm ¹¹. The commercial use of a flame cultivator dates back to at least the 1940's, though patents for flaming equipment were granted in 1852. An excellent review of flame cultivation and its development over the years can be found in Parish et al. ¹⁶⁹.

Aside from the initial investment in equipment, the primary cost of this method of weed control is in the purchase of propane fuel. Intense heat from flame cultivation ruptures cell walls causing plant death ¹⁶⁹. Weeds should be less than 5 cm tall and if used in an emerged crop, then the crop should be at least double the size of the weeds for maximum weed control and minimum crop injury ¹⁶⁹.

Weed species that had unprotected growing points (e.g. common lambsquarters and common chickweed) were susceptible to flame cultivation ^{8, 155}. Effectiveness of flame cultivation was also related to plant size. Sensitive species with 0- to 4-true leaves were controlled 95% with propane doses of 10 to 40 kg·ha⁻¹ ⁸. Weeds with 4- to 12-leaves required propane doses of 40 to 150 kg·ha⁻¹ for 95% control ^{8, 11}. Weed species with protected growing points, like shepherdspurse [*Capsella bursa pastoris* (L.) Medic.], tended to regrow following flame cultivation unless the plants were very small at the time of treatment ^{8, 155}. Annual bluegrass (*Poa annua* L.) could not be controlled with a single flame cultivation treatment, regardless of plant size or propane dose ⁸. Integration of flame cultivation with mechanical cultivation and/or herbicides is recommended as flame cultivation alone will often not control all weeds ¹⁶⁹.

5.2.12. Biological control

Due to the limited number of herbicide options in vegetables, biological control has been viewed as one alternative for weed management^{35,36}. Biological control has been successful in perennial cropping systems (e.g. rangelands) where the weed and control agent can equilibrate over time. In classical biological control, eradication of a weed population is not the ultimate objective. Instead, the goal is to reduce the weed population and/or competitiveness of the weed with the crop. Low densities of the weed are desirable in order to maintain populations of the control agent. Classical biological control in a frequently disturbed, short-growing season vegetable production system is not likely to succeed.

The potential to release high populations of a biological control agent to eliminate weed presence has been explored¹³⁹. Researchers have identified, isolated, and demonstrated the efficacy of potential biological control agents for yellow nutsedge and purple nutsedge^{114,180}. Rust caused by *Puccinia canaliculata* has been shown to kill over 90% of nutsedge leaves by the first week of June and inhibit tuber production over the course of the season¹⁸⁰. The range of this rust is reported to include Massachusetts to California and south to Florida and has been shown to be specific to yellow nutsedge. Beste et al.¹⁶ did not find any reduction in yellow nutsedge populations or increase tomato yields one year after application of *Puccinia canaliculata* in a tomato system. Yellow nutsedge tuber biomass, however, was reduced and there may be a fit for this particular biological control agent in multi-year weed management systems.

Kadir and Charudattan¹¹⁴ found that *Dactylaria higginsii*, a fungus, effectively attacked many weeds within the *Cyperaceae* family, including purple nutsedge, yellow nutsedge, and green kyllinga (*Kyllinga brevifolia* Rottb.). Weed shoot numbers, weed shoot dry weight, and weed tuber dry weight were reduced at least 67%, while all of the crops tested were not affected by the fungus. Greenhouse studies demonstrated that this fungus affected weed-crop interference. While purple nutsedge densities of 160 tubers/m² were shown to reduce tomato yields 68% in the absence of *Dactylaria higginsii*, tomato yields were not reduced by this density of purple nutsedge, relative to the weed-free control, when *Dactylaria higginsii* was included in the system¹¹⁵. However, field evaluation of this system especially under sub-optimal humidity will be needed to determine the full potential of this fungus in weed control.

Other researchers have isolated potential biological control agents for common purslane and pigweed species^{158,203}. Common purslane was defoliated (>80%) when attacked by the leaf mining sawfly (*Schizocerella pilicornis*) larvae and a foliar-feeding weevil (*Hypurus bertrandi*), reducing weed growth >60% in a field study¹⁵⁸. However, while causing significant injury to common purslane, other weed management techniques were still required. Three species of pigweeds; slender amaranth (*Amaranthus viridis* L.), livid amaranth (*A. lividus* L.), and spiny amaranth (*A. spinosus*); were controlled when treated with the fungus *Phomopsis amaranthicola* (6 x 10⁷ conidia/ml)²⁰³. There was evidence to suggest that weed susceptibility to this fungus decreased with plant size.

5.2.13. Herbicides

Although a variety of weed control strategies have been discussed up to this point herbicides remain important in weed control. Herbicides have dramatically altered vegetable production by eliminating the need for mechanical weed control.

The following considerations should be kept in mind while selecting herbicides for application: 1) the weeds that are present or expected to appear, 2) the soil characteristics (such as texture and organic matter content), 3) the capabilities and limitations of the various herbicides, including the spectrum of weeds controlled, 4) the best herbicide application method (i.e. preplant incorporated into the soil, pre-emergence surface applied, or post-emergence to the crop), and 5) any special consideration such as rotational restrictions.

During the first eight weeks after planting for most vegetables, fields should be checked at least weekly to determine the need for foliar-applied herbicides or cultivation. After eight weeks, fields should be checked periodically to evaluate the success of the weed management program. As previously mentioned, if weeds are controlled for the first eight to ten weeks in most vegetable crops, then crop loss can often be avoided since later emerging weeds seldom have much effect production or value.

Properly selected and applied herbicides are effective weed management tools. Herbicides can be selective, in which unwanted plant species (i.e. weeds) are controlled without significantly damaging desired plant species (i.e. crop), or they can be non-selective, in which all or most vegetation is controlled. Herbicides can be applied to the soil to prevent weeds from emerging or sprayed over the top to kill weed plants.

Herbicides applied to the soil are either sprayed to the surface or mechanically mixed into the soil. Soil-surface-applied herbicides often provide poor weed control when rainfall or irrigation does not occur within one week of application. On the other hand, herbicides that are mechanically mixed into the soil are often more effective when inadequate rainfall

occurs after application. The success of soil-applied herbicides depends upon moisture for herbicide activation and the presence of a high concentration of the herbicide in the upper 5-cm of the soil. This is where most annual weed seeds germinate, thus if the herbicide is located too shallow or too deep, then weed control will be jeopardized.

Herbicides applied to plant foliage are often classified as either contact or mobile herbicides. A contact herbicide causes injury only to the tissues of the plant to which it is applied. Paraquat (Trade names: Gramoxone Max, Boa) is an example of a contact herbicide. With contact herbicides, adequate spray volume and weed coverage is critical, as the herbicide will usually not move within the plant. Mobile herbicides, for example glyphosate (Trade name: Roundup, others), are able to translocate or move throughout the plant. Thus, these mobile herbicides may be applied to one portion of the plant (leaf) and move to another portion of the plant (roots) often traveling through the plants xylem and/or phloem. The addition of an adjuvant (e.g. surfactant or crop oil concentrate) with most foliar-applied herbicides is often recommended to enhance spray coverage and plant absorption of the herbicide. The manufacturer may add adjuvants prior to marketing a product or may recommend applicators add a specific adjuvant to the spray tank when applying the herbicide.

Soil-applied and foliar-applied herbicides that are selective and non-selective are available for most vegetable crops. When these products are used according to recommendations, they can control various weeds effectively and efficiently, reducing labor inputs, and increasing economic returns to the growers^{54, 61, 147}.

Rotating crops and selecting a different herbicide program for each crop effectively prevents the buildup of problem weeds and helps keep the overall weed population at lower levels. Crop rotation and properly planned herbicide rotation will also hinder the selection of herbicide-resistant weed biotypes and thus increase sustainability.

Many herbicides persist in the soil. This makes it unsafe to plant crops that are not tolerant of the herbicide until enough time passes for the herbicide to dissipate⁹. When developing herbicide programs for crops that will precede or follow a specific vegetable crop, rotation restrictions for each herbicide must be considered. This information can be found on herbicide labels. Many commonly used herbicides such as sethoxydim (Poast), glyphosate (Roundup, others), and paraquat (Gramoxone Max, Boa) do not carry over to the following crop. However, many herbicide labels contain significant rotational restrictions to many vegetable crops and can pose a serious threat if not followed closely^{84, 111}.

6. Insect Management

Integrated pest management (IPM) is defined as “an ecologically based pest control strategy that relies heavily on natural mortality factors such as natural enemies and weather, and seeks out control tactics that disrupt these factors as little as possible”⁷⁴. This concept is compatible with sustainable pest management since it emphasizes an ecological balance rather than ecologically disruptive pesticide control measures¹⁷². IPM is recognized as a primary tool for sustainable agriculture in both the USA and around the world^{218, 242}. However, insect management in commercial vegetable crops in the USA still typically consists of intensive measures like chemical pesticides even though the total amount of pesticides used has declined during the last decades. Pesticides continue to be included in discussions on sustainable agriculture⁶³ and it appears that pest management practices are slow to change. However, it is fairly evident that sustainable practices will require much less dependence on a single tactic approach such as pesticides. One major problem in vegetables is that they are generally high-value crops whose market value can be affected as severely by slight blemishes in the appearance, as the direct reduction in yield. Given the high risk to value posed by insect pests, how do we approach vegetable insect management in a way that abruptly reduces dependence on the traditional calendar spray programs?

Over the last four decades, IPM has become a standard for sustainable pest management in vegetable production systems,^{72, 94, 159, 216}. Integrated pest management attempts to employ all possible control tactics into a unified, and balanced, system approach usually in the context of an IPM model. The more robust/complex IPM models in crops (e.g. the POMI model⁸⁵, the CIC-EM model²², the ICEMM model¹⁵, and the TEXCIM-40 model²²⁶) consider short-term costs as well as some long term costs in the development of decision criteria for the use of pest control tactics. Vegetable IPM has great potential for improving the sustainability of fresh produce in the USA⁸⁸, but whether or not IPM has been fully understood and widely accepted by consumers on a worldwide basis is debatable^{89, 249}. One serious obstacle is the complexity of pest management systems¹⁶⁶, another is the lack of a streamlined approach that allows for quick understanding and implementation by producers.

IPM models certainly can be simplified to certain basic components needed for implementation on a given farm. It has been proposed that an IPM program can be condensed down to three simple components: 1) arthropod pest identification and classification, 2) selection of pest management tactics, and 3) development of decision criteria for the potential use of tactics¹⁹¹. Pest management tactics are defined here as any activity implemented by a pest manager for the expressed purpose of mitigating economic damage to a crop by a pest organism. Examples include the use of biological control

agents, pesticides, use of traditional host plant resistance, cultural pest controls, pheromone traps, genetically engineered resistance, and many others.

6.1. Identification and classification of the Arthropod pest problems in vegetables

Vegetable crops are diverse and in addition the arthropod complexes associated with each crop can be diverse. Geographical location of the vegetable production areas can have a tremendous bearing on the type and intensity of pests that occur in a particular system. For example, the primarily spring-summer onion production in New York typically has only two major insect pests, the onion thrips (*Thrips tabaci*) and the onion maggot (*Delia antiqua*)¹⁰³, whereas in winter onion production in Georgia, western flower thrips (*Frankliniella occidentalis*), tobacco thrips (*Frankliniella fusca*) and seedcorn maggot (*Delia platura*) are important. California has bulb mites (*Rhizoglyphus* spp., *Tyrophagus* spp.), maggots (seedcorn maggot as well as onion maggot), pea leafminer (*Liriomyza huidobrensis*), thrips (onion and western flower thrips), and wheat curl mite (*Eriophyes tulipae*) as potential pests. From these few examples it is obvious that geographical location can greatly affect pest diversity. Also, it should be noted that specific production areas utilize different seasons for growing. Summer vs. winter production can have major consequences on the pest complex for a given region. Even when dealing with the same species of insect, there can be differences in biotype (e.g. whiteflies; Brown et al.²⁴) and response to insecticide (e.g. whiteflies; Wolfenbarger et al.²⁵⁹) across regions. Thus, accurate and detailed identification is critical for developing an IPM program.

6.2. Pest impact and classification

From a pest management stand point, the level of inputs and acreage can have direct bearing on the management of a specific pest and pest classification in terms of its economic impact. For example, if a soil insect population of wire worms was distributed in uniform clumps and attacked tomato and watermelon (*Citrullus lanatus* L.) plants equally, the cost of damage from a clump of wire worms in a tomato field would be much greater than in watermelon based on simple distribution of resources alone. In addition, since the total budgeted cost per acre is greater in staked tomato than watermelon, the budget amount available for pest control in tomato will tend to be proportionally greater (e.g., \$336 for tomato; Westberry and Mizelle Jr.²⁵⁵ vs. \$92 for watermelon²⁵⁴).

Classification of vegetable pests can be done in various ways, for example by the plant part they damage (e.g. foliage, fruit, root pests) or their taxonomic classification (*Lepidoptera*, *Homoptera*, etc.). One very useful way for making pest management decisions is to rank them in terms of relative importance or potential economic impact to the vegetable crop. This is subject to change over time with the introduction of new pests, changes in the level of pest populations due to external factors, such as insecticide resistance etc. and therefore needs annual updating. It is important to recognize that at best a potential for economic damage can be estimated before the cropping season begins, but a simple low=no control action required, medium=potential action required, and high=action required most seasons categorization is useful for planning an IPM program. Another useful way to categorize pests relates to when control actions are needed to be taken relative to the time line of the vegetable growing season. Specifically, actions can be used as either prevention, avoidance or as cure based on interactions between pest population dynamics and crop phenology and the availability of control tactics. For the purpose of this categorization, preventable pests are those that can be eliminated or reduced to non-economically important population levels with pre-season control tactics. Avoidable pests are those whose damage can be mitigated with tactics used during the season that don't directly kill the pest, but avoid economic damage to the crop, such as changing planting dates. Curable pests are those that can be killed or reduced to populations below economic injury levels¹⁰⁰ with existing controls such as augmentative release of biological control agents or pesticide sprays. It is important to categorize pests once they have been systematically identified so that the pest manager can interpret the basic information provided in this first component. All of this information will be needed in the selection of control tactics and establishing of decision criteria for their eventual use. An example of the control strategies for staked tomato for south Georgia, USA is given in Table 4.

Table 4. Arthropod pests of staked tomatoes, their economic importance, and methods of control.

Pest	Importance ¹	Control category ²
Thrips	high (virus)	a, c
Armyworm complex	high	c
Tomato fruitworm	high	c
Cabbage looper	high	c
Hornworms	high	c
Aphids	medium (virus)	a, c
Stinkbugs	medium	c
Whiteflies	medium (virus)	a, c
Tomato pinworm	medium	c
Leafminers	medium	c
Mites	low	c
Flea beetles	low	c

¹ Based on observation from 1996-2001 in Georgia (major associated pest in parenthesis).

² p=preventable (e.g. plow source fields), a=avoidable (e.g. early planting date), c=curable (sprays).

6.3. Selection and integration of control tactics or sustainable practices

Some major insect pest control tactics available for vegetable crops that have been traditionally used are listed in Table 5. One of the major tactics that has been promoted as the most effective way to move toward sustainable pest management in vegetables is biological control, either classical, augmentative, conservation or other forms¹⁰². The basis for this philosophy is that diverse natural control or increased biodiversity is self sustaining when more balanced equilibriums can be obtained in an agroecosystem⁶. Other major tactics that have been suggested as critical to sustainable vegetable production is cultural control¹⁸¹, crop management¹⁴² and host plant resistance (e.g. in crucifers¹⁶⁵ and cucurbits¹⁶⁴). Traditional breeding programs to produce resistant vegetable cultivars have resulted in various insect resistant cultivars⁶⁹ and are an established component of modern IPM. The development of host plant resistance has accelerated and should continue with the development of genetically modified vegetables with built in resistance (e.g. bt sweet corn).

Pesticides, especially broad spectrum toxins, are considered highly disruptive to the ecosystem and excessive use of this tactic can be detrimental to sustainable agriculture even though IPM can be used to moderate use. Biorational or highly selective insecticides are generally thought to be more compatible with natural enemies, but what is evident is that more balance between chemical and biological control tactics is needed¹⁷⁴. Cultural practices such as deep tillage can be disruptive, but as with biorational pesticides, some cultural practices like minimum tillage with cover crops can be much less disruptive. Reflective plastic mulches have been reported to be useful for reducing thrips-vectored viruses in tomato¹⁹³, but the plastic by-product after use can become another environmental hazard if not recycled. Minimum tillage can reduce certain pest pressure and has been shown to be effective in reducing the incidence of thrips and whitefly transmitted viruses. Other tactics such as mechanical pest barriers, pheromone disruption, trapping, etc., that can work for specific pest problems can be effective, but sometimes cost prohibitive for commercial use. Pheromone traps are generally used for pest monitoring rather than control.

6.4. Development of decision criteria for management actions

In order to develop decision criteria for the use of control tactics against a given pest or pest complex, it is useful to begin by identifying major constraints of each of the tactics in the context of sustainable practices. Also, it is useful to have an idea of the compatibility across the different tactics and their ability for integration into a system. From the list of tactics in Table 5, several general observations can be made. First, extensive use of broad spectrum chemical pesticides, although initially very effective, is not compatible with releases of biological control agents and generally leads to pest resistance, control failures, and in the worst scenario, total crop failure. However, total reliance on biological releases has also resulted in pest control failures and crop damage in the short term. Most likely, not enough biological agents are currently used in field situations because of the cost of applying a high enough rates of beneficials for effective inundative control. Highly reflective plastic mulches have been very useful in reducing insect-transmitted viruses, but the question is what to

do with the plastic residues after the mulch has deteriorated beyond its usefulness in the field. Likewise, each of the tactics listed will have certain constraints. The key to effective integration of control tactics for sustainable pest management is to have in place clear decision criteria that a farm manager can rely on for choosing a tactic or tactics, deciding when to use them, and the intensity/frequency of use. Examples of general decision criteria for vegetables are listed in Table 6.

These decision criteria have to take into consideration both short- and long-term economic and environmental sustainability. One major tool to accomplish this is the use of economic thresholds for pests or pest complexes based on economic injury levels¹⁰⁰. Generally this is determined at the crop or field level and is focused on short term goals, such as mitigating direct dollar yield loss in that particular crop. However, this can also be applied to different scales of production, e.g., regional levels in the case of determining eradication or quarantine standards, and take into consideration long-term consequences to vegetable productivity. The information for developing thresholds is based on pest-crop interaction data that determines economic injury levels for a given pest (e.g. whitefly in cantaloupe¹⁹²). These data can be complex when looking at interactions between pests, such as insect vectors of virus or other pathogens. Generally, in order to simplify the use of thresholds, only key pests with high economic impact are considered on a routine basis and occasionally other pests with medium economic impact are considered if an economic threshold is approached.

Environmental economics relative to vegetable economic thresholds can be defined fairly well¹⁰¹, but without consumer pressure for the use of sustainable agriculture, there will be reluctance to change large scale agriculture from what has traditionally been an environmentally exploitive production system. What has caused a shift in the mind set of pest managers is the prevalence of resistance to pesticides¹⁷⁴. This phenomenon has made it clear that to even maintain effectiveness of a single tactic, chemical controls, a more balanced and integrated approach will be required. In addition, EPA regulation of agricultural pest management is pushing for more sustainability in our current vegetable production systems. However, industry will not have the ability to change over to a completely new system of sustainable agriculture if it is not economically feasible. This is evident in certain reduced input, no-till systems where some vegetable crops have not been able to be economically produced. In the long-term, however, a slow shift in pest management decision criteria towards economically viable sustainable production using all tactics available for a balanced approach can be envisioned.

Table 5. Control strategies for arthropod pests of field vegetable crops

Strategy	Examples or comments	Effectiveness ¹	Control category ²
Biological sprays	<i>Bacillus thuringiensis</i> , others	high to low	c
Biological releases (field)	parasitoids, predators	low	p, c
Bio-rational sprays	spinosad, azadiractin and others	high to low	c
Chemical (broad)	organophosphates, pyrethroids, nicotinoids, and others	high, but resistance	p (pre), c
Chemical (specific)	IGR's like dimilin and others	moderate	c
Crop rotation	usually short term	low	p
Early maturing cultivars	depends on market windows	moderate	a
Eradication/quarantine	good for some isolated pests	high	p, c
Fertilizer management	affects pest-crop interaction	low	a
Host plant resistance	selected, bred or GMO's	high	p, a, c
Inter-cropping/covers	rye between beds	moderate	a
Mechanical barriers	floating row covers	high if used	p
Pheromone disruption	diamondback, beet armyworm	low to moderate	p, a
Pheromone traps	pickleworm (to trap)	low	p, a
Plant population density	can increase pest escapes	moderate	a
Planting date	good if market permits	high	a
Reflective mulch	silver plastic in tomato	high	p
Sanitation	pepper pods with weevils	high	p
Sterile release	area programs not in use	low	p, c
Tillage	no-till, minimum or selective	high	p, a
Trap cropping	where pest pressure is low	moderate	p
Water management	evening overhead irrigation	moderate	p, a

¹ Based on observation from 1996-2001 in Georgia, ² p=pest prevention, a=pest avoidance, c=pest cure.

Table 6. Management criteria for controlling arthropod pests of field vegetable crops.

Criteria	Decision “Trigger”	Control category ¹	Time of decision
Economic thresholds	predetermined action threshold for a given tactic like sprays	c	in season
Market restrictions	e.g., market windows determine plant dates and harvest, etc.	p, a	preseason
Regulatory factors	e.g., pesticide labelling, quotas, quarantines, etc.	p, c	in and preseason
Soil environmental factors	e.g., prior erosion level too high initiating soil conservation	p	preseason
Ecological concerns	wildlife habitat management	p, a	preseason

¹ p=pest prevention, a=pest avoidance, c=pest cure.

7. Disease Management

Effective disease management is dependent on the successful implementation of several tools that are geared towards preventing all diseases of a particular crop from causing losses in yield and quality. Knowledge of the types of pathogens that affect each vegetable crop grown, their life cycle and time of infection, parts of plant affected, the method of agent distribution, and the biological factors that favor disease spread is the key to choosing the most effective disease management strategy. Disease management in sustainable vegetable production systems relies on integrating cultural practices, the use of physical barriers, biological control, the judicious use of chemical controls, and other means to be effective at suppressing diseases.

7.1. Cultural practices for disease prevention

Sustainable disease management for production of any crop relies on the successful use of many cultural practices. Maloy ¹³⁶ lists three general strategies for effective disease prevention: 1) suppress inoculum development or destroy existing inoculum through tillage, crop rotation, pruning, solarization, flooding, burning, sanitation, and weed control; 2) assist crops to escape potential attack from pathogens by site selection, resistant varieties, seeding dates, planting layout, pruning and thinning, drainage, cultivation, and control of vectors or disseminating agents; and 3) regulate plant growth to minimize susceptibility by avoiding weak or lush growth, and maintaining plant vigor by proper seedbed preparation, rate of seeding or planting, cultivation, fertilization, and irrigation.

7.1.1. Site selection

Soil drainage is a primary factor affecting plant diseases and thus an important consideration in the selection of site. Soils that are poorly drained or have a high water holding capacity are more conducive to root and collar diseases caused by the water molds such as *Pythium* or *Phytophthora* ¹³⁶. Avoidance of low-lying areas in fields can also delay epidemics of the aforementioned disease agents because many of these epidemics begin in these areas and allow the pathogens to become established earlier than they would if vegetables were planted to well-drained areas only. Since many diseases are favored by high humidity often resulting from reduced air movement, locations adjacent to windbreaks may not be ideal ¹³⁶. The direction a site faces, will affect the amount of sunlight that reaches the soil or lower canopy, which in turn, affects temperature and relative humidity, thus affecting diseases.

7.1.2. Resistant varieties

Utilization of disease resistant varieties is the ideal way to reduce losses to plant diseases. If durable resistance can be incorporated without sacrificing acceptable horticultural characteristics, then this offers the single most effective disease management tool available ¹³⁶. Resistant varieties are also very useful in sustainable systems because they require low chemical inputs without sacrificing yield. However, resistant cultivars generally have resistance to one or two major diseases and may be susceptible to certain other diseases. Therefore it is important for growers to understand the

importance of the diseases in their area and the availability of varieties that are adapted to their specific growing region. Host plant resistance usually takes one of two forms: 1) horizontal- general, multigenic involving minor genes, and 2) vertical- monogenic, involving major gene²⁴³. Horizontal resistance is usually not complete but may confer some resistance to several races of a pathogen and very long lasting. Vertical resistance is usually complete but usually provides resistance to only one race of a specific pathogen. This type of resistance may not last for very long due to its highly specific nature which may be overcome by selection in the pathogen.

7.1.3. Crop rotation

Crop rotation is an age-old method of managing soilborne plant pathogens. This method works by planting non-related crops in the same area in a cycle such that pathogens cannot build up on any particular crop. If a particular pathogen attacks many host species, rotation may not be as successful, whereas if a pathogen attacks one or a few species rotation can be used successfully²⁶⁴. Also, some pathogen propagules may last longer in soil than others thus requiring longer crop rotations. Omnivorous fungi that produce thick-walled resting structures such as *Sclerotium rolfsii*, *Rhizoctonia solani*, *Pythium* and *Fusarium spp.* are soilborne fungal pathogens that are difficult to control with rotations of 1 to 2 years. However, 2 to 4 year rotations utilizing non-related, non-host crops such as corn and sorghum [*Sorghum bicolor* (L.) Moench] combined with deep turning significantly reduced inoculum of *S. rolfsii* in peanut²³⁰. Studies have also indicated that increasing the years of bahiagrass (*Paspalum notatum* Fluegge) from 1 to 3 years in a vegetable rotation decreased the severity of soilborne diseases caused by *Pythium spp.*, *Rhizoctonia spp.* and *nematodes* on snap bean and cucumber while increasing yields²³².

7.1.4. Sanitation

Pathogenic agents can live and reproduce between crops in plants that survived harvest, cull piles, and crop debris or stubble. These plant materials give pathogens a “bridge” from one season to the next and serve as initial sources of inoculum for upcoming crops. Sanitation reduces, excludes or eliminates the initial inoculum from which epidemics begin²⁴². Crop debris can be eliminated by deep plowing, burning or removal. Plowing can accelerate the breakdown of previous crop debris while temporarily increasing organic matter and soil fertility through mineralization of plant material. Burying crop debris is probably the most common and easiest to implement of the forms of sanitation. Gilbertson et al.⁸⁷ observed that populations of two bean bacterial pathogens could be reduced if deep-turned rather than allowed to remain as debris near the surface. Burning of crop residue can have many beneficial effects. First, much of the nutrition is maintained in the soil through ash. Conway et al.⁴⁸ discovered that by burning fern debris of asparagus (*Asparagus officinalis* L.) infected with *Cercospora asparagi*, *Cercospora* blight could be reduced in the upcoming crop. Burning can also kill many organisms through heat and studies have shown that both nematode and soilborne fungi can be suppressed this way⁴⁹. Removal of plant debris by pruning is mostly an important way to control plant diseases in woody plants but recently vine pulling of potato stems has been used to suppress *Rhizoctonia* tuber infections¹³⁶.

Another form of sanitation is the use of pathogen-free seed or other planting material^{10,140}. Starting with disease-free planting stock is a must in any disease management system. Proper cleaning of pathogen-infested surfaces or plant material using approved chemical or methods is also a form of sanitation. Disinfection and disinfestation are ways of removing or eliminating pathogens that are intimately associated with a host (pathogens in seeds or plants) or that are in non-vital associations with a host (seed surface, plant debris, soil, machinery, containers, working areas), respectively¹³⁶. This type of sanitation eliminates primary inoculum at the source or any place the host crop is handled.

7.1.5. Tillage

The disease suppressive effects of reduced tillage are thought to be associated with the increase of natural beneficial organisms that may compete, parasitize, or chemically suppress plant diseases⁴⁶. Ristiano et al.¹⁹⁴ determined that *Phytophthora blight* in pepper could be reduced by growing pepper in a no-till wheat cover crop. The method of disease reduction was attributed to suppression of soil inoculum movement by the wheat stubble. Sumner et al.²³⁴ obtained that while deep turning reduced populations of *Rhizoctonia solani*, populations of *Pythium spp.* were unaffected. This is because *Pythium* can survive in the plow layer for several months as free oospores and deep turning only brings up viable

oospores to the soil surface. Overall the effects of tillage on soilborne diseases in sustainable systems is poorly understood because the positive yield effects observed in reduced tillage studies may be attributed to increased water holding capacity and greater fertility rather than the impact on plant diseases ⁴⁶.

7.1.6. Soil pH and fertility

Proper fertilization and pH can be helpful in reducing incidence of certain diseases ¹³⁶. Overfertilization with nitrogen stimulates juvenile growth and predisposes plants to certain foliar diseases such as downy and powdery mildews. Underfertilization with N may lead to weak, senescent tissues that favor *Alternaria*, *Botrytis*, and *Sclerotinia* blights. Soil pH has a direct effect on several plant diseases. Alkaline soils promote common scab of potato (*Streptomyces scabies*), and *Phymatotrichum* root rot. Acid soils favor clubroot of crucifers (*Plasmodiophora brassicae*), southern blight (*Sclerotium rolfsii*) and many plant parasitic nematodes. Nutrients such as P and K promote tissue maturation and increase plant hardiness thereby reducing disease susceptibility.

7.1.7. Plant spacing and intercropping

Plant density can reduce or increase plant disease losses. High plant populations can create dense canopies, which in turn, create microclimates favorable for disease development ¹³⁶. Dense plantings can stay wet longer because of reduced sunlight penetration and poor air circulation ⁹⁶. Wide plant spacings have been shown to reduce losses to some diseases due to the distance the pathogen has to travel to reach the host. Onion white rot (*Sclerotium cepivorum*) cannot grow through soil and must spread by contact between two plants. Thus, if onion plants are spaced well apart, disease is suppressed ¹³⁶.

Intercropping reduces disease infestation by creating a barrier to the movement of aerial inoculum and of insects that transmit diseases ^{237, 238, 240}. Allen ⁵ indicated that induced resistance through pathogen interactions and increased distance between plants are possible reasons for decreases in disease with intercropping.

7.1.8. Irrigation and water management

Water is an important influence on disease development and dissemination. Agrios ⁴ states that moisture influences diseases in the following manner: 1) affects fungal spore germination and penetration of the host by the germ tube; 2) activates bacterial, fungal, and nematode pathogens that invade plants; 3) moisture in the form of splashing, running and mechanically moved water aids in pathogen dispersal on the same plant or from plant to plant; and 4) too much water creates more succulent plants thus increasing their susceptibility to certain diseases. Peet ¹⁷³ summarizes the useful water management practices for disease control as: 1) planting in wide rows arranged so as to increase air flow between rows; 2) irrigating early in the day so as to give plants a chance to dry before evening; 3) working with plants only when foliage is dry to reduce pathogen spread; and 4) taking into account the types of diseases and the conditions that favor them in determining irrigation frequency.

7.1.9. Mulches and trellises

Mulches and trellises can reduce losses to plant diseases in the following manner: 1) reducing splashing or water movement as a method of dispersal of pathogens by creating a barrier between the soil surface and the host crop; 2) preventing direct contact between plant parts and the soil surface which prevents diseases transmitted directly from the soil; and 3) causing feeding disruption of insects that transmit diseases ^{136, 240}.

7.1.10 Solarization

Reduction of plant pathogen and nematode populations using solarization can be an effective, non-chemical means of reducing crop losses to these pests ^{116, 117}. Ristiano et al. ¹⁹⁵ showed that soil solarization six weeks prior to planting significantly reduced southern blight caused by *Sclerotium rolfsii* in bell pepper. Keinath ¹¹⁸ demonstrated that soil

solarization was as effective at reducing belly rot of pickling cucumber caused by *Rhizoctonia solani* as the recommended chemical chlorothalonil. Solarization actually significantly increased the value per hectare of picking cucumber compared to chlorothalonil in one of three years in the aforementioned study.

7.2. Biological disease Control

7.2.1. Organic amendments and composts

Plant diseases can be suppressed by the use of organic soil amendments either by increasing microbial activity, increasing competition and/or antagonism of pathogens by beneficial biological organisms, or by reducing the inoculum potential by stimulating the germination of *hyphae* that is soon followed by lysis⁵⁰. Studies in California have indicated that the incidence of corky root caused by *Pyrenochaeta lycopersici* was higher on conventionally managed farms than on farms managed organically²⁶². Lower microbial activity of the conventionally managed soil was thought to be the cause of the higher incidence of corky root. Chitin soil amendments have been shown to suppress nematode populations by increasing the chitin-feeding microflora of the soil²⁰⁰. These chitin-feeding organisms produce chitinase that degrades the nematode body wall.

Composts have also been shown to decrease plant diseases. Composting enhances the proliferation and diversity of the soil microflora. Hoitink et al.¹⁰⁵ indicated that there were two main mechanisms of disease suppression with composts, “general” and “specific”. Examples of general suppression are: 1) competition for nutrients by microflora proliferation suppresses *Pythium* and *Phytophthora* diseases; and 2) general antibiotic production by compost enhanced soil microflora produce non-selective toxins that suppress plant pathogens. Examples of specific suppression are: 1) hyperparasitism of which the fungus *Trichoderma* spp. is best known. *Trichoderma* spp. suppresses both *Rhizoctonia* and *Sclerotium rolfsii*; 2) specific antibiotic production against specific pathogens; and 3) systemic acquired resistance¹⁰⁴. The primary constraints on the use of composts for suppressing plant diseases are compost quality and consistency¹⁰⁵.

7.2.2. Biopesticides

Biological antagonists of plant insects occur naturally in nature and can be manipulated to suppress insect infestation in cropping systems. These naturally occurring pest management tools are collectively known as biopesticides. They consist of beneficial organisms (bacteria, viruses, fungi, and protozoa), beneficial nematodes, biochemical plant extracts, and plant activators that induce resistance in plants to insects or are lethal to the insects.

Biocontrol organisms suppress plant pathogens by competing in the infection court, inhibiting the pathogen using antibiotics, or directly parasitizing pathogen mycelium or spores. A fungal antagonist, *Trichoderma harzianum*, has been used successfully to treat corn and bean seeds to protect the seedlings from damping-off disease^{45, 132, 167}. Once an antagonist is released into the environment, growers would then be able to use their managerial skills to maintain populations of the beneficial organism in the field through rotational systems and soil amendments⁴⁵. Another method of manipulating biological control organisms would be by the repeated release or application of these organisms⁴⁶. *Bacillus subtilis*, the bacteria shown to have disease suppressive qualities, has been commercially formulated and registered as a broad spectrum protectant/resistant activity inducer in tomato, pepper, and leafy vegetables⁹⁹. *Bacterium Pseudomonas syringae* for *Fusarium* control in seed/storage potato, fungus *Gliocladium catenulatum* strain J1446 for the control of *Pythium* and *Rhizoctonia* in several vegetables, bacterium *Pseudomonas fluorescens* strain PRA-25 for *Pythium* seed rot and damping off in pea, snap bean and sweet corn are also available commercially¹⁶¹.

Extract from inula (*Inula helenium*) plant is available for controlling downy and powdery mildew, and gray mold in cucumbers¹⁶¹. Similarly a protein biopesticide, harpin protein, is being marketed for inducing resistance to bacterial spots, wilts, blights and certain fungi in wide range of crops¹⁶¹. Harpin is one of a class of proteins produced by *bacterium Erwinia amylovora* that causes the fire blight in apples and pears. It acts by activating a natural defense activity called system acquired resistance (SAR) in the host plant.

The use of biopesticides is still very limited and represented less than 1% of the total crop protection market in 1997¹³³. Most of the crop protection market is accounted for by Bt based products. *Bacillus thuringiensis* (Bt) is a naturally occurring soil bacterium that have been used to control caterpillars and beetles. According to Copping⁵¹, there are 185 biopesticide products (72 bacteria, 47 fungi, 40 nematodes, 24 viruses, and 2 protozoa) available worldwide for various pest control uses.

7.3. Chemical disease control

Fungicides and bactericides have been used in conventional agriculture for years for preventive and therapeutic control of plant pathogens. Broad-spectrum fumigants such as methyl bromide have been used to eliminate weeds, diseases and nematodes from soil to which a crop, usually of high value, is to be planted. However, although very effective, the continued use of these materials is expensive and heavy reliance on therapeutics as the sole means of disease control has led to problems with fungicide/bactericide resistance, contamination of soil and groundwater as well as possible ozone depletion²⁴⁸. These chemical controls, if used judiciously in a prescribed manner, can be part of a sustainable agriculture system. Knowledge of disease biology, host susceptibility and disease history in particular growing areas may determine whether fungicides are warranted.

7.4. Holistic disease management approach

Cook⁴⁹ and Conway and Power⁴⁷ formulated eight principles for holistic plant health: 1) know the yield limitations of the agroecosystem, 2) maintain soil organic matter content, 3) use crop rotations and include forage legumes, 4) use pathogen-free seed (transplants and planting stock included), 5) minimize the nutritional stress of the crop, 6) use pest resistant cultivars, 7) maximize benefits of beneficial organisms, and 8) use pesticides when necessary.

It should be noted that there are few systems where all of these inputs are available at once but usually some combination of most of these principles can be utilized. The impact of each input and how it interacts with other practices in a system needs to be evaluated individually before it can be successfully integrated into a crop management system⁶⁵.

8. Economics of Sustainable Vegetable Production

8.1. Management of vegetable enterprise

Proper management of the following factors are essential for economic vegetable production: 1) human resource and farm firm management, 2) continuous research and development, 3) continuous technological innovations, 4) improved agricultural practices, 5) compliance with vegetable market demand and regulations, 6) highest vegetable quality and productivity, 7) socio-political and socio-economic constraints, and 8) unforeseen contingencies.

8.1.1. *Human resource/ farm firm management*

Even the best business plan may not materialize without a competent management. There are risks and opportunities involved in the production of vegetables, which the farm management must know, clearly define and identify. The strategist must determine the kind of resources- material, technical, financial and managerial is needed to successfully undertake the operation. Developing a good strategy is a necessary condition for success.

It is the management's responsibility to guarantee that positive results are achieved. The setting up of an organizational structure, processes and behaviors that would create a favorable atmosphere for efficient productivity and profitability is imperative. The following questions would have to be addressed. Who will do what? Who decides if what is done is correctly executed? Is there suitable management expertise at each production level? Are there competent workers at each production level? Will a personnel development-training program be adequate? How often should re-training be scheduled? Who decides whom to hire, when and why? How do we motivate workers and which incentives are hygienic and/or would have a positive impact on the workers? Which production technique should be adopted and which machinery needs to be purchased and why? Which data needs to be collected and which record needs to be kept? Who will analyze the information collected? Who decides when and how to utilize the collected information?

Strategic managers must possess human resource management skills. They will have to deal with family, labor or business conflicts on a daily, weekly or monthly basis. There are two basic risks that every farm organization faces- financial and agribusiness. Financial risk deals with how much capital is needed to run the farm. Agribusiness risk can be subdivided into six categories: production, price, casualty, technological, personal, and miscellaneous risk and uncertainty. Determining crop yield is an example of production risk, while commodity price determination is a marketing risk. The problems caused by other business firms, partners or individuals that have direct or indirect repercussions to your company

are classified as miscellaneous risks. Since one is operating under uncertainty, the strategic farm manager would have to understand risk management strategies. Furthermore, management is responsible for maintaining farm records, farm computerized accounting system, enterprise budgeting, obtaining and utilizing agricultural loans, and maintaining environmental quality while striving to optimize profits¹²⁹.

8.1.2. *Continuous research and development*

Sustainable vegetable production requires research at all levels of the production process. To determine soil quality and soil suitability for certain vegetables, such attributes as texture, depth, structure, bulk density, pH and the electrical conductivity needs to be taken into consideration. In addition, soil fertility and management must be addressed at least annually. A soil and tissue analysis is constantly required to determine nutrient availability and possible plant uptake.

Entomological, nematological or pathological analyses are required to determine the presence of pests, nematodes or diseases. A decision to plant cucumbers for instance requires knowledge of gummy stem blight (*Didymella bryoniae*) and its control and the costs of such control. Growing cabbage, collards, carrots, and snap beans require the control of *Alternaria spp.*

Vegetables are susceptible to several fungal, bacteria, virus and nematodes. Furthermore, new disease and pest outbreaks are inevitable irrespective of the production methods adopted. Thus, constant vigilance for such incidences and knowledge of their effective control is essential for uninterrupted high crop yields. Fogain et al.⁷⁵ reported that small-scale farmers do not implement integrated pest management (IPM) techniques due to the lack of information on pests and diseases, control measures, new technologies and the lack of finances.

An economic analysis is essential to determine the feasibility of the growing different vegetables in terms of financial impact assessment, and identifying costs and benefits. Other important areas of research include fertilizer application, precision irrigation, varietal studies, etc.⁷⁶. Without continuous research and development, sustainable production at the highest level is not possible.

8.1.3. *Continuous technological innovations*

Technological innovation in agriculture is important to reduce average costs of production and to manage large-sized farms. Farmers must keep abreast of these changes to take their full advantage. It is generally agreed that early adopters of a new technology derive most economic benefit from it because of cost curve shift in their favour in comparison to the competition. Farmers, however, are always in dilemma about proper time of buying new farm equipments to benefit from the best of technologies. Unfortunately, by the time a farmer obtains the returns on his/her investment, several new models become available and the existing one is rendered obsolete. Moreover, new agricultural equipments are usually very expensive. As a result, farms tend to be highly indebted¹²⁰. Prudent purchasing decisions based on the knowledge of the full range of agricultural equipments available in the marketplace and comparative price structure, suitability of a particular model for the farm size and the objectives, competitive benefits of the acquisition, and estimated rate of return on investment would help keep equipment cost to the minimum with the maximum possible over-all return.

8.1.4. *Improved agricultural practices*

Knowledge of changes in methods of various agricultural operations and suitability of those changes to particular farm situations is essential to take advantage of new farming practices with minimum risks. A farmer who switches from tillage to no-tillage or from non-irrigation to irrigation is adopting improved agricultural practices. The same applies to a farmer who rotates crops, plants cover crops and utilizes integrated pest management. Improved agricultural practices can be expensive, thus before adoption the return on investment and long-term benefits should be weighed carefully against the costs.

8.1.5. *Compliance with market demand and regulations*

Studies and empirical evidence have proven that an appreciable number of farmers usually focus most of their attention in

the production of their vegetables. They start thinking of the market only after the crops are already planted. Most frequently, the producer's knowledge of the market's distribution channels, price and demand trend is limited. This limitation inhibits the gains that can be accrued especially of the producers committed to a particular market¹⁸⁵. Vegetable growers can target either the domestic or overseas market or both. The requirements are similar in some aspects and dissimilar in others, with the foreign market being more stringent. Compliance with market demand and regulations involves a wide range of personnel, which includes but is not limited to credit/investment banks, suppliers of seeds, planting materials, fertilizers, chemicals, machineries etc.

The vegetable marketing involves the growers, brokers/exporters, wholesalers/importers, retailers and the public sector. The growers have the obligation to produce cost-effective crops, provide agreed volume, maintain quality specifications, and supply the product at a predetermined time and schedule. They also are required to adopt satisfactory cultivation techniques also known as good agricultural practices (GAP) which includes integrated pest management (IPM), harvesting, packaging and providing required information about their crops to their customers.

The brokers/exporters have the responsibility to re-pack (if necessary), prepare product for either shipment or airfreight, arrange and guarantee transportation, develop effective communication linkages with producers/importers, alternating of intelligence, segmenting and creating new markets and guaranteeing sufficient cash flow. On the other hand, the responsibilities of wholesalers/importers include distribution and custom clearance, ascertaining and creating retail and wholesale marketing channels, guaranteeing timely sales, storage, transportation and transmitting gathered marketing information and counseling. The retailer sells the produce; provide consumer and marketing news and carries out sales promotion.

Proctor¹⁸⁵ enumerated the following as the key functions of the public sector operators in horticultural industries: 1) market intelligence, 2) inspection of quality, phytosanitary and pesticide residues, 3) research, development and extension, 4) licensing grower, exporter, trader, 5) foreign exchange provision, 6) export receipts, 7) credit, 8) infrastructure, 9) freight negotiation, 10) tax policy, 11) pricing control, and 11) exchange rate control.

Despite the complexities encountered in the export markets, there are several benefits such as (1) generation of good cash flow, (2) increasing sales volume, (3) distribution of fixed costs to a greater extent, (4) superior utilization of excess capacity, (5) neutralizing the impact of cyclical decrease in domestic sales, (6) appreciation of foreign technologies, (7) developing savoir-faire expertise needed to be competitive overseas, and (8) improve growth potential and profitability needed for sustainability^{110, 185}. An export vegetable grower must remain fully abreast of foreign market demand and all market restrictions and/or regulations. These restrictions differ from market to market and from country to country. The most common restrictions are import tariffs, import quotas and the tariff-rate quota. The import tariff is simply a tax that is imposed on all goods entering into a foreign country or market. This tariff could be a fixed amount per unit of a given product (specific tariff) or a fixed percentage amount of the total value of the product (ad valorem tariff). The import quota limits and specifies the quantity of a product that enters a foreign country or market. Import license is required prior to shipment of a product to another country. A tariff-rate quota is a combination of both the import quota and import tariff. This tariff system permits a given portion of the product preferential entrance (usually zero duty), and the excess is being taxed at a higher rate^{76, 189}.

The North America Free Trade Agreement (NAFTA) for instance, allows free entry of fresh vegetables exports from the US to Mexico whereas fresh vegetable importation from other sources are subject to various Mexican Official Standards, abbreviated as NOMs. Fintrac Inc.⁷³ reported that a 5% tariff is levied for fresh vegetables exported to Bermuda plus a 1.01% "wharfage tax" based on the value of the total consignment. The wharfage tax is a compensation for the utilization of the seaport or airport of entry.

Packaging requirement for fresh vegetables is one of the difficult obstacles for growers. There are more than 1,500 different packaging materials in the US today, ranging from cartons, bags, crates, hampers, bulk bins, rigid plastic packages, paper and mesh bags to palletized containers. This number continues to escalate with the advent of new technology and the changing behavior of wholesalers, food service buyers, processors and consumers of vegetables. Despite the high cost of packaging materials, it is very important that growers and shippers appreciate the importance and role that packaging material play in the produce industry. Also, the quality of packaging materials is crucial to the success of the product²³.

8.1.6. Highest vegetable quality and productivity

Quality is an important aspect of the vegetable industry, whether the crop is sold locally or oversea. Quality and productivity are intertwined. A grower must target the required quality, produce the required volume and guarantee continuity to be successful.

Inception of every business is as a result of a vision. Total Quality Management (TQM) calls for building a system, using methods, tools and processes to achieve that vision²⁰². Irrespective of the business sector to which one belongs, the new concept of quality centers around customer satisfaction, i.e. a knowledge of what, when and how the clients prefer the product is vital.

An integral part of the TQM is the quality of the product per se. This refers to the overall cosmetic appearance (OCA) of vegetables before, during and after harvest and the post-harvest physiology. Certain metabolic and physiological changes, which render vegetables susceptible to bacteria and fungal infestation, are inevitable^{157, 224}. Other quality problems that might affect the OCA of vegetables are physical or mechanical damage, pathological decay and even chemical injury. Physical damage may occur at each production stage i.e. from planting, harvesting, packaging, transporting/shipping, storage, ripening, supermarket and the final consumer. The study by Schenk et. al.²¹⁷ illustrates that even truck vibration during transportation of vegetables causes enormous quality damage to the crop. If quantified, this and other quality damages obtained at each production and delivery stage within the chain amounts to millions of dollars in losses to the vegetable industry.

The ISO 9000 is another aspect of TQM which is being introduced in the vegetable industry. ISO 9000 is “a set of international standards” which was adopted by the EU in 1987 and requires compliance by any country involved in business in the European Community. Initially, this requirement was limited only to the manufacturing sector. Unfortunately, the agricultural industry has been included in the equation. Larger multinational companies such as Del Monte Fresh Produce, Dole and Chiquitta are making sure that each of their divisions around the world obtains the ISO 9000 certification. Although the certification criteria are expensive, the return to investment compensates for the cost and only the early adopter benefits. The cost of obtaining certification could be unaffordable for a small firm. ISO 9001-9004 provides information on various and specific quality control processes^{187, 202}.

8.1.7. Socio-political and socio-economic constraints

The socio-political and socio-economic constraints have no direct impact on vegetable production. But, indirectly, it is a powerful factor to be reckoned with. For instance, a recent report reveals an outbreak of pepper anthracnose disease caused by two fungi, *Colletotrichum capsici* and *C. piperatum*¹²⁷. The disease is seed-borne and can be found in debris of diseased plants. Even though several control measures exist, current labelled fungicides cannot check this outbreak. Assuming that plant pathologists, after field trials, recommend the best chemical control but the government refuses to approve its use. What then will be the economic impact to the farmers especially those producing pepper or other vegetables susceptible to anthracnose, e.g. limabean (*Phaseolus limensis* L.), cucumber, eggplant, etc.? Empirical evidence of such events exists such as the ban on Bravo (chlorothalonil) and Lorsban (chlorpyrifos) in Hawaii.

8.1.8. Unforeseen contingencies

Cultivation of vegetables is a risky business and full of uncertainties. Some of the risks can be minimized, corrected or avoided, but others are left to divine intervention. The weather is a classic example. Excessive rainfall causes flooding which could be detrimental to certain vegetables. Insufficient rainfall causes drought, which has adverse effect to farming especially for those who cannot afford an irrigation system. Several studies have indicated that high and low temperatures may cause yield loss to certain vegetables in the temperate and tropical zones, respectively^{90, 92, 171, 199}.

The root temperature of certain crops is intolerant to temperature fluctuation. Low temperature is especially detrimental at the beginning stage of certain plant growth and development as it raises the stiffness of the cell wall, which subsequently affects the “turgor-driven cell extension processes”^{171, 261}. The vulnerability of the photosynthetic process in most plants renders the process the first target for heat-waves damage^{76, 199}.

8.2. Cost of sustainable vegetable production

It is not altogether clear whether sustainable production will reduce or increase costs. With less external inputs it would appear on the surface that this method of production would result in reduced costs. Less fertilizer, pesticides, and other costly items would be a source of cost savings. This may be offset by increased land requirements for crop rotation and larger tractors and specialized equipment for no-till or reduced-till production. Although it is difficult to put a price on

increased management oversight and skills, with sustainable production a more intensive management is required. Planning that requires looking several years ahead is required. Crops must be managed more closely especially where using cover crops, no-till or limited till production. Competition from weeds and cover crops can quickly reduce yields, particularly early yields, which may be the most profitable harvest for a particular crop.

Quality produce with documentation of safe production will be the hallmark of vegetable production in the future regardless of the type of production system. Sustainable production can be an important part of the increased concern for safely produced vegetables. Many buyers are requiring third party audits to document safe production practices. This can dovetail into sustainable production practices where increased management with the necessary documentation can be easily augmented with the requirements of third party audits.

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