Organic Vegetable Production in California—Science and Practice

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SUMMARY. This article summarizes the current status of organic vegetable production practices in California. The production of vegetables organically is growing rapidly in California, led in large part by growth in the market demand for organically grown produce. Key aspects of organic vegetable production operations such as certification and farm production planning, soil management, weed management, insect management, and plant disease management involve special practices. Many practices have not been thoroughly researched and the scientific base for some practices is still being developed.

Organic vegetable production in California has increased during the 1990s led in large part by expanding nationwide demand for organically grown fresh fruits and vegetables. Organic vegetables from California also are increasingly being exported to growing overseas markets. In 1995, registered California organic fruit and vegetable growers produced farm gate sales in excess of $95 million from 1452 farms. By 1998 the number of registered farms had grown by nearly 60% to an estimated 2300 (Tourte and Klonsky, 1998). These statistics are conservative however, as estimates suggest that the volume of fruit and vegetables coming from registered organic operations may be only 30% to 40% of the total volume of produce grown organically in the state (Tourte and Klonsky, 1998).

Organic agricultural operations have special needs for production, planning and management beyond those of conventional farms because of limitations imposed by organic registration and certification. New legislation may eventually establish national standards, which will require certification by a USDA-approved certifying agency. Currently, registration is a legal requirement for sale of organic produce in California and certification is a private, independent process used by growers and marketers to maintain the integrity of the organic product in the marketplace. Clearly, organic vegetable production is expanding to meet the needs of a growing market but the expansion is taking place on a very limited scientific research base.

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Registration and certification process

REGISTRATION permits the legal sale of produce or a product as organic in California. The regulating agency is the California Department of Food and Agriculture (CDFA), usually acting through the local county agricultural commissioner. The CDFA maintains a list of materials that can be used in an organic operation (CDFA, 1999) and there are strict limits on the farm inputs that are allowed. Registration requires an annual affirmation by the grower of compliance with CDFA standards. Restrictions change from year to year and additional information is available through county agricultural commissioner's offices or through the CDFA (CDFA, 1999).

CERTIFICATION is a process whereby an organic production, handling, processing, or retailing enterprise is certified as following organic production and handling practices. The certification process is regulated by private, independent certifying agencies that in turn are regulated by the CDFA. Certification allows a product to be marketed as certified organic. It is a much more complete and comprehensive process than registration and usually requires an annual farm inspection, maintenance of an audit registry of specific crop management, handling, and input use, and an affidavit of compliance. The certifying agency may also require a comprehensive long-term program for soil and pest management.

In California, registration and certification currently permit use of the terms organic and certified organic only after a period of at least 3 years during which no prohibited product has been used. CDFA permits a product to be marketed as transitional organic if the grower follows organic production practices but has not yet completed the minimum time requirement to be registered organic. Some certifying agencies will also certify transitional product.

As the organic market evolves, processors and handlers are also becoming certified and each processor or marketer may have specific certification requirements. Growers should identify their most promising markets and make sure that their certification will meet the requirements of those markets. If the product is for export, the grower uses the requirements of the countries where the product will be sold. Certifying agencies such as the Organic Crop Improvement Association are less active in California but more active internationally and may have standards that more closely correspond to the standards of some foreign markets. There is a trend overall for California-based certifiers to communicate and cooperate with international agencies to maintain broad marketing options for California growers.

Farm management

Different aspects of farm management are complicated by the special requirements for organic vegetable production management. Several of these considerations are summarized in Table 1.

Organic vegetable farmers view soil quality or health as a foundation to successful production. Outlined here are specific factors that address organic soil management.

Organic soil management

SOIL QUALITY ASSESSMENT. During the last decade, there has been considerable discussion related to assessment of soil health and the related impact of soil management practices (Karlen et al., 1997; Sojka and Upchurch, 1999). Good soil quality in one context may not be directly comparable to another and quantitative assessment is often difficult. There is, however, a growing awareness and recognition that much like air or water quality, the quality of soil has a profound impact on the health and productivity of a given agroecosystem and on the ecosystems that interface with it (National Research Council, 1993). Unlike air or water quality, for which rather rigidly defined quality standards have been established, the definition and assessment of soil quality is more problematic (Sojka and Upchurch, 1999). Parameters that are frequently identified as soil quality indicators are listed in Table 2.

ROLE OF ORGANIC MATTER AND HUMUS. Soil organic matter (SOM) content is frequently identified as a primary component of soil quality assessment and increasing soil organic matter is a goal of most organic production operations. SOM influences many soil properties including infiltration rate, bulk density, aggregate stability, cation exchange capacity and biological activity, all of which are related to a number of key soil functions (Sikora and Stott, 1996). SOM serves as a slow release reservoir for plant macronutrients, especially nitrogen (N), and also aids in plant micronutrient nutrition. It facilitates infiltration of water and air into the soil, increases water retention by the soil and is important in maintaining soil tilth. Over time, increases in SOM can lead to a larger and more diverse population of soil organisms and may thus enhance the biological control of pests and plant diseases. Large quantities of fresh organic mat-

Table 1. Special farm management considerations unique to organic vegetable operations.

Farm management
• Planning, record keeping for certification / registration compliance
• Field use, planting, or harvest timing restrictions due to certification
Crop or product mix
• Marketing limitations restrict product mix
• Certification restrictions on field management
• Limitations in organic seed or transplant availability
Material use / cost
• Bulk materials require special handling, storage
• Limitations on availability, cost, or uniformity of fertilizer or soil amendments
• Field / land use due to rotation, soil building, or cover crop management
Postharvest handling
• Chlorine use resticted to 4–10 ppm ($mg \cdot L^{-1}$) in dump tanks
• Other aspects of handling optimized to compensate for restrictions on disinfection
• New marketers and handlers lack handling knowledge or experience
• Added prewashing useful but costly
Marketing
• Little market info available due to developing markets
• New markets and marketers—restrict marketing experience

ter added to the soil, however, may stimulate plant pathogenic organisms and seed and seedling pests such as cabbage maggots (*Delia radicum* L.) and wireworms (*Limonius* sp.), which can result in serious losses. Other potentially negative implications of efforts to increase SOM as a means of improving soil quality such as increased bypass flow and transport and greater phosphorus solubility have recently been chronicled by Sojka and Upchurch (1999).

Soil organic matter contains a number of fractions of varying composition and activity. Humus is the most resistant and mature fraction of soil organic matter. It is very slow to decompose and may last for hundreds of years. Residues that are slow to decompose such as hay or corn (*Zea mays* L.) stalks are more efficient at producing humus than more readily decomposable materials such as green manure residues (Fox et al., 1990; Scow, 1997). Although relatively little is understood about the benefits of humus or other organic matter fractions on crop growth, organic crop management is often directed toward increasing total soil organic matter. Native organic matter levels are relatively low in California soils, generally ranging from less than 1% to a little more than 2%, and organic matter levels fall when the soil is brought under cultivation. Studies have shown that it is unreasonable to expect to increase appreciably overall soil organic matter (Scow, 1997) but a relatively small increase may markedly change the soil quality parameters in a given field (Colla et al., 2000).

A number of prior studies of soil organic matter related to addition of organic soil amendments and green manure have been in vitro type studies but Duxbury et al. (1989) conclude that additional applied field studies are necessary because in vitro studies "have little relevance to the behavior of soil organic matter as a source or sink of nutrients in soils". And the organic production environment may potentially alter the dynamics of soil microbial communities to such an extent that to have relevance to organic agriculture, the studies should be done in an organic production environment.

In organic production systems, soil fertility is augmented through applications of materials such as compost and manure and by the use of cover crops. Organically managed soils that routinely receive these deliberate inputs typically differ in other soil quality indicator properties besides fertility when compared to conventionally managed soils (Sivapalan et al., 1993). Two major projects that are currently underway in California's Central Valley, the Sustainable Agriculture Farming Systems (SAFS) Project in Davis, Calif., and the Biologically Integrated Farming Systems (BIFS) Project in Five Points, Calif., have compared soil quality indicator properties under different management systems including organic, and have found that organic soil management can result in fundamental differences in a number of soil health indicator properties including water infiltration rate (Colla et al., 2000), microbial biomass carbon, N (Gunapala and Scow, 1998), and disease suppression (van Bruggen, 1995) in the case of the SAFS comparison, and microbial biomass carbon and N and SOM in a number of BIFS comparisons (J.P. Mitchell, personal communication). The practical significance of these management-induced differences is the focus of intense ongoing research. Preliminary analyses from the SAFS comparison project, however, suggest that while organic systems might be leakier in terms of N losses during the transition period when relatively high N loading is often done, these systems may eventually cycle N more efficiently and thereby result in greater nutrient conservation (Scow et al., 1994).

Management of soil quality. A wide variety of practices are typically employed to maintain or improve soil health in organic vegetable production systems in California. These practices are generally part of long-term, site-specific management programs that aim at developing fertile and biologically active soils that readily capture and store water nutrients, have good tilth and suppress plant disease. Deliberate and routine carbon inputs are essential in organic production environments to achieve this goal. Special care is needed in the selection of organic carbon sources to assure short-term productivity while building long-term soil quality.

Organic soil amendments. While composts and manures are frequently considered to be mainstays of fertility management programs in organic systems, these amendments often vary widely in nutritive value and are increasingly being applied as a basic carbon source to enhance overall and long-term soil health. The carbon content of these materials is also typically quite variable, though generally ranges from 20% to 40% on a dry weight basis. Annual applications of composts and manures at rates of 3 to 10 tons / acre (6.72 to 22.4 $t \cdot ha^{-1}$) as are commonly made in organic vegetable systems in California thus add significant amounts of carbon to the soil. Though very few studies have been conducted to monitor changes in key soil quality indicator properties or processes that may result from applications of these amendments under the broad diversity of organic vegetable systems in California, the use of organic amendments is generally associated with improved tilth, lower bulk density and increased water infiltration.

Cover crops. Cover cropping or green manuring is widely seen as an important part of soil quality and fertility management in organic produc-

Table 2. Indicators of soil quality.

Physical properties	Chemical properties	Biological properties
Bulk density	pH	Microbial biomass carbon
Rooting depth	Electrical conductivity	Microbial biomass nitrogen
Water infiltration rate	Cation exchange capacity	Earthworms
Water holding capacity	Organic matter	Enzymes
Aggregate stability	Mineralizable nitrogen	Disease suppressiveness
	Exchangeable potassium	
	Exchangeable calcium	

tion systems in California. Cover crops can provide a practical and economical means for supplying organic matter, enhance soil fertility, suppress weed growth, attract beneficial insects, spiders and mites, and reduce nitrate leaching loss to the groundwater during periods between crops (Jackson et al., 1993a; Miller et al., 1989; Shennan, 1992). There may be reluctance to use cover crops in many farm operations because of limitations on planting and harvesting of summer cash crops and, in milder growing areas, organic vegetable growers may target early and late market windows. Depending on the specific cropping situation, the use of cover crops also can have potentially adverse consequences such as soil moisture depletion, temporary immobilization of plant nutrients, increased pest problems, increased management and associated costs. Recent research in the Sacramento Valley suggests that cover crop-based production systems may favorably influence annual water balances (Colla et al., 2000). Growing concern for elevated atmospheric CO_2 levels and global warming may result in even greater interest in cover crops as an important means to store carbon and to improve agricultural resource use efficiency. The key to the effective and profitable use of cover crops lies in the creative design of management options to take advantage of opportunities in which they can be grown to maximum advantage within vegetable crop rotations without excessive financial loss due to land not used for cash crops. Even with the obvious benefits of a green manure cover crop, there are limitations to green manure use.

Considerable information currently exists within California's main vegetable production regions on how to select, grow and incorporate cover crops (Miller et al., 1989). This information is readily available through county cooperative extension advisors and can be used to establish small-scale, on-farm evaluations of cover crops for specific management goals. While much of this information has been developed for winter cover crop species, several recent studies have evaluated late-summer or other nonconventional cover crop windows (S.R. Temple, personal communication). For example, while an October-planted, March-incorporated rye (*Secale cereale* L.) or vetch (*Vicia* spp.) cover crop typically produces dry matter at 10,090 , or 5,600 lb / acre (9,000 or 5,000 $kg \cdot ha^{-1}$), respectively in the Central Valley, an August-planted and November-incorporated sudangrass (*Sorghum sudanense* (Piper) Stapf) crop may provide twice as much biomass (Mitchell et al., 1999).

Cover crop species mixtures are gaining wider adoption throughout California because they may provide multiple benefits to a production system and may serve as insurance for conditions which are unfavorable to a single species. Recent research conducted in the Sustainable Agriculture Farming Systems Project in Davis suggests that legume cover crops may be particularly important factors in the development of key humic acid fractions that typically distinguish organic soils from conventionally managed soils and which may be significant indices of soil quality improvement (W.R. Horwath, personal communication).

Conservation tillage

Studies involving a variety of tillage methods indicate major gaseous losses of carbon immediately following tillage, but point to the potential for reduced soil carbon loss and enhanced soil C management through the use of conservation tillage (CT) crop production practices (Reicosky and Lindstrom, 1993). Though these practices have been developed primarily for erosion control in other parts of the US, recent concerns regarding the need to sustain soil quality in areas such as California where CT is virtually nonexistent (Conservation Tillage Information Center, 1999), as well as potential global climate change have reemphasized the importance of CT and how it might be implemented on a broader scale to help reduce soil C losses, improve soil quality, and sustain agricultural productivity.

Although CT systems are not in widespread use currently on organic vegetable farms in California, studies are underway in California on reduced tillage crop production systems and on the feasibility of using them in organic contexts. The basic feature of these systems is the use of surface organic mulches that are derived from cover crops grown off-season. Winter annual cover crops such as rye and vetch have been used successfully as both a cover crop and as a mulch in a variety of CT systems. As cover crops, these species recycle nutrients, reduce soil erosion, add organic matter to the soil and, in the case of vetch, fix N. When mowed and converted to mulch, they reduce weed emergence, lower soil temperatures during the hot summer months, reduce water loss from the soil and act as a slow-release fertilizer (Abdul-Baki and Teasdale, 1993; 1997).

Table 3. Characteristics of organic soil amendments and fertilizer materials that limit efficient use.

Nutrient availability[z]
• Rarely known
• Varies with material type, conditions
• Varies with environmental conditions
Physical or chemical composition
• May not be reported
• Inconsistent, changes during storage
• Variable, nonregulated
• Moisture content significant, variable, or unknown
Bulk
• Handling difficult, costly
• Special storage needs
• Affects uniformity of material and application
Uniformity
• Variable among materials
• Variable within a material lot
• Changes during handling, and storage
Information
• Little available
• Variable or contradictory
• Sources variable, or inconsistent

[z]For nutrition of current crop.

A major limitation to CT or cover crop mulch systems in organic crop production is the management of the cover crop so that it does not compete with or reduce the growth of the crop that is planted into it (Herrero, 1999). A wide variety of management options are currently being evaluated to accomplish this (Creamer et al., 1995). Timing cover crop maturity so it is completing its life cycle at the time it is mowed, rolled or planted into, may be a useful strategy in certain contexts. However, this approach generally assumes that planting or transplanting the vegetable crop into the cover crop mulch will not be done until late spring. Using irrigation cutoff and relying on increasing temperatures may also kill certain cover crop species so that they do not effectively compete with the vegetable crop. Given the immense array of cover crop species available for use as surface mulches, it is likely that rapid progress can be made in further refining the economic and ecological benefits of CT production systems for organic vegetable producers.

ROTATIONS. Judicious crop rotation may be useful for increasing short-term SOM and for achieving healthy, fertile and productive soils. Amounts of post harvest crop residues in organic vegetable production systems in California vary widely depending on the crop and the intensity with which it is harvested. Rotations that include small grain crops such as wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), oats (*Avena sativa* L.), rye, or triticale (*Triticum* ×*secale*), that are harvested for seed, typically add 8,970 to 11, 210 lb dry matter / acre (8,000 to 10,000 $kg \cdot ha^{-1}$) to the soil after harvest (Mitchell et al., 1999). Including these crops in a vegetable rotation may also lessen disease incidence and help with nematode control. Broccoli (*Brassica oleracea* L. var. *botrytis* L) residues typically provide nearly 7,000 kg of dry matter. Other vegetables such as tomato (*Lycopersicon esculentum* Mill.), lettuce (*Lactuca sativa* L.), onions (*Allium cepa* L.) and garlic (*Allium sativum* L.) may add on average, 2800. 1345, 785, and 560 lb / acre (2,500, 1,200, 700 and 500 $kg \cdot ha^{-1}$) dry matter, respectively.

SOIL FERTILITY MANAGEMENT. Organic growers face special challenges in developing a soil fertility program. Soil fertility and weed management have been identified as the most important factors limiting yields in low input and organic production systems in the Sustainable Agriculture Farming Systems Project trials in Davis (Chaney, 1996; Scow et al., 1994; Temple et al., 1994a, 1994b). Organic growers in California struggle to manage soil fertility in a cost effective manner given the lack of detailed information available on fertilization management in organic production systems.

The diverse types of soil amendments and organic materials often used for fertilization on organic farms in California present special problems for efficient use as a nutrient source for the current crop (Table 3). Some of these limitations, bulk, for example, also has benefits associated with the mass of organic material contributing to overall soil organic matter. The real challenge in organic systems is to build overall soil organic matter while providing adequate nutrition to the growing crop essentially through organic matter decomposition processes.

DETERMINING NUTRIENT REQUIREMENTS. Soil testing is essential to assess nutrient levels. Regular field testing is often a requirement for organic certification. Fertilizer recommendations based on soil tests are site and crop specific and are usually adapted from conventional fertilizer trials. In rare cases, this information may be complemented by specific organic field data, but few controlled field trials have been conducted to determine crop response to organic amendments in organic production environments. A soil test has limited use as an indication of N availability or N fertility requirements and vegetables are quite selective and variable with regard to timing and rate of N use.

Management of nutrients such as phosphorus (P), potassium (K), sulfur (S), calcium (Ca), and magnesium (Mg) is often directed toward raising these levels to optimum levels in the soil nutrient pool as determined by a soil test. Many cultivated soils in California have relatively high levels of P, K, S, Ca, and Mg. These nutrients will accumulate in soils and reach relatively high levels and thus are often not as critical to manage as N. Broadcast additions of these nutrients may occasionally be made before planting to assure availability or to prevent depletion in the soil pool. And organic growers typically apply these materials as part of application of large volumes of compost and other organic amendments (Clark et al., 1998) as sources of N. When soil tests indicate that nutrient imbalances exist (e.g., unfavorable Ca:Mg ratio), application of individual nutrient sources may be necessary.

Crop quality and uniformity may be as important as yield with many vegetable crops. With fresh vegetables, fertility management often is directed at improving size, color or uniformity. It is especially important to maintain high levels of available N when quality is a concern. Additional P may also be needed in cold soils because root growth is slow and the young seedling cannot take up P quickly enough from a limited soil volume. Phosphorus availability may improve with banded preplant application of organic P sources even when soil P test levels are high.

Nitrogen is different from other macronutrients because it moves out of the root zone through leaching or gaseous loss to the atmosphere. Nitrogen availability was one of the most important factors determining tomato yields during transition to organic pro-

Table 4. Common organic fertilizer materials and their approximate analysis (dry weight basis).

	Fertilizer (%)		
	Nitrogen	Phosphorus	Potassium
Fish meal or powder	10–11	6	2
Chicken manure	2–3	1.5	1.5
Processed liquid fish residues	4	2	2
Feather meal	12	0	0
Seabird and bat guano	9–12	3–8	1–2
Alfalfa meal	4	1	1
Cottonseed meal	6	0.4	1.5
Soybean meal	7	2	1
Bone meal	2	5	0
Kelp	<1	0	4

duction (Scow et al., 1994; Scow, 1995; Temple et al., 1994a) and microbial activity in the organic system may play an important role in this. Even with careful attempts at fulfilling nutritional needs organically, an organic vegetable production system may not reach N fertility levels acceptable for plant nutrition (Scow, 1996; Temple et al., 1994a, 1994b). A relatively small portion of the N from organic amendments is readily available in mineral forms. However, N mineralization continues in a typical row crop environment and if organic N levels are adequate, N will be available for plant uptake. Soil microbial populations compete with the growing crop for mineralized N and will also limit crop response to rates and timing of applied amendments.

Nitrogen nutritional requirements for organic vegetables in California require an initial preplant supply and may require subsequent banded and incorporated applications. Short season crops such as leafy greens, beets (*Beta vulgaris* L.), or radishes (*Raphanus sativus* L.) may produce well with residual N from a green manure crop or from preplant incorporated applications alone. Longer season organic vegetable crops following a green manure may require one or more additions of N later in the season (Scow et al., 1994; Smith et al., 1992; Temple et al., 1994a, 1994b).

Studies with field corn in Iowa have shown that early season soil NO_3-N levels of 15 to 26 ppm ($mg \cdot kg^{-1}$) soil are adequate for optimum yields (Binford et al., 1992; Blackmer et al., 1989; Blackmer, 1996). Relatively less is known about critical soil NO_3-N levels for vegetables in California and values may differ because of the importance of short-term N fluctuations on vegetable crop yield and quality. Vegetables may require equal or higher levels of soil NO_3–N over a longer part of the season because of more restricted root systems and potential effects of N deficiency on fresh market quality. Soil NO_3-N of 25 ppm represents approximately 100 lb / acre (112 $kg \cdot ha^{-1}$) N in the top 12 in (30 cm) of soil and greater than 20 ppm is adequate to delay subsequent side dressing in lettuce on the central California coast (Hartz, 1998).

As part of the long term sustainable farming systems project at University of California, Davis, preplant incorporation of a high N green manure led to residual soil NO_3-N peaks after 3 to 4 weeks followed by a return to relatively low levels (<10 ppm) for the remainder of the season (Scow, 1996; Shennan, 1992). During a 4-year transition to organic production, the organic tomato system derived 85% of the N from a vetch cover crop (Chaney, 1996), but frequent N deficiency was reported from organic plots dependent upon green manure alone for production (Scow et al., 1994; Scow, 1995; Temple et al., 1994a). The NO_3-N availability from green manure is variable from season to season and is dependent upon many factors including the quality of green manure. Fox et al. (1990) reported that from 11 % to 47% of the N had been mineralized after 12 weeks following green manure incorporation (depending on the species of cover crop). The relationships among microbial parameters and soil N in organic fields are complex and subject to the variability related to the short-term fluctuations in factors affecting them (Scow, 1995).

NUTRIENT SOURCES. Organic matter decomposition in soils can provide much of the N, P, and S for crop nutrition. Phosphorus from organic amendments reacts quickly, is bound to soil minerals (Parnes, 1990), and moves very little from where it is placed. Potassium, Ca, and Mg are relatively soluble from plant residues or soil organic matter fractions and soil minerals also contribute to the soil pool of these nutrients. Organic matter provides a valuable balanced source of many minor elements. Other mineral based soil amendments can be used as sources of macro or micronutrients. They rarely are needed on organic farms in California because of prior cropping history or application of relatively high rates of compost.

Organic fertilizer materials generally are less concentrated nutrient sources than conventional fertilizers and amounts as high as 20 ton / acre (49.4 $t \cdot ha^{-1}$) or more, may be applied to a field at one time. These fertilizer materials as a group are quite variable with respect to particle size and distribution, moisture content, nutrient content, and nutrient distribution. Some of the inconsistency is inherent in the materials because of the nature of the production and handling process and because they continue to change during transport and storage. Some growers independently attempt to determine and record the composition of specific organic fertilizer materials. Soil microbial activity is quite variable spatially and temporally due to the inherent heterogeneity of soil components (Scow, 1997). The addition of nonuniform organic materials further diminishes the predictability of factors such as nutrient availability that are dependant upon microbial processes.

Bulk dry or liquid materials and composts may be top-dressed and incorporated. Liquid materials such as processed liquid fish, liquid soybean meal, or sodium nitrate may be applied through drip irrigation systems. Fresh manure has limited use in organic production systems because of relatively high transport costs, potential pollution problems, and possible crop injury. Organic certifying agencies often limit type or timing of application of manure to organic production fields. Fresh manure application might be further limited by public perception of food safety issues.

Growers may need special facilities or equipment to handle these materials as moisture content adds to the bulk and cost. Organic fertilizers frequently have a relatively small proportion of soluble nutrients and other nutrient fractions that are unavailable or only slowly available to the plant. Organic materials may need to be applied as much as two to four weeks earlier than conventional fertilizers in anticipation of plant nutritional requirements. Nutrient availability will depend upon microbial activity and lack of mixing and extremes of moisture or temperature will retard microbial turnover. The composition and particle size of the material can affect the rate of microbial decomposition and nutrient availability.

Green manure crops can be an economical mean to add organic matter and provide N for the succeeding crop. A green manure crop that includes an N-fixing legume is the most economical means to provide N to a succeeding crop. Nonleguminous cover crops will not contribute N, but may trap soluble nitrate-N and prevent losses due to percolation and runoff (Jackson et al., 1993b; Wyland et al., 1994). These cover crops and green manure crops may also harvest P or K from deeper in the soil profile making them more available to the succeeding crop.

Typically, a 120 to 160 d leguminous green manure crop contributes between 150 and 250 lb / acre (168 and 289 kg·ha^{-1}) of N (Miller et al., 1989). Several studies show serious limitations to green manure as the sole source of N for vegetable production. Plow down of high N green manures may lead to high peaks of excess available NO_3-N followed by subsequent decline (Campbell et al., 1994; Doran and Smith, 1991; Sarrantonio and Scott, 1988; Scow, 1996) and the synchrony of N availability and plant need is very critical for normal production (Doran et al., 1996, Robertson, 1997; Wagger,1989). Studies show that managing N from green manure is considerably more complex than from N fertilizers (Shennan, 1992) and N from a vetch green manure crop was not adequate for subsequent organic corn or tomato crops even when supplemented with preplant poultry manure (Cavero et al., 1997, 1998; Scow, 1996, Temple et al., 1994b).

When green manure is not practical for a production system, composts and other approved organic amendments are useful. Composts are also a valuable source of N for sidedress application to long season vegetables following incorporation of a preplant green manure. Compost also provides P, K, S, Ca, Mg, and other minor elements in low but reasonably balanced amounts. Composts are a relatively economical organic source of nutrients, but they are quite variable depending upon source, feed materials, and process. Even with good quality compost, the N available to the succeeding crop varies from a net loss (Douglas and Magdoff, 1991), to variable rates from 4% to 35% (Castellanos and Pratt, 1981), to as much as 57% of applied N (Buchanan and Gliessman, 1991).

Much more research is required for composts to be used effectively as a reliable N fertilizer for vegetables (Hartz et al., 1996; Hartz and Giannini, 1998; Hue and Liu, 1995; Roe, 1998). A recent review of compost research concludes that little information is available to guide vegetable growers on the most efficient rates and timing for compost application (Roe, 1998).

The challenge with compost is to know and understand the composition and to determine how to use it most efficiently. Poor quality or immature compost may actually decrease the availability of N to the growing crop. The carbon to nitrogen ratio (C:N) of a compost is one indication of the maturity and nitrogen availability. As the C:N increases above 20:1, there is increasing tendency to tie up nitrogen from the soil. A compost with a C:N of less than 20 will generally release N to the succeeding crop. Other quality considerations are age, particle size, pH, salt concentration, and purity (the volume of soil, sand, etc. mixed with the compost). Compost analysis is based on dry weight, thus moisture content will add to the weight and lower the nutrient analysis. It is not unusual for commercial composts in California to have moisture contents of 25% to 30%.

Many compost studies have involved municipal solid waste (MSW) compost or compost in addition to mineral fertilizers. Research reports of vegetable crop responses to compost alone are quite variable (Roe, 1998) perhaps due to variability of compost materials and N rates. Research conducted with bell peppers (*Capsicum annuum* L.) found that feather meal performed the best of seven different organic fertilizers (compost, pelleted chicken manure, fish meal, liquid fish, liquid soybean meal, feather meal and seabird guano), but compost was the most cost effective (Gaskell, 1999). The pattern of weekly residual soil NO_3-N following compost application reaches a peak after 3 to 4 weeks and then falls to background soil levels. Repeated application of organic N sources may be one way of improving N availability and augment N from green manure or preplant applied compost.

A number of approved organic fertilizers are available commercially (Table 3). Many of these materials are by-products of processing industries.

Commercial formulations and nutrient analyses of these materials are quite variable. In general, they range from 1% to 12% nitrogen and provide P and / or K along with N. The short-term availability of nutrients can be quite variable among these materials and depends largely on the nature of the material and how it was processed. In general, most of these fertilizers should be applied and incorporated uniformly before planting. They also may need to be applied in one or more supplemental top-dress applications, depending upon the growing cycle of the crop. Dilute liquid teas from these materials are sometimes applied to the soil or sprayed directly on the plant in an effort to improve nutrient availability, but research reports on the efficacy or cost-effectiveness of these teas are rare.

Other simple fertilizer materials, which primarily offer only one macronutrient, include mined sodium nitrate (N), blood meal (N), rock and colloidal phosphate (P), mined potassium sulfate (K), green sand (K)

Certain by-products of the meat processing industry such as blood and bone meal have recently come under scrutiny because of food safety concerns and the potential for disease transmission. Mined Chilean sodium nitrate, a source of N, has been an important component of organic fertilizer programs because of its low cost, solubility, and ease of use. However, many certifiers plan to restrict future use of sodium nitrate because of the long-term adverse effect of sodium on soils.

Many studies confirm that composts and other organic fertilizers can be valuable sources of nutrients for intensive vegetable production but the variability of the results limits the use of compost in organic production (Hartz et al., 1996; Roe, 1998). Only limited data is reported on crop response to organic fertilizers. Repeated application of compost or other organic amendments may be one way of improving N availability. Reported studies thus far have not attempted to quantify the specific relative N contributions of a green manure, compost, or other organic fertilizers and N sufficiency for long season vegetable production. Much remains to be determined regarding the efficient use of commercially available composts and other organic fertilizers with or without a prior green manure incorporation.

Organic fertilizer sources commonly contain one or more minor elements. Additional conventional minor element fertilizers may be permitted by a certifying agency in specific circumstances for correction of minor element deficiencies. Application of approved source materials will raise soil levels to a range where they are not deficient. A number of liquid materials and teas are also available which provide one or more minor elements. Some of these may be used in irrigation systems or applied to foliage (Schwankl and McGourty, 1992). Field trials evaluating the effectiveness of applying minor element fertilizers when soil levels are adequate do not show consistent response by the crop. Costs of these materials are extremely variable and the value of the material in a specific situation will often depend upon cost. Some synthetic minor element fertilizers may contain hazardous materials as fillers or contaminants and there is debate over use of these materials even in small amounts in organic production systems.

Specific approved nutrient sources of K, Ca, and Mg may be useful when indicated by a soil test. Materials such as gypsum, lime, or potassium magnesium sulfate have been in use in agriculture for many years and their value is thoroughly tested. These materials may be used to correct deficiencies or imbalances of potassium, calcium, or magnesium or also, in the case of lime, to raise soil pH. Gypsum is also applied to replace exchangeable sodium before leaching a high sodium soil or to improve water infiltration on clay soils with poor structure.

Materials derived from kelp and other processed seaweed contain nutrients and, often, plant hormones and growth regulators. Microbial soil stimulants are claimed to enhance growth and, in some cases, to reduce soil pests. Brix mixes, humates, foliar nutrient and sugar solutions, and other materials are applied to raise nutrient or sugar levels (Brix) in plant sap in an attempt to improve plant resistance to pests. Little replicable scientific information exists which clearly establishes the efficacy or cost / benefit of these materials in crop production.

Materials lists have been developed by the CDFA Organic Program (CDFA, 1999) and independent certifying agencies and offer a broad range of materials to supplement crop nutritional needs. Materials from organic or natural sources may have dangerous levels of contaminants such as salts, heavy metals, boron, etc., which could accumulate to toxic levels on a given field.

The transitional period for new organic operations is frequently the most demanding for soil fertility management. This is because the benefits of soil building and soil organic matter improvement have not yet been realized but the grower has few soluble fertilizer materials available. Growers gain experience during the transitional period and, as the soil organic matter builds; the benefits are often reflected in improved soil management.

Weed management

Managing weeds in organic vegetable systems requires the use of many techniques and strategies in order to achieve economically acceptable weed control and yields. Cultural practices used to produce vegetables often provide an opportunity for the crop to gain an advantage over the weeds: e.g. use of transplants, preemergent flaming of weeds, pregerminating weeds, plastic mulches and close cultivation. The goal is for the crop to outcompete and reduce the availability of resources for weeds. If the use of various organically acceptable techniques can give the crop a competitive advantage, subsequent hand weeding operations and costs can be minimized. The following are many of the common techniques that are available to organic growers to manage weeds in vegetable production operations.

Water management. There are a number of ways that careful irrigation management can assist growers in reducing weed pressure on their crops.

1) The Mediterranean climate of California with dry summer weather allows growers to use a dust mulch to avoid weeds (Bell, 1989). Weeds are germinated by an irrigation, killed by cultivation and the top few inches of soil are allowed to dry and form a dust mulch. Large seeded vegetables such as corn (*Zea mays* L.), squash (*Cucurbita pepo L.)* or beans (*Phaseolus vulgaris* L.), are planted through the dry soil into the zone of soil moisture. The seed of these crops can germinate, grow and provide partial shading of the soil surface without supplemental irrigations that would otherwise provide for an early flush of weeds.

2) Drip irrigation is widely used on many types of vegetables in California. Drip irrigation tape buried 6 to 8 inches (15 to 20cm) below the surface of the bed can provide moisture to the crop and minimize the amount of moisture that is available to weeds on the surface (Grattan et al., 1988). If properly managed, this technique can provide significant weed control during the nonrainy periods of the year.

3) Pregermination of weeds just before planting a cash crop is widely used in organic vegetable production. The germinated weeds are killed by shallow cultivation or flaming before planting the cash crop and can reduce initial weed pressure (Schlesselman, 1989).

Crop competition. Crops that grow vigorously can often out compete weeds (Lanini and LeStrange, 1991). Increasing the density of the crop by decreasing the in-row spacing or using closer row spacing improves crop competition (McWhorter and Sciumbato, 1988; and Norris, 1992). This allows the crop to close the canopy more rapidly and reduces the ability of weeds to compete. Some crops compete effectively with weeds if given an early competitive advantage (e.g. tomato, broccoli (*Brassica oleracea* L.), beans and sweet corn), while others never establish a competitive canopy (e.g., onion (*Allium cepa var. cepa* L.) and garlic. The use of transplants give the crop an advantage over the weeds because they are larger and more developed at planting. With help from subsequent cultivation and / or hand weeding operations, the crop can develop a full canopy more rapidly and crowd out weeds.

Reducing the weed seed bank. Practices that reduce weed seed production reduce weed pressure and can help reduced weeding costs over time. The longevity of weed seed in the soil necessitates the practices that minimize or eliminate additions to the seedbank (Norris, 1981). Short season crops such as lettuce (*Lactuca sativa* L.) can provide opportunities for frequent cultivations and rapid turnover of crops, thus reducing the ability of some weeds to mature and set seed. The use of highly competitive cover crops such as cereal rye (*Secale cereale* L.) and oats (*Avena sativa* L.) can fill in niches, out compete and smother weeds (Aldrich and Kremer, 1997; Bugg et al., 1996). Carrying weed plants with mature seed out of the field during hand weeding operations for subsequent disposal can also significantly reduce weed seed in the field (Schlesselman et al., 1989).

Cultivation. Cultivation is a time-tested technique to control weeds in vegetable production. Many approaches and philosophies regarding cultivation exist (Bowman, 1997). California vegetable operations employ close cultivation on crops such as lettuce and broccoli in which up to 80 to 85% of the bed is cultivated early in the cropping cycle. Cultivators set up on sleds allow for careful guidance of the implement and speeds of up to 5 miles (8 km) per hour.

A new generation of cultivators have been developed to remove weeds from between the seed rows, and in some situations, from the seed row (Wallace and Bellinder, 1992). Spring-tine cultivators, torsion Bezzerides cultivators (Bezzerides Bros., Orosi, California), Budding in-row weeders, and brush hoes all have action that can be adjusted to take out weeds between and close to the seed row. Some of these cultivators can remove weeds from the seed row on crops with tough stems (i.e. cotton). Computer guided cultivators that can distinguish between the crop and weeds are being developed and may soon be available to selectively remove weeds from within the seed row (Slaughter et al., 1995).

It is easier to remove weeds by cultivation while they are small (Lanini and LeStrange, 1994). Proper timing between cultivations depends on the speed of weed growth: In spring the 2- to 3-week period is about right, in the fall or winter, longer periods between cultivations may suffice. Even the best cultivators will not eliminate all weeds, thus hand weeding is often needed. Costs of hand weeding following cultivation varies due to weed pressure. Vegetables planted at high densities on the bed afford little opportunity for cultivation (i.e., bulb and green onions) and can have hand weeding costs as high as $600 or more per acre ($1482 / ha); Crops such as summer squash where cultivation can be used effectively, will have weeding costs as low as $150 per acre ($370 / ha) (Klonsky et al., 1994).

FLAMERS. Flaming is a popular method of controlling weeds in organic vegetable production operations in California. It is used on a wide variety of crops preemergence: peppers (*Capsicum annuum* L.), carrots (*Daucus carota* L.), onions, parsley (*Petroselinum crispum (Mill.) A.W. Hill var. crispum)*, potato (*Solanum tuberosum* L.) and parsnips (*Pastinaca sativa* L.) (Melander, 1998). In addition, flaming can be used with due caution postemergence on young onion (Rifai et al., 1996) and garlic or as a directed treatment to the base of tougher crops such as sweet corn when they are twelve or more inches (30 cm) in height (Schlesselman et al., 1989; Tim Prather, personal communication). Flaming is one of the more economical methods of controlling weeds in organic vegetable operations with the costs varying from $30 to 35 per acre ($74 to $86 / ha) depending upon the amount of propane that is consumed in the operation (Klonsky et al., 1994).

STERILIZATION. Soil sterilization in organic agriculture involves using heat or naturally generated biocides to kill weeds. Large quantities of fuel and water are required for steam sterilization and, as a result, this technique is expensive and its use is limited to small acreages of high-value vegetable operations such as in greenhouse culture. Ozone is a naturally occurring biocide that is being experimented with as a soil sterilant (Pauwels, 1989). Ozone is generated mechanically and then injected into the soil. It shows promise for reducing weeds but it is unclear at this time if this technique will be an organically acceptable practice.

Soil solarization involves placing a clear plastic mulch over a tilled, moist soil to allow the solar energy to heat the soil and kill germinating weed seeds (Bell, 1984; Bell et al., 1985; Stapleton and Garza-Lopez, 1988; Egley, 1990; Abu-Irmaileh, 1991; and Elmore et al., 1991). It is frequently used in interior and desert valleys where summer daytime temperatures frequently exceed 80 to 90 °F (27 to 32 °C). It has been successfully used on small seeded crops that are expensive to hand weed such as carrots and onions. Along the coastal production districts, the temperatures are not reliably high enough to justify its use.

MULCHES. Opaque plastic mulches blocks light, preventing weed germination or growth (Bonanno, 1996). They are used on crops such as peppers, strawberries (*Fragaria ×ananassa Duchesne)* melons (*Cucumis melo* L.) and tomatoes (Monks et al., 1997). The most common plastic color for weed control is black, as it completely blocks light. However, brown and green mulches are used because they allow more heat to be transmitted to the soil, but still offer the benefits of weed control (Purser, 1993). Certain weeds such as yellow nutsedge (*Cyperus esculentus* L.) are not completely controlled by plastic mulches, as they are able to penetrate the plastic (Igbokwe, 1996). Other weeds are also able to grow in the openings provided for crops. Plastic mulches are expensive (i.e., $250 to 300 / A; $618 to $741 / ha) and disposal after crop harvest is a problem because they are currently not recyclable.

Layers of organic residue mulches such as municipal yard waste, straw, hay, wood chips, etc., must be maintained in a layer four or more inches (10 cm) thick in order to provide control of annual weeds (Makus et al., 1994). Organic residue mulches breakdown with time and the original thickness typically reduces by 60 percent after one year (Handreck and Black, 1989). Coarse green waste works better as a mulch. Organic residue mulches are rarely used in vegetable production in California because of their costs, as well as the additional hauling and spreading costs.

Cover crops can be grown, under cut and left on the beds to form an organic mulch (Creamer et al., 1995). Plants used to produce organic mulches include various cereals, clovers (*Trifolium ssp*.), vetches (*Vicia ssp*.) and fava beans (*Vicia faba* L.) (Abdul-Baki and Teasdale, 1993 and 1997). Organic mulches provide some weed control, as well as other benefits on the growth of vegetables. They are currently the subject of a great deal of research in the interior valleys on crops such as processing tomatoes (Herrero, 1999), but at present, their use is limited.

BENEFICIAL ORGANISMS. Weeds suffer attacks from disease and insects as do crops. However, at present, most instances of biological control of weeds occur in range or noncrop areas and are of little consequence to vegetable growers. There is interest in developing microbial agents that selectively attack the above ground portions of weeds and weed seeds of vegetables and field crops. Research is currently underway evaluating these approaches (Kremer, 1993; and Steve Fennimore, personal communication).

CHEMICAL CONTROLS. Herbicides are chemicals that kill or suppress plants by affecting plant physiological processes. The number of herbicides that are organically acceptable are limited and include contact materials such as acetic acid (vinegar) (Lanini, 1997; Spencer, 1997), citric acid, solutions of sodium nitrate, as well as a preemergent material, corn gluten (Liu et al., 1994; Bingaman and Christians, 1995). Herbicides can be used to selectively control weeds by timing of the application, placement of the material, or by differential crop and weed tolerance of the treatment. Weeds that emerge before the crop can be killed using contact type herbicides (acetic acid, etc.). Corn gluten is a preemergence material that is applied to the soil to suppress weeds as they germinate. Currently, the use of these organically acceptable herbicides is limited because of marginal efficacy and high cost

Insect pest management

The major emphasis in organic vegetable production systems is on using cultural and biological control methods for insect pest management.

The selection of appropriate crop rotations and crop residue incorporation will help prevent build up of many pest species (Onstad et al., 1999). Growing the same crop continuously on the same field contributes to increasing numbers of insect pests. Pests may also migrate from neighboring crops and influence management decisions. In the San Joaquin Valley, for example, when plant bugs such as lygus (*Lygus elisus*, Van Duzee*)* migrate into fresh market bean fields, it is not possible to stop substantial crop loss with the use of any available products approved for organic vegetable growers. For the organic vegetable grower, often the best solution to pest problems only comes with a thorough understanding of local conditions and knowing what cultivars or crops to grow and when to plant them in order to avoid the most severe problems (Dosdall et al., 1996).

It is a valuable practice to keep records of the pest problems, where and when they occur and what control strategies worked. Good record keeping will help build the foundation for next year's pest control strategy.

MONITORING FOR PESTS AND BENEFICIALS. Proper identification of the pests and beneficials that are present in the crop is very important. Identification of the immature life stages such as eggs, nymphs and larvae will greatly aid in preventing economic damage to crops.

Many of the key pests in vegetable crops are described in pest management manuals and literature available from the University of California Agriculture and Natural Resources Communications Services (Oakland, Calif.). An experienced pest control advisor can help alert a grower to potential problems before crop losses occur. In some situations, pheromones can be used to prevent feeding damage by mass confusion of males and preventing mating (Wang et. al., 1997). It is important to determine when biological control factors are beginning to impact the pest population. Understanding the life cycle and biology of both pests and beneficials will help the grower make the best use of the insect community that develops with the crop.

To follow the activity of pests and beneficials in the crop, it is important to make regular weekly checks in the field with a hand lens and inspect the underside of foliage for the first signs of insect activity. Many pest species are very small and not often noticed until considerable damage has occurred. More frequent checks may be necessary during periods favorable for rapid increase of pests such as two-spotted spider mites (*Tetranychus utricae*, Koch). The use of a sweep net in cover crops, field edges and adjacent crops to check for insect activity can help determine which potential beneficials or pests may be developing that could move into crops.

Tolerance levels or action thresholds have to be considered for different pest species and different crops. If the pest feeds on the fruit or part of the vegetable that is sold, then tolerances are lower. Pests feeding on portions of the plant that are not sold, such as the leaves of a tomato plant, can often be tolerated at much higher levels. Insect and disease control options, including organic options that are updated regularly, are available for pests of vegetable crops in University of California, Agriculture and Natural Resource publications. Much information about pest control techniques, photos of pests, models of pests and information on integrated pest management research can be obtained through the University of California Statewide Integrated Pest Management Project (Strand et al., 1999).

Cultural control

The time of planting and harvesting can be coordinated to avoid certain pests that build up in crops. Crops such as sweet corn can be grown with less earworm, (*Heliocoverpa zea* (Boddie)) damage in June and early July while corn harvested in August and September will have more damage. In crops such as squash, where aphids like green peach aphid (*Myzus persicae* (Sulzer) can transmit virus diseases, succession planting will allow aphids to build up and severe damage may occur in the later cultivars. Planting later crops upwind may help reduce the spread of disease. In some areas, midsummer and late season plantings must be located in isolated fields. Many pests such as plant bugs (Miridae), flea beetles (Chrysomelidae), squash bugs (*Anasp tristis* (Degeer)) and many caterpillar species (Lepidoptera) can build up in early crops and cause extensive damage in later plantings unless they are controlled before they mature and reproduce.

In California, the incorporation of a grass species into the crop rotation is recommended, as grasses tend to be resistant to most of the insect and disease pests of the more common cash crops (Weaver et al., 1998). Resistant cultivars and trap crops are useful tools for the organic grower and may help control build up of damaging pest species (Halford et al., 1999).

Planting field borders or strips within the field with plants that are different from the main crop can provide habitat for beneficial arthropods and can slow the spread of pest species in the field. Flowering plants along borders and edges of fields can provide habitat and food for beneficial insects. Research has shown that substantial numbers of beneficial insects can move from hedgerows up to 23 feet (76 m) into adjacent vegetable fields (Long et al., 1998). Insect, weed and wildlife pest management in borders can be challenging. The borders need to be checked to make sure that pest species are not building up and migrating out of the borders into the cropping areas.

Certain soil and nutrient conditions can be associated with pest problems. High organic matter content can lead to an increase in problems with symphylans (Symphyla), springtails (Collembola, cutworms (Lepidoptera), and seedcorn maggots (*Delia platura.,* *(*Meigen*))*. Soil tillage can destroy insect life stages and expose them to birds, predators and speed the breakdown of plant residues. Sandy soils will tend to support higher nematode (Nematoda) and wireworms, such as the sugarbeet wireworm (*Tetanops myropaeformis* (Rder)), populations.

Organic growers farming on sandy soils will need to be more careful with crops such as tomatoes, members of the cucurbit family (Curcurbitacaea), and most root crops. Longer fallow periods will be required or more frequent grass rotations will be necessary to prevent a buildup of soil pests. Growing sensitive crops when soil conditions are not favorable for pests will help prevent damage. Fall and winter planted vegetables may escape damage that would be severe if the same crops were planted in the spring and summer period.

Pest barriers can be incorporated into high value vegetable plantings. Floating row covers and plastic tunnels are effective in reducing access by many pest species (Orozco et al., 1994). Reflective mulches have been effective in preventing early aphid infestations in row crops such as tomatoes, and squash (Csizinszky et al., 1999). Sticky barriers can be useful as monitoring devices; however they have seldom been effective in control of pest species (Kim et al., 1999). Mechanical control by vacuuming and destroying lygus bugs in strawberries has proven effective if frequent passes through the fields are made during critical periods.

Biological control

Many opportunities for enhancing biological control exist in organic farming systems. With most organic farms using few pesticides, it is possible to build up large numbers of parasites and predators, which will aid in controlling pests. The addition of biocontrol organisms may be most cost effective during the transition from conventional to organic production systems (Corbett and Rosenheim, 1996). Care should be taken to determine that the introduced biological control organism is well adapted to a particular site and is the correct predator or parasite species for the pest indicated. Multiple releases of the biological control agents may be required to adequately suppress the pest populations. There are now over 125 suppliers listed that sell biological control organisms (Hunter, 1997).

When pests such as aphids build to high levels, they will often be controlled by native populations of ladybird beetles (*Coccinellidae*), lacewings (*Neuroptera*), syrphid flies (*Syrphidae*), or wasp parasites (*Hymenoptera*). For many growers this control may be too late to prevent extensive damage to the crop. If the aphids are vectors of virus pathogens, it only takes a few of them to cause extensive losses. In this case, predators and parasites are not likely to prevent spread of disease into or through the field.

Chemical control

Some microbial insecticides such as the various Bts, (*Bacillus thuringiensis subspp.)*, are readily available. The primary use is to kill larvae of butterflies and moths (*Lepidoptera*). Bts have little effect on other organisms but are effective on the pest for only one or two days. Heat, cold, time, rain, and diseases can all affect the viability of biological control agents.

There are a number of organically acceptable chemical insecticides, which may be useful in specific circumstances. If a particular pest needs to be treated to prevent economic losses, a selective spray material may be used but preferably only as an isolated application. Organic growers should be aware of the legal requirements in California for pesticide use in agricultural crops. For organic growers, three of the most important factors in choosing a pesticide are low mammalian toxicity, minimal effect on beneficial organisms and adequate coverage of the crop. Pests are often feeding on the undersides of the leaves and most organically approved pesticides must contact the pest in order to be effective.

Many organically approved pesticides degrade rapidly in the environment. This will allow more rapid establishment of biological control but in some cases may result in repeat applications for pests. Insects can become resistant to pesticides used frequently and over time those pesticides may become less effective. Pesticide resistance is not as likely to develop to materials such as oils and soaps that will control insects by physical actions such as suffocating or dislodging the pest from the crop.

Plant disease management

California agriculture, in general, is noted for its great diversity of crops. Because of this diversity, growers are faced with various disease problems for each of the many crops they might produce. This challenge is accentuated for organic vegetable growers because they usually produce a wide array of vegetable crops and do not use synthetic fungicides and fumigants. The world market will continue to be extremely competitive and require California growers to supply high quality, disease-free produce having acceptable shelf life. This makes disease control a challenging task for organic vegetable growers.

For controlling diseases in an organic system, California growers generally have developed strategies having an ecological basis (Gliessman, 1995; Pankhurst and Lynch, 1995; van Bruggen, 1995). For example, as much as possible the organic system encourages the growth and diversity of soil-inhabiting and leaf-epiphytic microorganisms that might have beneficial and pathogen-antagonistic influences. Increasing the genetic diversity of the crop rotation is another ecological management step. Integrating disease management decisions with insect and weed control and with general production practices is another step consistent with this approach.

Resistant plants and cultivars

One of the most important components in an integrated disease control program is the selection and planting of pathogen-resistant cultivars. California organic vegetable growers rely on such cultivars because their use is nondisruptive to the environment and is compatible with other disease management practices.

However, the greatest limitation of this option is that resistance is not available for all crops. For several of the most damaging plant diseases, such as late blight (*Phytophthora infestans* (Mont.) de Bary) of tomato and white rot (*Sclerotium cepivorum* Berk.) of onion and garlic growers do not yet have cultivars with acceptable resistance. There are no known resistant cultivars for most of the smaller acreage specialty vegetables, such as arugula (*Eruca sativa* Mill.), broccoli raab (*Brassica rapa* L. subsp. *rapa*), cilantro (*Coriandrum sativum* L.), fennel (*Foeniculum vulgare* Mill.), jicama (*Pachyrhizus erosus* (L.) Urb.), mizuna mustard (*Brassica campestris* L. subsp. *nipposinica*), radicchio (*Cichorium intybus* L.), red mustard (*Brassica juncea* (L.) Czernj. & Coss. subsp. *rugosa*), Swiss chard (*Beta vulgaris* L. subsp. *cicla*), tah tsai (*Brassica campestris* L. subsp. *narinosa*), tomatillo (*Physalis ixocarpa* Brot.), and many Asian vegetables and herbs. In other cases resistance is present in cultivars that lack adequate horticultural characteristics. For celery (*Apium graveolens* L.), there are cultivars with acceptable resistant to the Fusarium yellows pathogen (*Fusarium oxysporum* Schlechtend.:Fr. f. sp. *apii* (Nelson & Sherb) Snyder & Hans.); however, many of these selections lack adequate color, yield, and other qualities. Finding a cultivar with multiple resistances can also be difficult for California growers. A lettuce (*Lactucae sativa* L.) cultivar that is resistant to lettuce mosaic virus may be quite sensitive to corky root disease (caused by *Rhizomonas suberifaciens* van Bruggen, Jochimsen, and Brown); a lettuce selection that resists corky root may be very susceptible to downy mildew (*Bremia lactucae* Regel).

The breakdown of resistance due to changes in the pathogen poses a constant concern for California growers. For example, during the past 50 years in California, a new race of the spinach (*Spinacia oleracea* L.) downy mildew fungus (*Peronospora farinosa* (Fr.:Fr.) Fr. f. sp. *spinaciae* Byford) would periodically occur in the state and cause significant damage to the previously resistant cultivars. Plant breeders would counter with new cultivars having resistance genes to the new race (Koike et al., 1992). Growers would then enjoy several years of mildew-free spinach until the development of yet another race. This back-and-forth dynamic has taken place for each of the seven races that has been confirmed in California.

Site selection

Experienced organic growers know that considerable time and effort are required for site planning. Growers try to monitor the distribution of persistent, soil borne plant pathogenic fungi such as *Armillaria* (Fr.:Fr.) Staude, *Fusarium* Link:Fr., *Plasmodiophora* Woronin, *Sclerotium* Tode:Fr., and *Verticillium* Nees. Because not all fields are infested with these fungi, growers attempt to plant susceptible crops in sites that do not have histories of such problems. Soilborne fungi such as *Phytophthora* de Bary, *Pythium* Pringsh., and *Rhizoctonia* DC. are often much more wide spread in California, so site selection is usually less helpful in avoiding these organisms.

Other site-specific situations also create risks that growers try to avoid. Pastures, foothills, riverbanks, and grasslands support weeds and natural vegetation that are often reservoirs for virus and virus-like pathogens. For example, the aster yellows phytoplasma and its six-spotted leafhopper (*Macrosteles fascifrons* (Stal.)) vector can be found in weedy grasslands in coastal California. Once this vegetation dries up in the summer, the leafhoppers migrate from the grasslands and move into nearby lettuce or celery fields, resulting in aster yellows disease in these fields (Severin and Frazier, 1945).

Pertinent environmental factors are also considered in selecting sites. Crops planted close to the Pacific Ocean are more at risk from downy mildew diseases due to the persistent humidity and cool temperatures. However, moving a few miles inland from the ocean can change these conditions and reduce downy mildew pressure. Soil factors are critical in avoiding some root and crown diseases. Choosing a site that has well draining soils reduces the risk of damping-off and root rot for sensitive crops such as spinach. In fact, the recent, significant increase of spinach acreage has caused some organic growers to place spinach in poorly draining fields, resulting in significant root rot problems.

Exclusion

Exclusion refers to preventing any materials that are contaminated with pathogens from entering the production system. For some diseases, seedborne pathogens are a primary means of pathogen introduction (McGee, 1981; 1995). When possible, growers purchase seed that has been tested and certified to be infested below a certain threshold level or treated to reduce pathogen infestation levels. Some seedborne diseases of concern in California are the following: lettuce mosaic and bacterial leaf spot (*Xanthomonas campestris* pv. *vitians* (Brown) Dye) of lettuce; black rot (*Xanthomonas campestris* pv. *campestris* (Pammel) Dowson), black leg (*Phoma lingam* (Tode:Fr.) Desmaz.) and Alternaria leaf spot (*A. brassicae* (Berk.) Sacc.) of cabbage (*Brassica oleracea* L. var. *capitata* L.); bacterial leaf spot (*Pseudomonas syringae* van Hall) of cilantro; bacterial leaf spot (*Xanthomonas campestris* pv. *carotae* (Kendrick) Dye), Alternaria leaf spot (*A. dauci* (Kuhn) Groves & Skolko), and Cercospora leaf spot (*Cercospora carotae* (Pass.) Solheim) of carrot (*Daucus carota* L. subsp. *sativus*); Septoria late blight (*S. apiicola* Speg.) and bacterial leaf spot (*Pseudomonas syringae* pv. *apii* (Jagger) Young, Dye & Wilkie) of celery; Septoria blight (*S. petroselini* (Lib.) Desmaiz.) of parsley (*Petroselinum crispum* (Mill.) Nym. ex. A. W. Hill); bacterial spot (*Xanthomonas campestris* pv. *vesicatoria* (Doidge) Dye) of pepper (Capsicum annuum L.) and tomato; bacterial speck (*Pseudomonas syringae* pv. *tomato* (Okabe) Young, Dye & Wilkie), and bacterial canker (*Clavibacter michiganensis* subsp. *michiganensis* (Smith) Davis, Gillaspie, Vidaver & Harris) of tomato. If transplants are used, these likewise should be as clean as possible from pathogen contamination and from disease. California organic growers are highly dependent on good quality, disease-free transplants of broccoli, Brussels sprouts (*Brassica oleracea* L. var. *gemmifera* DC.), cauliflower (*Brassica oleracea* L. var. *botrytis* L.), celery, leeks (*Allium porrum* L.), lettuce, pepper, tomato, and other vegetables.

Disease control materials

Once vegetable crops are in the field, it will sometimes be necessary to apply, if available, protectant or eradicant spray or dust materials for disease control. Unfortunately for organic producers, the choices of effective, proven materials are limited.

Inorganic control materials, primarily copper and sulfur based fungicides, are generally inexpensive, widely available, and pose minimal problems to the environment. However, disease control efficacy varies. Copper fungicides registered in California have some activity against a wide range of fungal and bacterial pathogens but generally are not extremely effective. Sulfurs also exhibit some activity against many pathogens, but usually only provide excellent control against certain pathogens such as powdery mildew fungi. Bicarbonate based fungicides have recently become available for control of plant diseases. Bicarbonates have shown some activity primarily against powdery mildews (*Erysiphe* R. Hedw. ex. DC.:Fr.; *Sphaerotheca* Lev.). However, field experiments and grower experience indicate that bicarbonates alone likely will not provide season long protection for an organically grown crop.

Oils, plant extracts, and other natural plant products are being investigated for use for disease control. Such products will be compatible with organic production practices, but reliable disease control has yet to be demonstrated. There is much interest in using microorganisms or the chemical by-products of microorganisms for disease control (Leggett and Gleddie, 1995; Mathre et al., 1999). However, the history of successful biological control of plant diseases in California has been discouraging. There are very few effective, economically feasible, and commercially available biological control materials at this time.

CULTURAL PRACTICES. Specific cultural practices can be implemented to help manage diseases.

Recent research has found that certain plants, in addition to being revenue-generating crops, also have suppressive effects on various diseases. For example, after broccoli crops are harvested and the plant residue is plowed into the soil, the decomposition of the broccoli stems and leaves releases natural chemicals that can significantly reduce the severity of Verticillium wilt and the number of *Verticillium dahliae* Kleb. microsclerotia (Subbarao et al., 1999). Broccoli as a rotation crop and even as a cover crop is now being used by California organic growers to harness this suppressive effect.

When devising crop rotation strategies, growers consider which crops and cover crops might increase disease problems (Koike et al., 1996). Purple vetch (*Vicia benghalensis* L.) cover crops, if planted in fields having a history of lettuce drop caused by the fungus *Sclerotinia minor* Jagger, can greatly increase the number of infective sclerotia of this pathogen (Dillard and Grogan, 1985). Growers also realize the risks involved with planting the same crop back-to-back or in consecutive seasons and try to avoid such rotations.

Time of planting can offer an opportunity for disease management. If cauliflower is planted in *Verticillium*-infested fields in the spring or summer, it is likely the crop will experience significant disease, but cauliflower planted in the same fields in the late fall or winter will exhibit no verticillium wilt symptoms. This is attributed to soil temperatures that are too cool for the fungus to develop. Proper soil preparation before planting can influence seed decay and seedling damping-off diseases by tilling to reduce plant residues left from previous crops and by making raised beds with good soil tilth and drainage.

For most foliar diseases, overhead sprinkler irrigation enhances pathogen survival and dispersal, and disease development. Bacterial diseases are particularly dependent upon rain and sprinkler irrigation. Therefore, organic growers try to limit or eliminate sprinkler irrigation if possible. In particular, the use of surface or buried drip tape for vegetable production has increased greatly in California in recent years and helps reduce the severity of certain diseases.

Sanitation is useful in disease control for certain crops. Once lettuce has been harvested, the remaining plants can act as a reservoir for lettuce mosaic virus. Plowing the field immediately after harvest is a sanitation procedure that eliminates this potential virus source. Lettuce drop occurs when sclerotia develop on lettuce plant residues and remain in the top few inches of soil. A sanitation step involves deep plowing in which mold board plows invert the soil and bury sclerotia. Note that this procedure is effective only if sclerotia are low to moderate in number (Subbarao et al., 1996).

Like other states, the use of composts in California organic systems is a fundamental cultural practice and growers are committed to compost programs. Composts are beneficial for a number of fertility and soil conditioning reasons and are considered by growers to be beneficial in disease management. Though research studies and empirical data that clearly document the disease control benefits of field-applied compost are lacking, organic growers in California will continue to use composts and to experiment with variations such as compost teas.

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