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Short Communication

Redirecting technology to support sustainable farm management practices

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ABSTRACT

Agricultural technology has increased farm production to unprecedented levels. However, return on investment is diminishing and environmental concerns conflict with current input intensive farm practices. Conventional technologies and their application such as crop breeding and management practices have focused on monocultural systems that are dependent on chemical inputs to produce optimum yields. Current profit margins are low or non-existent with these conventional non-sustainable practices and must be changed if the family farm is to survive. We propose an ecologically based approach to farm management that strives to reduce reliance on chemically intensive inputs through better use of multiple attributes inherent within agroecosystems. This approach requires a redirection in the development and application of current and emerging technologies. Examples of redirections in research and development programs for pest management practices, genetic engineering, and precision agriculture necessary to provide a more ecologically-based and sustainable farming approach are illustrated.

1. Introduction

Despite the emergence of new agricultural technologies and increased use of chemical inputs, returns on investment in crop and animal production systems are diminishing. For example, in the United States, crop losses due to pathogens, animal pests and weeds, have increased from 34.9% in 1965 to 42.1% in 1988–1990 (Oerke et al., 1994), in spite of a 170% increase in pesticide use over roughly the same period, 1964–1985 (Edwards et al., 1990). From 1993 to 1998, there was no increase in the average prices farmers received for their commodities, though they experienced nearly a 14% increase in farm production expenditures during that period (USDA-NASS, 1999). Apart from return on investments, there are considerable external costs associated with high input and substitution agriculture such as damage to natural resources, loss of biodiversity and other ecosystem services (Pretty et al., 2000; Tegtmeier and Duffy, 2004; Sandhu et al., 2008). More recently, cotton losses to pests between 2001 and 2003 were still 29% of yield potential (Oerke, 2006). Lewis et al. (1997) argued that these escalating trends could not be resolved through the prevailing operational paradigm driven by an ever-increasing array of therapeutic tools. Rather, we must shift to an approach that emphasizes the “built-in” inherent self-sustaining strengths of agroecosystems. Yet, the tools being delivered through the existing agricultural research, extension, and industrial infrastructure are predominantly pesticides, chemical fertilizers, and similar interventionist technologies. Herein, we examine and propose technological redirections necessary for equipping practitioners with tools crucial to implementing the shifts advocated by Lewis et al. (1997).

2. Central premise

Agroecosystems operate in accordance with basic ecological principles. The well-known *S*-shaped curve (Odum, 1971) depicts the typical progressive development of an ecosystem, whereby growth of vegetation and animals begins slowly, then rapidly increases and subsequently levels off (Fig. 1). The “successional trends” of the plants, animals, and general complexity of an ecosystem follow a similar curve toward increasing diversity, and species interactions (Flint and Van den Bosch, 1981). Oscillations are greatest during the rapid growth phase with equilibrium and stability becoming maximized at the upper plateau where the system reaches its climax. Conventional agricultural practices typically operate in the linear portion of this curve (Fig. 1) and in opposition to the progression toward equilibrium. Through use of equipment such as harrows, mowers, and plows, large portions of the biomass are often removed and/or tilled annually, thereby forcing the growth process to start over. Furthermore, mechanical cultivation and chemical pesticides are used to restrict diversity and promote monocultures. Other inputs such as fertilizer are used to foster rapid, lush growth of the crop. On the short-term these practices often are spectacularly effective. However, such interventionist approaches lead to withering of the inherent strengths of the system and an increasing proliferation of consequences that in turn leads to a treadmill of therapeutic inputs.

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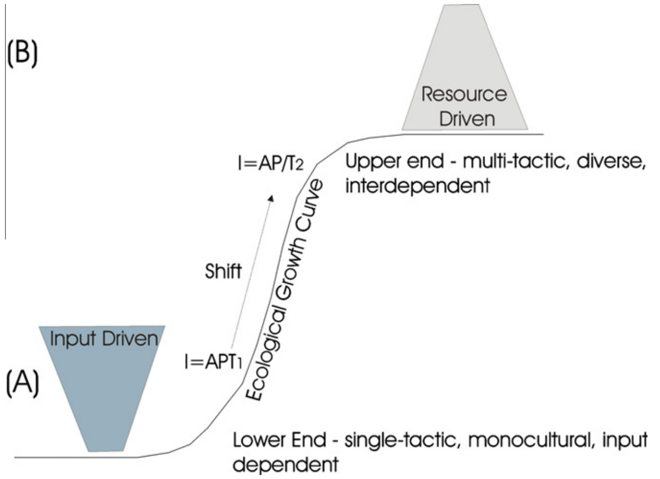

Fig. 1. (A) Current technologies (T_1) are directed toward high input approaches that disrupt ecological strengths and balances, thus operating at the lower end of the growth curve. (B) Proposed re-directed technologies (T_2) would operate at the upper end of the ecological growth curve, thus fostering the renewable inherent strengths of ecosystems.

In addition to agriculture, this broad-scale development and unbridled use of interventionist technology, stemming from modern-day reductionist science predominates our culture, including the various disciplines of industrial development, medicine, construction, and landscape design (Lewis and Jay, 2000). Thus, the equation popularized by John and Anne Erhlich, $I = P \cdot A \cdot T$, declaring environmental impact as directly proportional to population growth (P), social affluence (A), and new technology (T) (Ehrlich and Ehrlich, 1991). As emphasized by Lewis et al. (1997), and as a matter of fundamental principle, application of external corrective actions into a system with chemicals and other energy-intensive inputs, can be effective only for short-term relief. Anderson (1996), speaking from an industrial perspective, framed the equation as $I = P \cdot A \cdot T_1$, with T_1 representing technology stemming from the first industrial revolution. He described this technology as linear, wasteful, extractive, abusive contributors to the impact rather than the solution (Fig. 1). Lewis et al. (1997) advocated that long-term, sustainable solutions must be achieved through restructuring the system so that inherent forces that function via feed-back mechanisms such as density dependence and multiple component interactions are added and/or function more effectively. Such an approach would operate at the upper part of the ecological curve (Fig. 1) and foster balance. Anderson (1996) characterized such cyclic, renewable, and nature friendly technology as T_2 and functioning in the denominator of the equation, $I = P \cdot A/T_2$, and becomes part of the solution rather than the problem. With such a shift the environmentalists, industrialists, developers, and others can become aligned and strive toward common goals of mutual benefit for our posterity and ourselves.

Herein, we propose specific examples for redirecting agriculture research, development, and management practices to provide and implement crucial T_2 technologies to replace T_1 technologies, as indicated in Fig. 1.

3. Utilizing and understanding plant defensive mechanisms

Plants exhibit a sophisticated and exquisite interaction with the surrounding ecosystem. Plant defensive mechanisms include chemicals produced as anti-feedants, insecticides, and natural enemy attractants (both constitutively and induced) that reduce the infestation from insects, nematodes, disease, and herbivorous vertebrates (Agrawal et al., 1999). Other defensive characteristics include the resistant plant epidermis, spines and waxes that inhibit entry into the plant as well as leaf domatia that provide shelter for predatory arthropods (Taiz and Zeiger, 1998). Many of the chemical compounds that protect plants against feeding herbivores and pathogenic organisms are constitutively produced, while other compounds are induced in response to specific organisms (DeMoreas et al., 1998). Both groups of chemicals may be plant structure specific, directly moderating the location and density of the attacking organisms. Another, but more indirect, defensive mechanism is production of volatile chemical compounds induced after feeding by herbivorous insects that attract members of a third trophic level (Turlings et al., 1995). Our expanding knowledge of the active role that plants play in their own defense and the effect of their genetic structure and available nutrients on expression of these traits will allow management of the system in ways that optimize these innate plant protection properties for the long-term.

3.1. Current T_1 direction

Conventional plant breeding strategies have focused on increasing production and developing varieties with enhanced plant-pest resistance. While these breeding programs have enjoyed substantial success, the diminishing benefits of single-tactic approaches are becoming apparent over the long-term. Historically, plant breeding for pest resistance has dealt with direct plant–herbivore interactions to the exclusion of the sophisticated and interdependent nature of plant interactions with multiple components of their environment. Though short-term pest reductions may occur, such one-dimensional plant protection characteristics do not incorporate consideration of density-dependence, pest countermeasures, and the net effects of the multiple components when considered over a large area. For example, nectariless cotton varieties have been developed to reduce attraction of lepidopteran herbivores, but were found to reduce parasitism of tobacco budworm larvae as well (Lingren and Lukefahr, 1977). In addition, newly developed crop varieties can have a reduced capacity to exhibit natural defensive mechanisms against herbivores than previous varieties. For example, commercial varieties of cotton, bred for enhanced production and constitutive release of resistant traits, produce volatile chemical signals at only one-seventh the level of naturalized varieties (Loughrin et al., 1995), reducing their ability to recruit natural enemies. This emphasizes the importance of conservation of landraces where genetic heterogeneity is highest in obtaining desirable traits for breeding for sustainability (Newton et al., 2010). The discovery that certain chemicals from feeding herbivores elicit plants to emit signals has lead to proposals to apply these elicitors to trigger attraction of natural enemies to a crop. Application of jasmonic acid not only reduced herbivorous feeding on tomato plants, but also showed an increase in the levels of parasitism of caterpillars (Agrawal et al., 1999). This approach to plant protection may appear ecologically sound on the surface. However, the large-scale use of such elicitors could create major disruptions in the natural foraging mechanisms of beneficial organisms by providing artificial emission of cues that are not aligned with the distribution of their host, food and other resources. Consequently, indiscriminate uses of chemical elicitors without regard to density-dependent feed-back mechanisms and multi-trophic interactions can result in major plant/pest/natural enemy imbalances.

Similar approaches are being employed in plant science associated with the development of pesticides and related chemical intervention. Under the current therapeutic paradigm, pesticides are developed without utilizing the multi-trophic interactions that naturally moderate pest populations. The pesticide properties of compounds constitutively expressed in plants have led to these chemicals as the active ingredient of numerous pesticides (e.g. pyrethrin and azadirachtin). Furthermore, some chemicals have been used to induce a systemic plant response that repels herbivorous insects or plant pathogens. Further studies are being conducted to use plant chemicals to induce bio-synthetic pathways that cause the plant to produce chemicals that are normally triggered by pest attack (Agrawal et al., 1999; Chadwick and Goode, 1999).

3.2. Proposed T_2 redirection

Plants have a multitude of traits that have been selected to optimize their collective interactions with the surrounding environment. The primary emphasis of a T_2 strategy should be the development of breeding and management strategies that maximize the genetic presence and phenotypic expression of these inherent renewable mechanisms. Two basic considerations should guide such an approach.

First, the selection and management of the desired traits must be based on a multitrophic/multidisciplinary perspective with a focus on the function and variation in genes in an ecological context (Weih et al., 2008). Since the various traits are operating within a complex network of interactions, a modification of any trait results in a shift throughout the system. Thus, the desirability of each trait modification must be assessed on the basis of the net impact across all interactions rather than on isolated components of the system. For example, as mentioned earlier, extrafloral nectar produced by cotton plants attracts not only lepidopteron herbivores but also is an important food resource for natural enemies of the herbivores (Agrawal et al., 1999; Lingren and Lukefahr, 1977). So the desirability of nectaried versus nectariless cotton varieties should be assessed on the basis of the sum role of this trait across these and other possible interactions. Also, recommendations for fertility supplements and many other management regimes often are developed based on plant production parameters with little attention as to how these actions may affect plant protection traits. However, pant signaling is vital to a plant's defense against the ravages of herbivores (Turlings et al., 1995) and proper nutrition is important to the operation of these mechanisms (Chen et al., 2008; Olson et al., 2009; Schmelz et al., 2003).

Secondly, the interactions of various components of an ecosystem are regulated through a set of feedback loops that provide for "balance" within functional fluctuating bounds. An understanding and fostering of these feedback loops should be a key component of all plant breeding and management programs. A central mechanism in this system is "density-dependent" and/or "induced" responses. Many of the defensive traits of plants are inducible and expressed in response to certain kinds and levels of damage. Other traits are constitutive and are expressed by certain parts of a plant at all times. For example certain traits may be constitutive in the fruit but only inducible in the leaves. Such a combination of inducible and constitutive expression appears to maximize the plant's defense of its fruit as compared to a constitutive expression throughout the plant (Pearce et al., 1988). The appropriate combined deployment of induced and constitutive expressions is crucial to the effectiveness and durability of plant defenses. Thereby, the selective modification of plant traits through breeding or other approaches should be guided by an understanding of these considerations.

4. Gene-transfer technology

Genetic engineering has made it possible to transfer genes from one species to another, thereby creating Genetically Modified Organisms (GMOs) with novel combinations of desired traits. The transfer of herbicide-resistant genes from naturally-occurring bacterial species and select plant species (Gould, 1991) into various cultivars has made it possible to chemically control weeds without harming crop plants. A more indirect method of gene transfer has been the use of Bovine Growth Hormone (BGH), a natural component of the pituitary glands of bovines. The gene associated with production of this hormone has been inserted into the genome of the bacteria, *Echershi coli* for mass production of the protein, which is subsequently injected into a bovine to increase milk production. These and other expanding gene-transfer technologies hold great promise for commodity production.

4.1. Current T_1 technology

The most widely known GMOs are various cultivated plants that have been modified by insertion of a toxin-producing gene from the bacterium, *Bacillus thuringiensis*. These GMOs express the bacterial product constitutively, and upon ingestion, are toxic or repellent to specific herbivores, thereby eliminating or reducing the need for more broadly toxic pest control inputs. Gene-transfer technology has also been used to develop cultivars with a herbicide-resistant gene in combination with the Bt toxin-producing gene. Thus, gene-transfer technology is used as a single-tactic approach with no feed-back mechanisms and very little knowledge of their effects on other trophic levels. For example, cases of resistance have already emerged in a number of targeted weeds as a result of the widespread use of genetically-engineered crops that express glyphosphate resistance (Webster and Sosnoskie, 2010). In addition, arthropod pests non-targeted by the *Bt* toxin and incorporated into many crops are emerging and threaten the benefits of the technology (Chen et al., 2008; Olson et al., 2009; Schmelz et al., 2003; Yanhui et al., 2010; Wang et al., 2008). The *Bt*-toxin also builds up and resides in the soil for up to 230 days exposing soil biota to potential harm that could disrupt decomposition and nutrient cycling (Marvier, 2001). T_1 gene-transfer technology also does not consider how gene insertion affects other plant attributes needed for plant vigor such as disease and drought or cold tolerance, or other bio-synthetic pathways involved in photosynthesis, respiration and growth (Zangerl et al., 1997). Current directions for T_1 gene-transfer technology do not seek to operate interdependently, and in harmony with self-regulating, density-dependent and other feed-back mechanisms. In the absence of these self-regulating, interdependent mechanisms, the important components of diversity, and pest-natural enemy synergy balances are disrupted.

4.2. Proposed T_2 redirection

A fundamental redirection of gene transfer research would produce T_2 technology that copies nature by incorporating traits that are tissue specific, have density dependent properties such as inducible versus constitutive expression and have effective linkage to other components of the system. For example, *Bt* toxin could be expressed in an inducible manner in plant leaves with constituent expression in plant fruits. Thus, both traits would be effectively coupled to other crucial plant biochemical pathways, such as disease tolerance, and respiration (Shelton and Wyman, 1990). The key to longer-term, ecologically-sound and effective genetic manipulations is to anticipate the countermoves and other ripple effects in the system, and to act in accordance with the sum benefit of these interactions. Gene transfer under T_2 technology would become much more knowledge-based and through total cost accounting, weigh the benefits derived from the technology along with all other considerations including environmental impact.

5. Natural enemies

The practice of biological pest control with natural enemies is a cornerstone of ecologically-based systems management. The spectacular and long-term control of the cottony-cushion scale in California after importation of the vedalia beetle in 1888, and similar results from other introductions worldwide, stands as the basis for the classical approach to biological control. In addition to the classical importation approach, biological control consists of the augmentative and the conservation approaches. Augmentative biological control involves the release of mass-produced natural enemies and is often employed as biotic pesticides for short-term pest suppression in annual crops. Conservation biological control incorporates habitat management and other cultural practices that promote the conservation and improved performance of natural enemies and their balance with pest populations. All of these approaches have been successfully practiced although the conservation approach has received less attention since the advent of broad-spectrum synthetic pesticides. Our recent and expanding knowledge of the foraging mechanisms of natural enemies and their interactions with plants through the mediation of chemical signals as discussed earlier provides an array of new tools for optimizing the use of natural enemies under each of these approaches.

5.1. Current T_1 technology

In keeping with the single-tactic mindset, augmentative control has received the most emphasis in recent years. Whereas, our investment in understanding plant/pest/natural enemy interactions and ways to foster inherent balances has been neglected. Natural enemies have been mass-produced and released with little knowledge of their quality and/or mechanisms governing performance in relation to the targeted pest and associated habitat. Furthermore, the foraging arenas of natural enemies are often of very poor quality, which may explain why naturally occurring species are not effective, and why the pest outbreaks have occurred in the first place. For example, monocultures often lack habitat and a food source for many natural enemy species, and insecticide applications can have lethal and sublethal effects on these species (Stapel et al., 2000). In addition, the chemical volatile emissions that guide natural enemies to the plant are dependent on proper water and nitrogen levels (Chen et al., 2008; Olson et al., 2009). So, improper agronomic practices can also create poor quality habitats, food and host resources, and foraging arenas. The results are often short-term or inadequate control of the pest species because the system lacks the interdependent, self-regulating and self-renewing properties of an ecologically-based system. Importation programs have generally been conducted with similar knowledge gaps affecting quality and performance.

5.2. Proposed T_2 redirection

A shift to T_2 technology would reduce inputs and have longer-term effects on pest control by ensuring the presence of natural enemy species, and their ability to effectively forage within the field throughout the growing season. An emphasis on the conservation approach to biological control using habitat management within and near the fields must play a lead role in this direction, and recent studies in New Zealand and Australia show how this method can successfully suppress pests in vineyards (Jacometti et al., 2007; Danne et al., 2010). T_2 technology would also focus on developing cultivars capable of enhanced signaling and other plant defenses when attacked. Additionally, habitats more friendly to and supportive of natural enemies could be designed, for example, through the use of cover crops within a field and vegetative management of field edges to provide both food and habitat for natural enemy species, water retention, weed suppression, nutrient building capacities (Schomberg et al., 2003) and other ecological services, such as wildlife conservation (Olson and Wäckers, 2007). Habitat design using optimal structure and diversity of species for particular pest management situations, with the vital connection to plant attributes and agronomic practices, would reduce inputs by supporting the interdependent, self-regulating and self-renewing properties of the system. The importation approach is employed within these designs when a necessary natural enemy species is missing, with the augmentation approach employed as a supportive backup for certain short-term needs. In summary, the primary emphasis would be maximizing the inherent and self-renewing attributes of plants and natural enemies through the conservation approach to biological control, which would also improve the effectiveness of importation and augmentation approaches.

6. Precision agriculture

The management philosophy that forms the basis of precision agriculture is borrowed from pre-mechanized farming predating the early 20th century. Before large agricultural machinery was developed and widely available, farmers managed their fields as spatially and temporally variable systems and managed inputs to meet the needs of various areas within a field using the diminutive tools at hand. Today, new technological developments make it possible to apply chemicals and irrigate fields in spatially variable amounts on much larger fields, measure crop yield variability using yield monitors on harvesting equipment, and use global positioning system (GPS) receivers to pin-point field location, and return to that location with a high level of precision. Consequently, information gathered or sensed in the field to determine soil and crop needs and stored with the corresponding field coordinates can be used to create maps of field and crop properties. Application maps created from the field and crop properties indicate the amount of chemical fertilizer, pesticide, nematicide, etc. required in variable amounts across the field. Using an application map, GPS receiver and a controller, chemicals are applied in variable amounts across the field.

6.1. Current T_1 technology

Conventional precision agriculture practices use standard and newly emerging technologies to improve therapeutic management strategies that continue to rely on external chemical inputs to support production. New precision technology can help reduce chemicals applied (cost reduction) and reduce chemicals leached into groundwater and run-off into streams, but still promote an interventionist and therapeutic strategy (T_1) that is not sustainable and will keep farmers reliant on chemical inputs into the foreseeable future. One example of the current therapeutic strategy applied to precision agriculture is the in-field sampling and lab testing used to determine the rates and locations of fertilizers, pesticides and lime applications. This practice must be repeated yearly and requires several field trips to adequately protect plants and maintain productivity levels.

6.2. Proposed T_2 redirection

Invoking a paradigm shift to redirect technology requires integrating principles of soil ecology, plant physiology and pest/natural enemy behavior into a systems approach to monitor or measure parameters that determine sustainable solutions to manage temporal and spatial field variability. This management strategy incorporates all the emerging technologies already discussed into a system where the thought process changes from continued use of therapeutics to development of a sustainable agroecosystem that operates at the top of the ecological growth curve. This paradigm shift should also become the research and development focus when creating decision-support systems (DSS) that are used as a management aid to farmers.

One of the crucial tools inherent to a redirection of precision agriculture to T_2 technology is the development and use of sensors. Remotely sensed data using plant reflectance characteristics has received the most attention and advances have been made in development of sensors and monitors that are field portable and that can provide near real-time response to the parameter being measured (Grohs et al., 2009; Evans et al., 1998; Murdock et al., 1997). The use of sensing and monitoring to only help manage the inputs required to maintain production does not promote sustainable agriculture. However, if the management philosophy is changed, sensing and monitoring technology can follow a path of sustainable use. By using sensors to assess the entire system in a holistic and dynamic manner, better management decisions can be made. For example, scientific research has shown that plants under nitrogen deficiency reflect intensities of light at specific wavelengths that are different from un-stressed plants (Evans et al., 1998) and plant vigor has been quantified using infrared aerial photography of wine grapes in California (Johnson, 1999). Plants also release specific volatile chemicals in response to leaf feeding by phytophagous species of insects (Paré and Tumlinson, 1997). Plant volatile measurements, as well as plant leaf reflectance sensors could determine the specific spatial and temporal patterns of crop stress and in conjunction with DSS, evaluate potential cause and effect relationships and sustainable decision-management strategies. For example, crop measurements may indicate that plants are stressed in a certain area. Further investigation may indicate that beneficial organisms are in low-density and have allowed pest populations to increase unchecked. A DSS may indicate that a change in crop rotations, addition of refugia around the field to attract beneficial insects, or choosing a new cover crop that harbors beneficial insects and keeps the agroecosystem operating in the upper part of the ecological growth curve (Fig. 1) is needed. Site-specific application of the proposed management approach will improve crop health site-specifically.

Volatile chemical emissions have not been traditionally viewed as a method to measure plant health. However, with the multi-trophic interactions between plants, phytophagous insects, and predatory and parasitic insects, mediated largely through volatile chemical emissions, it appears that a wealth of information is concealed within the plant canopy. To date, there are no sensors with the quick response time and resolution necessary to monitor arrays of volatile chemicals or the lack of them within an entire field, although electronic nose technology is making advances in measuring the quality and quantity of odors (Gardner and Bartlett, 1999). Highly sensitive insect odor detection systems used as volatile chemical detectors (Weissbecker et al., 1997; Rains et al., 2006), or as models for development of an artificial sensor may provide a method to detect specific plant pathogens, and other pest infestations, along with aerial photographs of light intensity used to detect stressed plants.

7. Discussion

To reduce the environmental and financial burden of current farm production practices, a redirection in agricultural technology is needed to create a more sustainable management strategy that preserves the long-term productivity of existing farmland for small, medium and large farm operations. Implementation of sustainable management strategies will require new research and technology development in a direction that purposefully encourages and promotes sustainable agroecosystems. This type of research is currently under-funded. The focus on better input-driven technologies must give way to technologies that foster sustainable and holistic management of agroecosystems and that concentrate on building the principles of a sustainable system. Technologies that must be re-directed include precision agriculture, biotechnology, decision-support software and crop breeding and landscape management practices. These re-directed technologies, along with knowledge of the inherent interactions and feedback mechanisms occurring within the multiple components in the agroecosystem, can be enhanced and utilized as part of a holistic and sustainable management strategy. The resulting farm management structure will rely on the inherent processes and strengths within the agroecosystem, with therapeutic solutions relegated to a back-up role.

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