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Agriculture, Sustainable

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Glossary

Bush-fallow cropping system An agronomic system in which soil fertility is maintained by allowing native vegetation to regrow following several years of cropping.
Conservation tillage Tillage that reduces soil disruption in order to conserve organic matter and water and reduce erosion.
Ecosystem services The benefits people obtain from ecosystems.
Legumes Plants belonging to the family Leguminosae, many of whose members can form symbiotic associations with nitrogen-fixing bacteria.
Multifunctional cropping system An agronomic system that incorporates different combinations of herbaceous crops, trees, and animals within a single farm unit.
Nitrogen fixation The transformation of atmospheric nitrogen into a form usable by plants.
Resource conservation The protection and enhancement of resources on which sustainability depends.
Rotation The sequence of crops grown in a single field.
Soil organic matter Material in soil containing organic carbon derived from the decomposition of mainly plant residue.
Trophic complexity The number and types of organisms that feed at different trophic levels within a community; also known as food web complexity.

Elements of Sustainability

Strictly defined, sustainability denotes any system capable of persisting. Because persistence depends on scale, *sustainable agriculture* is entirely scale dependent. An agricultural practice that is sustainable at the scale of an individual field may lack sustainability at the larger farm scale if the inputs required to maintain stable production eventually exceed the capacity of the farm to provide them. Likewise, farm-scale sustainability must be evaluated in the context of local and global regions, and global sustainability requires consideration of global output versus the long-term costs of that output and the ability of global resources to accept those costs.

Of course costs are not simply economic. They are also social and environmental: If a cropping system requires large inputs of nitrogen fertilizer that leak from the system to pollute groundwater drinking supplies and distant coastal fisheries, a system that may be sustainable at the field scale becomes nonsustainable at the farm and regional scale – even though the long-term supply of fertilizer is stable and the economic cost of fertilizer to the farmer is easily borne by higher grain production. Landscape models now being developed for farmer decision making on alternatives and for development extension planning are becoming increasingly available (Nassauer and Opdam, 2008).

Sustainable agriculture must therefore be defined not just in terms of its long-term economic productivity but also in terms of its environmental and social benefits and costs. Many of these costs are value-laden. For a society that values family farms, for example, sustainability must be evaluated in terms of the impact of farming practices on the social structure of rural communities: Do markets and policies favor large-scale producers to the exclusion of those who operate family farms and the rural communities in which they live? For a society that values biodiversity, sustainability must be evaluated in terms of the impact of farming practices on wildlife health and habitat. These considerations take sustainability arguments into sometimes contentious territory because people have different social and cultural values. What is socially acceptable in one nation or to one segment of society may be socially unacceptable to another. These differences must be clearly defined when evaluating sustainability.

More specifically defined, sustainable agriculture is any suite of agronomic practices that are

- economically viable,
- environmentally safe, and
- socially acceptable.

These elements provide an operational definition of agricultural sustainability. There are many ways to blend them into an overarching definition, and many authors – and policymakers – have done so. In 1990, for example, the US Congress defined sustainable agriculture as "an integrated system of plant and animal production practices having a site-specific application that will, over the long term:

- satisfy human food and fiber needs,
- enhance environmental quality and the natural resource base on which the agricultural economy depends,
- make the most efficient use of nonrenewable resources and on-farm resources and integrate, where appropriate, natural biological cycles and controls,
- sustain the economic viability of farm operations, and
- enhance the quality of life for farmers and society as a whole."

One should always keep in mind the subjective nature of these constructs, however, and that sustainability is a relative term. Although it may be difficult to foresee what ultimately will be sustainable, one can usually judge whether one set of practices is likely to be more sustainable than another at a societal scale.

Development of the Sustainability Concept

Sustainable agriculture as a descriptive term evolved toward common usage in the United States in the early 1980s as a mixture of concepts, ideas, values, and development direction that many believe is a vision for what agriculture should be. As with most visions, it has had strong impetus from a small group of critics of the conventional paradigm, notably Wes Jackson in his 1980 book *New Roots for Agriculture* (Jackson, 1980), and by 1984 the term was in widespread use. By 1991, the term had been fully ''legitimized'' as evidenced in the National Research Council's (NRC) documentation of the many U.S. Department of Agriculture, university, and other programs in sustainable agriculture throughout the United States and abroad (NRC, 1991).

Many of the philosophical roots for sustainable agriculture that coalesced in the 1980s were traced from as far back as the Greek and Roman philosophers by Harwood (1990). The public agenda debate over sustainable agriculture of the 1980s embodied many of the older concepts but certainly not any one in its entirety. The notion of land ownership, cultivation, and personal connectedness to the land as a grounding for personal responsibility, morality, and sense of purpose can be found in the writings of English philosopher John Locke in the 1600s, those of Thomas Jefferson in the late 1700s, and recently in the poetry and books of Wendell Berry. Wes Jackson applied the concept to the 1990s in his book *Becoming Native to This Place* (Jackson, 1994), which focused on homecoming and on being native, i.e., developing an ecological literacy in a holistic sense, through being, living, and having personal experience with one's ecosystem. The values in having a sense of place, a connectedness, have changed from an earlier focus on moral and political values; these values have nevertheless become a part of the vision.

The concepts of conservation and natural resource preservation are woven throughout sustainability, derived from the earlier work of Aldo Leopold and others. Louis Bromfield in *Malabar Farm* (Balantine, 1947) and the prolific writings of Edward Faulkner, beginning with *Plowman's Folly* (Faulkner, 1943), had major impact. Faulkner's work had a significant influence on both JI Rodale and his son, Robert, who carried the notion further to one of regenerative agriculture (Rodale, 1983), defined as an agriculture which not only maintains the natural resource base but also restores and increases its productive potential.

Organic, biodynamic, and the many schools of thought and broad literature surrounding these terms made major contributions to the sustainability debate. The ''humus farming'' school, with its focus on management of soil organic matter and the interconnectedness of soil health, plant health, and that of animals and humans, was a foundation for this philosophy. Several schools of organic practice originated in Europe and England, but the movement was popularized as organic agriculture in the United States by JI Rodale in his widely read book *Pay Dirt* (Rodale, 1945).

Each of these philosophical roots contained the notion of a holistic structure of agriculture – an interconnectedness between people, other living organisms, and the soil. Organic agriculture today continues a focus on ''the living soil,'' on optimizing the use of biological processes and on avoiding the use of synthetic chemicals and fertilizers. Most sustainable advocates agree with a biological focus and hope to reduce but not necessarily eliminate chemical use.

Major impetus for the new vision also evolved from the 1960s era of intense agricultural development. The magnitude of the chemical revolution with its newly available pesticides, herbicides, and fungicides plus the availability of concentrated, more easily handled fertilizers very much narrowed the global agricultural development focus to the high productivity of major cereal crops. The very real specter of massive starvation in China and hunger and food deficits in India, Bangladesh, and many other countries drove the agricultural development of the 1960s. The low cost of oil and gas and prosperous northern economies all combined for infrastructure development, high agricultural inputs, and the well-known green revolution of this period.

A backlash of environmental impact, embodied in Rachel Carson's *Silent Spring* (Carson, 1962), the oil crisis of the early 1970s, and concern over a growing gap between rich and poor people and nations all set the stage for the new vision. The senescence and decline of rural communities in the United States during the 1970s and 1980s added urgency to the social dimensions of agriculture. The narrowness and focus of the development debate of the 1960s set the stage for a new, broader vision that included revisiting the old and much introspection amid assurances of decreasing real food prices and near-term global food security.

The 1980s and early 1990s produced a plethora of sustainable agriculture development writings. *Future Horizons: Recent Literature in Sustainable Agriculture* (Hegyes and Francis, 1997) is an excellent review of this broad literature. The terms ''low-input sustainable'' and ''alternative agriculture'' appeared frequently and are still used by many non-American authors, particularly with reference to organic production systems. The *American Journal of Alternative Agriculture* was founded in the mid-1980s, and in 1989 the NRC's report, *Alternative Agriculture* (NRC, 1989) brought the name ''alternative agriculture'' to prominence. Alternative agriculture was defined, in these sources, as any food or fiber production that has:

- a more thorough incorporation of natural processes;
- reduced use of off-farm inputs, with less harm to the environment and consumers;
- a more productive use of the biological and genetic potential of plants and animals;
- a better match between cropping patterns and the physical capacity of lands; and
- an improved emphasis on conservation of soil, water, energy, and biological resources.

Alternative agriculture is not synonymous with organic agriculture (which completely avoids synthetic chemical inputs), but they share many of the same farm management practices and approaches.

The 1980s and 1990s led us from a primary focus on engineering and chemistry in agriculture toward a greater emphasis on biology – from an age of ''alchemy'' to the age of ''algeny'' (Rifkin, 1983). The adoption of the term ''agroecology'' signaled a reemphasized trend in holistic thinking and analysis. A shift in emphasis within the field of ecological science toward managed ecosystems in the late 1980s added significant perspective. Entomologists, agronomists, and other scientists began to use an ecological, process-oriented approach. Stephen Gliessman's *Agroecology: Ecological Processes in Sustainable Agriculture* (Gliessman, 1998) is an example of one book on this topic. The infusion of ecological thinking has added clarity to our understanding of overlays of subsystems, of spatial hierarchies, and of how complexity makes up an agricultural ecosystem. It has added to the understanding of multiple functions of an agricultural system and to the notion of ecosystem services. Most importantly, agroecology has taken the analysis of sustainability to a process level of understanding that allows us to understand gradients of change in production systems across time and space.

Giving greater voice in development direction to farmers has been another significant dimension in sustainable agriculture. It was very apparent that much, if not most, of alternative agriculture had originated with farmers. Philosophical direction had been heavily influenced by farmer-writers. The resurgence of on-farm research in the developing world of the 1970s (Harwood, 1979) was followed by similar emphasis with farmer collaborators in the United States in the 1980s and 1990s. Farmers have been increasingly invited to serve on steering committees and research grant award committees for sustainable agriculture projects.

Farm family well-being and that of their rural communities has been another major area of merger and inclusion in the sustainability vision. The many links and interdependencies between human and community development and sustainable agriculture are being considered in the structure and design of food systems. In 1986, Dahlberg, presented a comprehensive and thought-provoking collection of writings on social, economic, and structural issues (Dahlberg, 1986). The importance of farm size, community interaction, and the global structure of the food system is seen to be critical to both social and economic well-being. Heffernan (1997) forcefully makes the point that with globalization of capital markets and the resulting centralization of control and ownership (of both input supply and product handling and processing) have come a reduction in market competition, a shift in the balance of economic power away from the producer, and a replacement of farm-level production instability with greater macroeconomic instability in the marketplace. Much of the current literature on the social dimensions of sustainable agriculture is found in *Agriculture and Human Values*, the Journal of the Agriculture, Food, and Human Values Society.

Economic dimensions of sustainable agriculture have been typically associated with whole-farm studies comparing organic with "conventional" farms in the late 1970s, exemplified by paired comparison studies in the Midwest (e.g., Lockeretz *et al.*, 1981). Other, single-farm studies have been reported, such as in the case studies of the NRC's report *Alternative Agriculture* (NRC, 1989). Most of these studies have shown organic farms, in most years, to be as profitable as conventional farms. Most of the sustainable agricultural production research of the past two decades has focused on comparisons of crop rotations and use of cover crops and other systems component practices.

There has been a growing crescendo of voices critical of the failure to account for the side effects, the "external costs" of conventional agriculture (e.g., Roberston and Swinton, 2005). These external factors impact communities, the environment, and human health. There is increasing criticism of the emerging structure, which includes farm scale, the patterns of movement of food, and the corporate concentration of input supply and processing on a global scale. A significant component of the sustainable agriculture debate concerns the desirability of some portion of foods being of local origin, with the size of that portion related to location and community development status (Shuman, 1998; Harwood, 1998).

Scientific projections for the required incremental and transformative changes needed in US agriculture in the coming decades are based on the integration of biological, social and economic interactions across a range of scales to provide the necessary increase in resource use efficiency to supply the multitude of products and services expected by society. Robustness at varying scales, based on productivity, resilience and resistance to shock must be increasingly incorporated into systems design (NRC, 2010).

Long-standing schools of thought and practice in agriculture, influenced by changes in science and technology and in food system structure, have thus provided much of the content of the present-day sustainable agriculture agenda or vision. The amalgam of ideas and component factors has provided an extremely rich background from which development direction can be modified. The breadth of the agenda and the level of dissatisfaction with the current system point to a very major underlying problem of the global, monetarily driven process that is directing and fueling current change.

Most of the sustainable agricultural debate concerns differences in goals and in ethical and value dimensions between farmers, agriculture as a sector, and national, international, and global interests as pointed out so clearly by Dahlberg (1985). Many of the resources used and managed by agriculture and many of the services and outputs from agriculture that are critical to ecological and human well-being lie outside the monetary process that is currently driving global agriculture. If the marketplace does not put value on those dimensions and the political process either cannot or will not value them, there is a high level of disarray. Much of today's sustainable agriculture debate revolves around these value differences. Many of these sustainability issues are deeply imbedded in the current public debate over genetically modified organisms.

Indicators of Sustainability

What agricultural practices are sustainable? This is an area of intensive research. Sustainable practices must meet the three criteria defined *in* Elements of Sustainability: They must be economically viable, environmentally safe, and socially acceptable. There is no single prescription for sustainability; sustainable practices will vary by cropping system, local environment, and socioeconomic system. Nonetheless, emerging research results suggest that locally sustainable systems tend to be more resource conservative than less sustainable systems and tend to rely less on external subsidies and more on internal ecosystem services.

Resource Conservation

Resource conservation means that those resources on which sustainability depends are conserved and even enhanced by agronomic management. Soil organic matter is a good example of an ecosystem resource that is easily reduced without effective management. Soil organic matter declines rapidly in almost all cropping systems following initial cultivation – typically to 40–60% of original values within a few decades. However, soil organic matter is a valuable resource, providing habitat and energy for soil organisms, a soil structure favorable for plant growth and water retention, and a chemical structure favorable for nutrient retention (Robertson and Grandy, 2006).

The loss of soil organic matter is often associated with a need for greater external inputs. Cropping practices that conserve or enhance soil organic matter buildup will invariably enhance the environmental and often the economic sustainability of cropping systems. Crops grown in high-organic matter soils have a better water and nutrient environment than similar crops grown in soils that are depleted in organic matter, and thus they may require fewer external inputs for the same productivity. Additionally, less soil erosion and lower runoff from high-organic matter soils better protects downstream environments from agronomic impact. Therefore, cropping practices that conserve soil organic matter can be considered more sustainable than those that do not.

Often, however, there are trade-offs that require any specific conservation effort to be evaluated in the overall context of sustainability. For example, conservation tillage typically slows or stops soil organic matter loss and thus can be considered a resource-conserving, sustainable cropping practice. However, tillage controls weeds in cropping systems, and in the absence of tillage weed control is typically achieved with herbicides, which have environmental and economic costs different from those of tillage. Is the maintenance of soil organic matter as sustainable in light of a more intensive reliance on herbicides? Ideally, such trade-offs can be minimized. For example, winter cover cropping can also reduce soil organic matter loss and additionally can reduce nitrate leaching and suppress weeds, without the need for additional herbicide (Snapp *et al.*, 2005). Each cropping practice must be evaluated in a whole-system context to adequately evaluate its contribution to a system's sustainability.

Ecosystem Services

Ecosystem services are the benefits people obtain from ecosystems, often categorized as provisioning, regulating, cultural, and supporting (Millennium Ecosystem Assessment, 2003). Unmanaged systems provide such services as a matter of course. Farms are historically valued for their provisioning services – food, fuel, and fiber production – but in fact provide a whole host of other services ranging from pollination and disease regulation (regulating services) to soil and nutrient conservation (supporting services) to aesthetic amenities and a sense of place (cultural services) (Swinton *et al.*, 2007). Ecosystem services are integral to the functioning of healthy ecosystems.

In modern cropping systems many services provided by the original ecosystem before its conversion to agriculture have been suppressed or ignored in favor of services provided by external inputs. In a nitrogen-poor native ecosystem, for example, biological nitrogen fixation by native legumes such as clover (*Trifolium* spp.) might be a principal source of fixed nitrogen; modern cropping systems instead rely almost exclusively on industrially fixed nitrogen provided as inorganic fertilizer (Robertson and Vitousek, 2009). In an unmanaged system, insect herbivory is suppressed largely by trophic and structural complexity that enables insect and vertebrate predators to keep plant pests at bay. In most modern systems insect pests are controlled with insecticides, which also kill insect predators. Managing a cropping system with legumes or with greater plant diversity (either within fields or in the landscape) would allow the ecosystem to provide more of the services now provided via external inputs. Legume cover crops can reduce the need for external nitrogen, and greater plant diversity can provide the structural complexity and refugia needed to support predator populations in otherwise monospecific landscapes.

Just as for practices intended to enhance resource conservation, practices established to reintroduce or enhance existing ecosystem services need to be evaluated on the basis of their total net contribution to sustainability. Although nitrogen fixation by legumes can lower the need for fertilizer inputs and benefit soil organic matter buildup as well as provide winter habitat for predaceous insects, there is little evidence that legume-fixed nitrogen is conserved more tightly than fertilizer-derived nitrogen. Thus, there may be no downstream environmental benefit associated with this ecosystem service. Likewise, animal manure produced on-farm and recycled back to the field may be less conserved than fertilizer nitrogen if the manure is added at a time of low plant nutrient demand. Ongoing research is helping to identify ways in which management can add ecosystem services that both enhance resource availability and reduce the environmental costs of agriculture. At the societal scale there is ongoing debate on how to value services provided by farms to their neighboring communities (Robertson and Swinton, 2005). Should farmers be compensated for managing their land in ways that provide services to local, regional, and national communities? Such payments occur on a small scale in some parts of Canada, the United States, and Europe today.

Examples of Sustainable Cropping Systems

Bush-Fallow Rotation Systems

Perhaps the best documented example of a locally sustainable cropping system is the bush-fallow rotation, also known as swidden and slash and burn agriculture, indigenous to many cultures before the advent of continuous cropping systems several hundred years ago, and still evident in the humid tropics today. In the absence of population change, the bush-fallow system allows a tract of forest or savanna to provide food with few subsidies other than human labor.

In these systems, a small section of native vegetation is cut and cropped. Crop nutrient needs are met by the decomposition of soil organic matter and perhaps by leguminous crops. Sufficient pest protection is provided by crop rotation, complex crop mixtures, and the proximity of fields to native vegetation. Weed suppression is performed by hand.

Once soil nutrients are depleted to levels that significantly compromise crop productivity, the plot is abandoned to "bush fallow" and another plot is cleared from native vegetation and cropped. Meanwhile, the now-abandoned but newly fallowed plot is undergoing secondary succession with attendant recovery of soil nutrient stores. By the time several more plots have been sequentially cut, cropped, and fallowed, the original plot will have recovered much of its original fertility and be ready to be cleared and cropped again.

Such agronomic systems are sustainable indefinitely as long as each cropped area is allowed sufficient time to recover its original fertility. However, when land becomes scarce because of development or population growth or both, the system can quickly fail. Native vegetation brought out of fallow too quickly will provide soil fertility for only a portion of the former cropping periods, so the crop portion of the rotation will either be shorter or yield less, forcing more of the native vegetation to be brought out of fallow earlier than planned in order to feed a growing population. Eventually, little native fallow will remain and crops will be grown continuously on soils that now lack much of their former fertility. One of today's greatest agronomic challenges is providing nitrogen and phosphorus to cropping systems that until recently have been in bush-fallow rotations, especially in sub-Saharan Africa where fertilizer is largely unavailable and most food is grown on small holdings of a few hectares. The maintenance of soil quality and adequate levels of soil organic matter to provide it are major concerns of tropical agronomists. Promising recent advances include the incorporation of more biodiverse rotations with modest fertilizer inputs to provide services elsewhere provided by intensive external inputs (Snapp *et al.*, 2010).

Multifunctional Agriculture

The successor to simple bush-fallow systems is mixed farming systems that have several production enterprises of different herbaceous crops, trees, animals, or combinations of crops and animals. In less developed or unstable economies requiring a high level of local, community, and farm family self-reliance, the production of a wide array of goods was primarily to meet family and local market needs and to ensure a year-round supply of food, fuel, and building materials. Farm and landscape-level diversity optimized stability within local environments and increased the resiliency of the system to a wide variety of disturbances. The diversity of land use provided a wide range of ecosystem services, including precipitation management, groundwater recharge, wildlife habitat, an environment usually conducive to adequate pest-predator balance, and some mitigation of harsh climatic conditions. The mixed plant community provided shade, wind protection, privacy, and many other, often seasonal, assorted products and services. This range of outputs has recently been termed the multifunctional character of agricultural land (Food and Agriculture Organization, 1999; Boody *et al.*, 2005) shown in **Figure 1.**

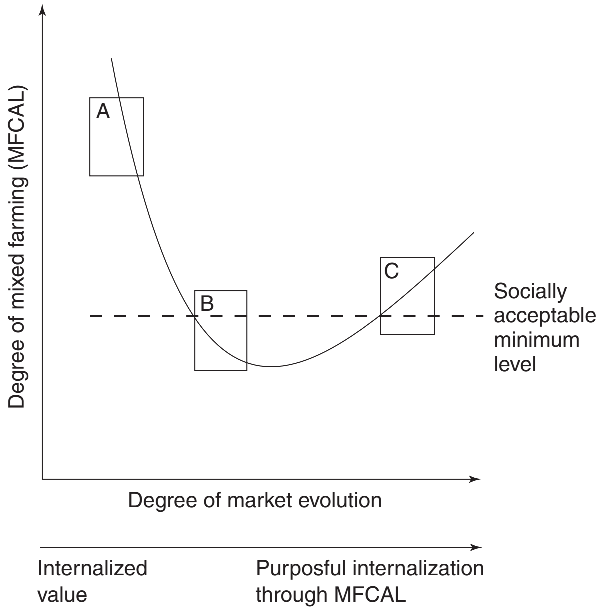

Figure 1 Changes in the purposeful development of the multifunctional character of agricultural land (MFCAL) as markets evolve (adapted from Fresco L, personal communication).

As infrastructure and markets develop, the need for a broad range of products and services decreases. When the costs of adverse environmental impacts such as groundwater contamination are not internalized, or when farmers are not rewarded for ecosystem services that their farms provide to the community or region, they do not include such values in their farm enterprise unless they are motivated and willing to make an altruistic contribution. Many farmers, in fact, do this now, but ultimately the more narrowly focused economic marketplace rules. Today's farms in highly developed economies frequently have a level of product and land use specialization that is well below an acceptable standard for long-term environmental and resource sustainability (**Figure 1, Box B**). In other words, the production base, the environment, and its ecosystem have not been stabilized and are being degraded. With continued market evolution, farmers may be increasingly compensated for the full range of ecosystem services as well as actual product output that they provide (Shuman, 1998; Soule and Piper, 1992; Robertson and Swinton, 2005) (**Figure 1, Box C**).

A more immediate incentive is to add crops and/or livestock to provide integration efficiencies. These efficiencies include the increase in yield of one crop following another, the savings in nutrient inputs, or the reduction in pest control costs (**Table 1**).

An increasing amount of information on the efficiencies of specific technologies for integration is becoming available in the scientific literature. The reduction in input requirements is often a key part. There is less direct research information on the relationship of many of these practices for mitigating environmental harm. An exception is the wealth of data on reduced soil erosion as a result of reduced or zero tillage. Currently, the predictive models of loss of pesticides, nutrients, or crop or animal residues are rudimentary. Direct

Table 1 Michigan maize, soybean, and wheat rotation efficiencies

System, advantages
Maize after beans
30 kg ha^{-1} nitrogen credit
No rootworm scouting or control costs
6–10% yield advantage
Maize after soybeans dry beans wheat (Michigan, second, third year of rotation)
No nitrogen credit (since maize follows wheat)
No rootworm control costs
Window for perennial weed control (either mechanical or chemical)
Greater than 10% yield advantage (because of the preceding bean/wheat sequence)
Maize after wheat plus frost-seeded clover
40 kg ha^{-1} nitrogen credit (60–70 kg N ha^{-1} with presidedress nitrogen test)
No rootworm control costs
At least 15% yield advantage
30–50% yield advantage if the farm is organic, where maize-after-maize is not advisable

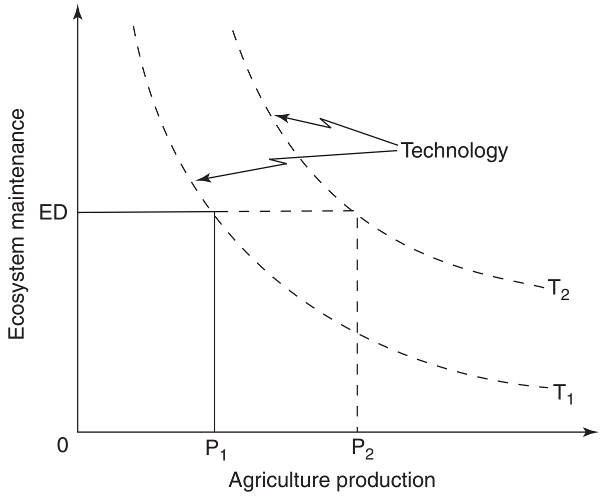

Figure 2 Effect of technology selection on the relationship between agricultural production and ecosystem maintenance. ED, environmental disturbances; T_1, inappropriate technology; T_2, more appropriate technology; P_1, agricultural production with technology T_1; P_2, agricultural production with technology T_2 (adapted from NRC (1993)).

measurements of loss from alternative rotations and use of cover crops are very difficult, expensive, and location specific. These rotation and cover crop practices are widely acknowledged as fundamental to sustainability. Their efficiencies are being quantified with respect to yield, input reduction, and soil quality and the prevention of soil loss. Michigan data show, for instance, that wheat in rotation loses less than 20 kg N ha^{-1} year^{-1} via groundwater leaching. Well-fertilized continuous corn averages 50 kg N ha^{-1} year^{-1}. Most U.S. farmers use at least a two-crop rotation.

Animal integration in crop systems is declining in the United States. Poultry and turkeys are increasingly produced in specialized production facilities not located on the farms where their feed is produced. They are usually located in areas where agricultural land is available for manure application, often on a contract "disposal" basis. The level of crop or animal diversity that is appropriate on a farm to balance the market forces for specialization with the need for biological efficiency and ecosystem maintenance is very situation specific. As enterprise integration increases with an effective level of appropriate technologies and their effective management (Figure 2, technology T_2), agricultural output can be maintained at a much higher level for a given amount of ecosystem disturbance. In other words, sustainable agriculture can maintain productivity at a much lower level of ecosystem disturbance. Very large-scale operations tend to have less diversity, in part because of the greater difficulty of managing diverse enterprises. Crop and animal management requires numerous and often frequent decisions to be made as conditions change that are often stimulated by visual, difficult to measure changes. The frequent presence and sensitivity of the manager, the experience in production management, and the ability to make decisions place limits on the scale of highly diversified operations. Every farm owner experiences this tension.

On a global scale, under conditions of high population density, small farms, and the need for producing a wide array of products in often marginal production environments, a very diverse type of farm enterprise mix is common. Trees become a very important part of farm productivity in the higher rainfall areas where they are a part of the native vegetation. Animals are more often than not a part of the enterprise because they consume crop residues and add significantly to overall productivity (Figure 3). In most developing countries there is very little area of undisturbed forest, and in only a few in which large tracts of land remain is there cattle only on farms. In the humid tropics the mixture of crops, trees, and animals

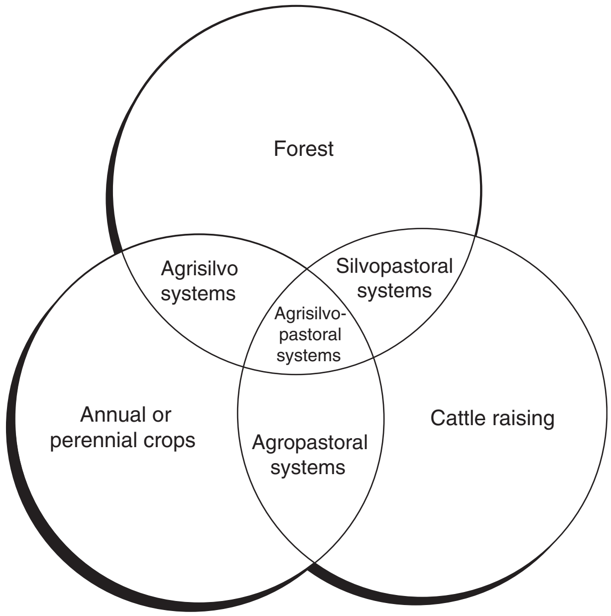

Figure 3 Combinations of enterprises in mixed farming systems (redrawn from Serrão EAS and Homma AKA (1993) Brazil. In: National Research Council. (eds.) *Sustainable Agriculture and the Environment in the Humid Tropics*, pp. 265– 351. Washington, DC: National Academy Press, with permission from Dr. Scott).

(agrisilvo-pastoral systems) represent the great majority of farms. Where human population is relatively high (> 300–500 persons per square kilometer) in rural areas, if there is poverty combined with modest levels of rainfall (less than 1500 mm year^{-1}) and/or cool temperatures for part of the year, fuel for cooking and heating becomes a problem. Resource degradation and loss of production potential often occur as the standing stocks of carbon (particularly in trees) and eventually the soil carbon stocks are reduced as crop and animal residues are burned. The system rapidly loses crop nutrient holding and recycling capacity, and its ability to intercept and retain rainfall decreases. Most developing country mixed farms have a larger portion of cash grain crops.

Many countries in eastern Africa (Kenya, Ethiopia, Rwanda, Tanzania, and Uganda) have these exacting conditions. Rural well-being depends on small farms (between 0.5 and 1.5 ha) supporting families by providing food, fuel, building materials and cash income (**Figure 4**). Ruminant animals (often dairy cows or dairy goats) are a key part of that production. The productivity of the animals and their welfare through the dry season depends on fodder trees and other perennials, which are nearly always mixed into the landscape in intricate patterns. There is always a high diversity of food and fodder crop species, which protect the soil from erosion in sometimes heavy rainstorms and give the systems overall stability and resilience. Improved varieties of both trees and crop plants and improved animal breeds are critical to ongoing improvements (Pye-Smith, 2010).

Figure 4 In Kenya's densely populated Central Province, multi-functional agriculture includes grain and tree crops as well as ruminant animals such as dairy cows that depend on trees for fodder (credit: ICRAF/C. Pye-Smith).

Conclusions

Our global food and fiber production systems are undergoing an enormous transformation, driven by rapid advances in the sciences of biotechnology, engineering, and food processing and chemistry. The increasing centralization in the manufacture of agricultural inputs and in the collection and processing of food is causing huge economic and social change. Many social and political values are being challenged. The global marketplace forces product uniformity and the geographical concentration of its production are driving farmers toward a level of specialization that results in farms with much less diverse crop and animal enterprises on the landscape than that desirable for the maintenance of many ecosystem services. Markets have not yet matured to adequately value these services, especially those that affect environmental quality, nor in most places have governments established disincentives in order to protect them. The greatest challenge to sustainability, with its many economic, environmental, and social dimensions, is the lack of public awareness, vision, and will to implement necessary changes. In some cases, research is needed to clarify the value of alternative strategies and to provide additional options for sustainable management.

In many if not most places food is not being produced sustainably, i.e., in a manner that is economically viable, environmentally benign, and socially acceptable to many who are affected by its production. On the other hand, new research is showing that sustainable cropping systems can be designed to operate effectively, using ecological knowledge to substitute for some of the management options now provided by external inputs, and in a way that has a less adverse environmental and social impact than conventional management. A better understanding of agricultural ecosystems and the services they provide, coupled with new technology, may provide the advances needed to feed – sustainably – a burgeoning global population in the decades to come.

See also: Agriculture, Industrialized. Agriculture, Traditional. Biodiversity as a Commodity. Ecosystem Services. Herbicides. Nitrogen, Nitrogen Cycle. Pesticides, Uses and Effects of. Soil Conservation

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