Regenerative, Semiclosed Systems: A Priority for Twenty-First-Century Agriculture

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This overview draws attention to several reasons to encourage the design of new agronomic systems, shifting from conventional open or leaky systems to more closed, regenerative systems: Current systems cause overconsumption of environmental resources, contribute to climate change, rely on increasingly expensive fossil fuel, and result in environmental (e.g., groundwater) contamination. Moreover, the agronomic–urban interface is growing, as are markets for ecologically friendly produce, the need for low-input farming systems in low-income regions, and disenchantment with the subsidization of conventional agriculture. There is reasonable biological and economic evidence to support advocacy for a shift to regenerative systems. Such a shift presents challenges—for example, although higher labor input enhances community well-being and rural social capital, it is costly. It also offers opportunities—for example, to adapt technologies to monitor and minimize wastage. Shifting to semiclosed systems would be accelerated by (a) routine life cycle analysis and costing; (b) calculation of the full costs to society of farm inputs such as pesticides; (c) food labeling and standards that draw attention to energy and other inputs; (d) government grants supporting the transition to semiclosed systems; (e) changing priorities for agronomic research; and (f) greater engagement of urban societies in agriculture through recreation and philanthropy.

Keywords: agricultural policy, agroecology, agronomy, sustainability, organic agriculture

The price of food when adjusted for inflation has declined more or less steadily since it was first recorded around 1770. Underlying this trend, which has been recognized for at least 50 years by Schultz (1954) and others, is the low level of income elasticity of demand for food, so that as income rises, demand increases for value-added services but not for the quantity of food. Agricultural scientists and farmers have responded by increasing production through advanced technology and greater use of off-farm inputs (such as fertilizers and transport) relative to on-farm inputs (labor and land). All of the above, in turn, cause aggregation of farms, resulting in fewer farms, farmers, and farm employees.

Global affluence, innovation, and competitiveness within the agricultural sector itself have therefore led to lower prices for agronomic products (e.g., grain); increased production; advanced technology; more inputs; a higher percentage of off-farm inputs; fewer farm workers; and longer and more complex chains of production, from supply to value adding and marketing. In turn, larger volumes of products, ever declining margins of profitability, and complex chains involving a number of managers (as distinct from the simplest model of a single farmer or producer who also acts as a retailer) all encourage a shift to more open systems. Fertilizer and other inputs are obtained wherever they appear to be cheapest in dollar terms, without consideration of renewability or life cycle costs. When used excessively, these inputs migrate outside their area of application (e.g., fertilizers enter groundwater), and by-products that in a traditional farming system might have been put to use or recycled on the farm (e.g., traditionally, leaves are used for wrapping food or recycled as manure) tend to be discarded as waste that is "too expensive" to use in open, complex food chains.

Reasons for this analysis

This overview presents reasons that researchers and policymakers should encourage the wide-scale transition from open or leaky farming systems to semiclosed or regenerative systems. There are at least eight reasons to encourage this transition:

1. Total global consumption, many argue, is no longer sustainable. As early as 1996, Wackernagel and Rees calculated that the global use of biological resources—humanity's "ecological footprint"—exceeds the capacity of the world's land and seas to create or renew those resources. Because agriculture is the largest user of land, a review of the regenerative efficiency of agronomic systems is in order.
2. The problem of greenhouse gas emissions, and the commitment of many governments to addressing rising temperatures and atmospheric concentrations of greenhouse gases, will focus attention on how agronomic

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practices can be modified to meet targets for greenhouse gas reductions.

3. Rising oil prices (173% from 2002 to early 2006) raise questions about the viability of the trend toward complex, globally distributed agrifood chains, and about the economics of the heavy use of inorganic fertilizers. Rising oil prices also make on-farm generation of energy (from wind, fermentation of biosolids, etc.) more attractive, thereby making systems more closed.
4. Large-scale, relatively open, high-input agronomic systems are being criticized for their impacts on landscape aesthetics, biodiversity, soil (e.g., structure, organic matter, biota), groundwater, and—not least—the fabric of rural communities. Agronomic consumption of water is a particularly pressing problem, which will be aggravated by global warming, growing urban populations, and irrigated agriculture.
5. Urbanization has led to awareness of the need to create agronomic–urban juxtapositions or mosaics, which implies reconsideration of less open, and possibly smaller-unit, farming.
6. Farming practices that are marketed in affluent countries as "good" (e.g., organic agriculture) are commanding price premiums, indicating an opportunity for further market differentiation and premiums.
7. Less affluent countries (e.g., in sub-Saharan Africa) need low-input farming systems because of the high costs or lack of availability of some off-farm inputs, such as inorganic fertilizers.
8. Disenchantment with continued subsidization of conventional agriculture is growing, especially among affluent urban taxpayers and the World Trade Organization. It is likely that agriculture will need to project and implement a new vision to capture continuing financial support from urban taxpayers in countries such as the United States.

These issues overlap and sometimes conceal contradictions. To minimize confusion, this overview begins with some definitions.

Defining agronomic systems

No agronomic system is closed, because its purpose is to produce an output—say, grain—which is removed from the farm and consumed. Minerals and energy are removed from the farm with the grain. Semiclosed systems, here described as "regenerative," are those designed to minimize external inputs or external impacts of agronomy outside the farm. For example, the extent to which a system can be called regenerative depends on how much the system minimizes its import of fertilizers and pesticides in excess of what will be removed within the grain or other products (e.g., corn stalks, or stover, to be processed into wallboard or car parts) and eliminates unused by-products. The term "regenerative" is proposed because "semiclosed" is cumbersome and unlikely to attract public support (see point 8, above). By contrast, relatively open systems—which, driven by historical reasons or by comparative prices, constitute mainstream agriculture—have progressively reduced labor and recycling on the farm and increased off-farm inputs (and possibly outputs) such as fertilizers, fuel, and pesticides.

A sustainable system may be defined as one that can maintain itself, whether biologically, economically, or socially, or it may be defined in relation to the level of management (e.g., inputs) required to maintain its biodiversity and outputs (Pearson and Ison 1997). Others define sustainability in terms of goals (for example, Pretty [1998] aims for "a thorough integration of natural processes"), in terms of some characteristics of the system itself, or in terms of the ongoing flow of outputs from the system (Smith and McDonald 1998). Because of these definitional ambiguities and other issues (e.g., scale; Pearson 2003), this overview avoids the term.

Organic systems are those that are certified under a regional or nationally registered scheme. They are examples of semiclosed systems. However, although the concept of a cyclical or regenerative system is the foundation of organic agriculture and is recognized by certification bodies, only the Australian National Standard explicitly mentions closed systems: "A developed organic or biodynamic farm must operate within a closed input system to the maximum extent possible."

Regenerative systems encompass a range of locally adapted "packages" aimed at minimizing inputs, leakiness, and chain distances. They include organically certified agriculture. However, the generic system (regenerative) is not synonymous with the specific example (organic); there are aspects of organic certification that are irrelevant or unhelpful to maintaining a regenerative system (e.g., no chemically treated fertilizer is allowed under any of the organic standards). By contrast, regenerative systems with minimized inputs and nonuseful outputs create opportunities for high-technology initiatives such as information technology and robotics. Nonetheless, this overview often cites studies on organic agriculture, as they provide relatively well-defined and independently researched examples of semiclosed or regenerative systems.

Analysis of agronomic options

Figure 1 illustrates the differences in cycling and use of energy and materials between conventional and regenerative agronomic systems. Conventional systems have evolved to consume relatively high levels of inputs with generally little or no recycling from processors and consumers. By contrast, the regenerative system relies less on inputs and more on recycling, eliminating waste from the agronomic system and minimizing it from the processing and consumption systems.

Impact of agriculture on environmental capital and climate change. Concern about the ability of the environment to maintain human life (e.g., Wackernagel and Rees 1996 and more recent analyses) has led to studies comparing the value of food production per hectare (ha) in terrestrial (crop and rangeland) systems with the value of natural capital, annualized in terms of water, biodiversity, soil and erosion control, aesthetics, and recreation, both globally (Constanza et al. 1997) and for catchments (Olewiler 2004). Environmental goods and services are generally calculated to have greater value than food production from the same land (Constanza et al. 1997, Balmford et al. 2002). This could be turned on its head as a justification for the full costing of food, but the real cost (as compared with the retail price) of food continues to receive little attention. Instead, these studies provide quantitative justification for government support (both financial and in preservation policies) for environmental goods and services. The logical consequence is that public policymakers may increasingly expect future research into agronomic systems to enhance value, and to account for the impact of innovative technologies in terms of both food production *and* environmental services. In this way, regenerative systems can be designed to strike a balance between environmental goods and services and the output of food, whereas conventional agriculture ignores environmental benefits or treats them separately.

There are also studies that quantify the off-farm impacts of agriculture on the environment and the costs of these external impacts to society. For example, Pretty and colleagues (2000) estimated the costs of the external impacts of agriculture in the United Kingdom to be on the order of £208 per ha; gas emissions accounted for about half this amount, and groundwater contamination by pesticides was another major item. Pretty and colleagues (2005) estimated that the real cost of the UK food basket is increased by £2.91 per person per week when negative external costs, from farm to consumer, are incorporated.

To be evenhanded, I should note that conventional agriculture also has numerous beneficial impacts, which have not been measured in studies such as Pretty and colleagues'. These include nutrient cycling (although in the context of controlling greenhouse gas emissions, carbon sequestration may become more important than cycling), landscape and aesthetic value, and, in some locations, water accumulation and supply. Hanley and Oglethorpe (1999) and others address these positive impacts. In the main, however, the negative impacts of agriculture are particular to leaky or open agronomic systems, whereas the positive externalities that are by-products of leakiness can be designed into semiclosed systems.

Greenhouse gas emissions and climate change are components of, but in the public mind separate from, environmental capital. Agricultural emissions vary widely, depending on the type of agriculture (e.g., Australia's agricultural emissions are high relative to other developed countries because of the country's relatively large livestock population) and on the complexity and efficiency of the food chains (e.g., transport emissions). Nitrous oxide (N_2O; largely associated with nitrification of fertilizer nitrogen) and methane from ruminant livestock usually account for two-thirds of agronomic emissions. These two important sources of greenhouse gases—fertilizers and belching cattle and sheep—represent inefficient uses of nutrients and energy that will improve, with benefits for greenhouse emissions, when agricultural systems become more closed and less leaky (e.g., in Australia [DEH 2005], in the United States [USEPA 2005], and in Canada [Environment Canada 2006]).

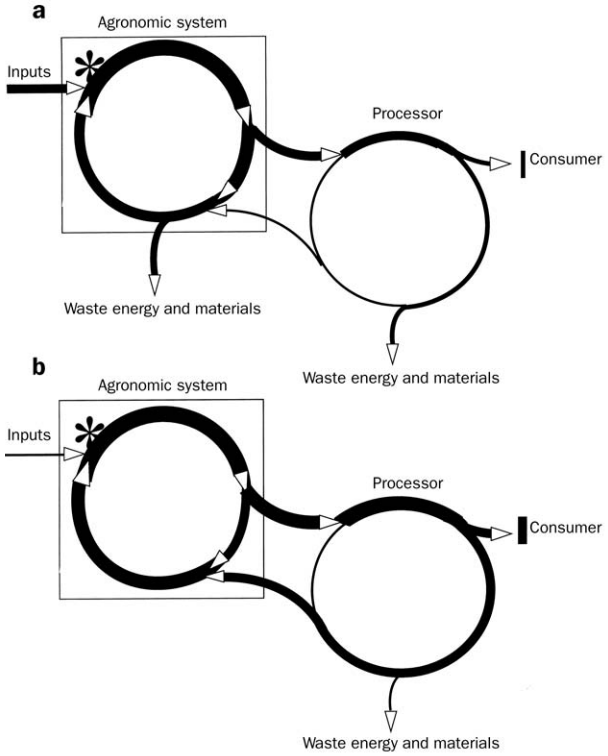

Figure 1. Schema of (a) current mainstream, conventional or industrial agriculture and (b) regenerative systems. The width of arrows is indicative of the relative flow of energy and materials; the asterisk represents energy capture within the agronomic system. In regenerative systems, inputs are much reduced because of direct in situ *energy capture (e.g., wind, fermentation of biosolids) as well as photosynthesis. The percentage of productivity that is harvested and processed (e.g., as biomaterials) increases, leading to relatively higher yields to the consumer, more cycling back into the agronomic system, and reduced waste energy and materials.*

Inputs and outputs of various agronomic systems. All agronomic systems are to some extent open; organic systems, which are a relatively low-technology example of regenerative systems, depend on lower levels of externally sourced inputs, some of which come from nonrenewable sources and all of which incur processing and transport energy and cost (Edwards-Jones and Howells 2001). Although not currently required, it would be helpful if all certified variants of regenerative systems (e.g., organic, perhaps some LEAF [Linking Environment and Farming]–certified systems) documented or even set limits to the amount or percentage of inputs that are sourced off the farm; this would proactively address contemporary urban concerns such as energy costs and environmental degradation associated with agriculture.

Off-farm inputs are less for regenerative than for open systems, but are seldom zero: Nutrient budget deficits in phosphorus and potassium, and sometimes sulfur, are often identified in organic systems (Berry et al. 2003). Soil organic matter routinely increases as systems become more closed (Pimentel et al. 2005). As some recent research indicates, soil quality and health are related to organic matter, with some interesting and perhaps ecologically significant complexities. For example, Popp and colleagues (2002) created a soil quality index involving soil water, organic matter, bulk density, and pH; all of these parameters are affected by organic matter. Further, they showed that the relationship between soil quality and crop production varied with the soil system: On poorer-quality soils, inorganic fertilizer and tillage were used to compensate for soil quality, but as the inherent soil quality became more degraded, inorganic inputs became less and less effective.

The higher level of soil organic matter in semiclosed systems, compared with open systems, creates greater sinks for both carbon (addressing greenhouse warming) and water (addressing the approaching global water shortage; Brown 2003). This also creates a soil microbial flora that is more abundant and more diverse. While this is philosophically attractive, given ecologists' quest to maintain biodiversity, Welbaum and colleagues (2004) cautiously conclude that it is not clear whether microbial species diversity is critical to soil health or "merely evidence of built-in redundance." Higher levels of soil organic matter and water in organic systems also produce more earthworms and microarthropods (Hanson et al. 2001). With modern molecular biology, it is now opportune to further study soil organisms and their function and management.

Efficiency of regenerative systems. The energetic efficiency of conventional farming systems compared with more closed systems has been studied through both model farm analyses and modeling. Loake (2001) reviews the energy inputs and outputs, and efficiency, of agronomic systems. Table 1 (Loake 2001, collated from Leach 1976) illustrates how different the mechanical energetics are for conventional and organic systems.

Loake goes on to estimate daily, seasonal, and annual human energy inputs in organic and conventional farming, concluding that although the regenerative (organic) system is more efficient overall, it relies more on human energy and might thereby create stress. Dalgaard and colleagues (2001), Flessa and colleagues (2002), and others have established, at least over short-term studies or audits, that lower energy use and greater energetic efficiency are commonplace in regenerative (e.g., organic) farming systems, at least where there are no anomalies of infrastructure (for example, the need to use more energy to transport organically certified beets to a processing plant, as there was only one available in the country; Tzilivakis et al. 2005). A recent study based on data collected in Pennsylvania for 21 years showed that organic corn farming, although requiring more human labor than did conventional systems, used 30% less energy because it needed less machinery, fertilizer, seeds, herbicides, and transport to the field, albeit using more human labor (table 1; Pimentel et al. 2005).

Regenerative systems generally require higher on-farm labor than open systems, as evidenced by a survey of 1144 farms in the United Kingdom and Ireland (Morison et al. 2005). While this is seen in conventional economics as a disincentive to shift to regenerative systems, the reverse might be argued: Higher labor density (so long as it is economical) maintains or increases social capital and community livelihoods. Furthermore, the higher labor inputs that characterize organically certified production need not be carried into all forms of regenerative agronomy: The application of fertilizers and pesticides through "precision agriculture," already employed in large-scale leaky systems, could be deployed to minimize or eliminate waste in semiclosed systems, and the economies of scale and substitution of technology for labor evident in industrial agriculture are equally applicable to regenerative systems.

In the Pennsylvania comparison, corn and soybean yields after a five-year transition were similar in both the conventional and organic systems, and higher in the organic system in drought years. Elsewhere, crop yields in semiclosed systems are reported to be similar to or lower than those of conven-

Table 1. Energy ratios in conventional and organic farming systems in the United Kingdom.

Ratio	Conventional system	Organic system	Ratio calculation	Components of ratio
Gross energy	0.0002	0.0025	Gigajoules (GJ) energy out divided by GJ energy in	Energy out = net yield. Energy in = solar inputs, processing inputs, home-related energy, fertilizers, fuels, electricity, machinery, and feed purchased.
Net energy	0.14	4.09	GJ energy out divided by GJ energy in	Energy out = net yield. Energy in = processing inputs, home-related energy, fertilizers, fuels, electricity, machinery, and feed purchased.
Farm gate	0.34	4.29	GJ energy out divided by GJ energy in	Energy out = net yield. Energy in = fertilizers, fuels, electricity, machinery, and feed purchased.
Direct human	30–35	4.3	Food energy output per person-hour of farm labor (megajoules per person-hour)	

Source: Loake 2001.

tional systems: Where weeds are a problem, lower yields, by as much as 38%, occur in semiclosed systems in Europe, in New Zealand, and elsewhere in North America (Pimentel et al. 2005). In the United Kingdom, Prince Charles's organically certified farm Highgrove reported wheat yields 50% lower than in neighboring conventional farms (Appleby et al. 2004).

The economic returns for organic systems—a measure of efficiency or productivity that takes account of market worth and not, for example, the costs of externalities—are generally similar to or higher than those for conventional systems. Samples of these are shown in table 2, but the table cannot adequately address the profitability of regenerative systems, for two reasons. First, costs based on organically certified farming are not necessarily applicable to regenerative systems in general. As explained above in the section "Defining agronomic systems," to date scientific comparisons of regenerative systems with conventional systems have been limited to organically certified regenerative systems, with their peculiar constraints that create higher labor costs, partly to avoid synthetic chemicals. From a narrow (on-farm) economic perspective, the financial viability of nonorganic regenerative systems is likely to be greater than that of documented organic systems. This is best demonstrated indirectly: The increasing shift to semiclosed (mostly organic) systems, at a rate of perhaps 10% per year, implies profitability (Kuminoff and Wossink 2001), and price premiums (e.g., for organic fruit and vegetables) are maintained despite this expansion (Oberholtzer et al. 2005). The specific case studies in table 2 generally show lower costs of inputs, except for labor (which could be interpreted as a consequence of organic certification, not of semiclosed systems per se). The lower yields common in regenerative systems are sometimes, but not always, offset by these lower costs; they are more than offset by the price premiums that remain common for the outputs. For example, Pimentel and colleagues (2005) found net returns for an organic system (based on lower costs for fertilizer and machinery, zero cost for pesticides, and higher labor) similar to those for a conventional system. Although the returns from the organic farm were lower than those from the conventional farm if the labor costs of the farm family operator were fully priced, the organic farm's profitability was still greater, assuming a premium of 10% or more on the organic produce.

Second, on-farm or whole-farm economic analyses such as those summarized in table 2 do not address the externalities associated with agronomic systems: for example, the costs of manufacturing fertilizer (in money and energy terms) and transporting it to the farm, and the costs of by-products such as excessive fertilizer or pesticides entering the groundwater. Naturally, given that these are difficult to estimate and are subject to many assumptions (Pretty et al. 2000), to date they have been estimated only at regional or national scales. Thus, although table 2 may be instructive, it does not obviate the need to assess the profitability of regenerative systems through an approach that considers costs from start to finish—a whole-of-life-cycle analysis—including off-farm societal as well as on-farm individual costs. This will also identify the leaks in current systems that it would be most advantageous to close.

Considering national energy use, Dalgaard and colleagues (2001) estimated how much energy was used in Denmark for current conventional cropping and how much might be used if the country converted to organic farming. For all crops, despite lower yields, the national energy use per unit of crop production was lower, by between 30% and 60% depending on the crop, in the regenerative system. Furthermore, Pretty and colleagues (2005) estimated that, because leakage from farmland would be minimal, the negative external cost of agriculture for the United Kingdom would diminish by £1129.5 million, or 75%, if the nation converted completely to organic systems.

Table 2. Comparative studies of the profitability of regenerative (specifically organic) and conventional agriculture.

Enterprise	Location	Profit comparison	Source
Corn, soybeans	Minnesota, United States	Net returns without price premiums same over four years; higher profit for organic systems with premiums	Mahoney et al. 2004
Corn, soybeans	North Carolina, United States	Gross returns 30% to 100% higher for organic systems as a result of price premiums, despite lower yields	Wossink and Kuminoff 2005
Corn, soybeans	Northeastern United States	Gross returns lower for organic systems because of labor, but equal if price premium is 10% or more	Pimentel et al. 2005
Flax, wheat, oats	Saskatchewan, Canada	Net returns more than double for organic systems as a result of price premiums and reduced expenses	Bromm 2002
Sunflower, wheat, corn, beans	Tuscany, Italy	Gross margins (without premiums) for organic systems –5% to +5%	Pacini et al. 2003
Various crops	Western Europe	22% to 37% higher costs of production for organic systems, more than offset by price premiums	International Farm Comparison Network, cited by Shadbolt et al. 2004
Apples	Washington, United States	Higher profitability for organic systems; same yields	Reganold et al. 2001
Dairy farming	California, United States	Costs of organic systems 10% to 29% higher due to feed, labor, herd replacement, but offset by price premiums	Butler 2002
Dairy farming	New Zealand	Costs of organic systems 10% to 20% higher (as for California)	Shadbolt et al. 2004

The need to design agronomic systems for urban–agronomic mosaics. Urban spread is a major phenomenon of the 20th and 21st centuries. It takes away high-quality land from agriculture, and it causes the boundary between urban residences and farmland to lengthen and the number of people along the boundary to grow. Table 3 provides statistics for the growth in area of some cities, and a superficial calculation of the likely lengthening of the urban–farming boundary associated with this growth.

As affluent urban populations have grown, the average density of the population has declined (table 3). More land per person has been utilized for living space, thus increasing humankind's ecological footprint even before adding to the calculation the amount of land it takes to feed the increased population and to dispose of its waste.

Table 3. Urbanization: Changes in total population, area, population density, and likely urban–rural boundaries from 1950 to 2000.

City	Population change (millions)	Area change (km^2)	Change in population density (individuals per km^2)	Estimated change in urban–rural boundary (km)
Toronto	3.69	1562	–4837	–
Vancouver	1.49	1006	–1415	–
Paris	3.80	2023	–4815	91
Philadelphia	2.22	3854	–2512	141
Seattle	1.92	2152	–1386	113

km, kilometer.
Source: Wendell Cox Consultancy 2005.

Urban spread has three consequences that will encourage a shift toward regenerative agronomy. First, with residential areas and farmland juxtaposed, there will be less tolerance for agriculture's local environmental impacts (e.g., herbicides or nitrogen in urban groundwater). Tolerance is best estimated in terms of the perimeter, rather than the area, of spreading urbanization: As the perimeter increases, the tolerance of agricultural impacts diminishes. Second, by creating a mosaic of land use and attempting to maintain economically viable farms within a greenbelt, society will increasingly value creative interaction between city dweller and farmer. For example, city dwellers may provide labor (e.g., crop picking as recreation) that compensates for a weakness in organic farm systems, or they may purchase locally produced food directly from the farmers (value adding through social connection between urbanite and farmer). Historically, this has involved mainly fruits and vegetables, specialty crops, and animal products, although in the future niche branding could broaden the range of periurban agronomic products. Third, as conventional farming loses viability on the perimeter of large urban centers or within green "islands" in megacities, there are more opportunities for urban agriculture, sometimes as a part-time activity of urban households.

The growth of urban–agronomic mosaics has led municipalities to legislatively restrict land use to preserve agriculture. In North America, Philadelphia (in 1968) was one of the first cities to pass such legislation, Seattle (in 1990) was one of the most successful examples, and Toronto (in 2004) was perhaps the most radical, at least in terms of the area that the municipality seeks to preserve as an agricultural greenbelt. The 1968 Pennsylvania act (Pennsylvania Municipalities Planning Code Act of 1968, P.L. 805, no. 247; *www.psats.org/mpc/index.html*) sought to accomplish "coordinated development" and "facilitate the present and future economic viability of existing agricultural operations." The Washington State Growth Management Act included "provisions to designate and protect forests, farms, mines and minerals" (Trohimovich 2002), while Ontario's Greenbelt Act 2005 envisages preserving 404,687 ha of farmland surrounding Toronto, although it is not yet clear how this will be achieved economically. The range of instruments for the preservation of agricultural land, and the diversity of the division of responsibilities between national, state, and local governments, suggests that "one size doesn't fit all," and that there may be opportunity for comparative analysis of the effectiveness of various jurisdictions in combating agronomic leakiness.

In the United States, all states except Michigan have differential tax assessment, based on current land use rather than market value. With differential tax treatment already in place, it seems a small step to introduce further differentiation to encourage the transition to regenerative systems, thereby addressing the problem of externalities and creating an opportunity for greater interaction between city dweller and farmer.

Attempting regeneration from the output side. Up to this point, this review has considered the shift to regenerative agronomic systems that results from minimizing inputs and increasing recycling within the farm. Equally challenging, however, is the question of how to create more closed agronomic systems from the output side. The transport of carbon and minerals from farms to urban consumers is inevitable—indeed, it is the objective of agriculture in increasingly urbanized societies. Nonetheless, the depletion of minerals from farms in some areas (e.g., sub-Saharan and northeastern Africa) is severe enough to threaten production (Pearson et al. 1995, van Straaten 2002). Moving to more closed agronomic systems through recycling of food wastes and urban sewage is difficult because of the high transport costs, taboos, and public health issues associated with recycling human excreta. These are all especially difficult issues in developing countries, where arguably there is greatest need for regenerative systems.

Output closure is developing rapidly, through recycling of biosolids from urban sewage to farms and tree lots. For example, 40% of human biosolids from towns and cities throughout Ontario, Canada, and 90% of biosolids from Sydney, Australia, are recycled onto farmland. While current guidelines for application rates are conservative (e.g., 30 to 50 kilograms [kg] nitrogen per ha per year in Ontario), the aggregates are impressive: If a human excretes 100 kg per year, 4% of which is nitrogen, the output for a city the size of Toronto or Sydney would maintain the nutrients for 200,000 ha of corn crops, provided the unharvested crop residues are recycled *in situ*. This would maintain half the farm area of the greenbelt for Greater Toronto, which is more than is necessary to achieve output closure, given that the majority of the greenbelt is likely to be grassland rather than harvested crops.

Issues that remain problematic for regeneration from the output side concern the energy used in transporting biosolids, dewatering, and the injection of liquefied biosolids in the soil. Odor, accumulation of heavy metals in acid soils, pathogens, and pharmaceuticals (40% of which are not absorbed by humans and therefore pass to feces) require and receive monitoring. On the other hand, perhaps biosolids are simply the beginning: Human urine, which is even greater in volume and higher in its concentration of nutrients than biosolids, provides another opportunity to move toward more regenerative agronomic systems.

Redesigning agronomic systems

There are two approaches to changing agronomic systems: (1) farmer-driven incrementalism and (2) a step change in thinking among farmers, scientists, urban taxpayers and voters, and policymakers. The future design and implementation of agronomic systems does not have to progress linearly from enhancement of conventional technology and thence to increasingly open systems with greater use of off-farm inputs. In an approach that counters the trend toward incremental additions of technology to already open systems, mainstream organizations such as the Agricultural Institute of Canada are promoting agronomic best practices that will make systems more closed (table 4). These management changes are relatively simple and can be implemented in the short term, although often they will entail some financial cost. In addition, groups of farmers around the world (e.g., in Denmark, Iowa, Australia) have worked together to eliminate or substantially reduce the negative environmental impacts of their farms (Pretty et al. 2001).

I believe that moving to regenerative agronomic systems will be the biggest contribution that can be made to the "greening of agriculture" (Francis 2004). By contrast, Trewavas (2004) has concluded that "when problems with agriculture emerge they usually hinge around poor management not mode of agriculture." My view takes account of the negative externalities associated with conventional agriculture, while Trewavas's conclusion seems based on maximizing the productivity of the internal agronomic systems. In this context of productivity, advocates of increasingly open systems, and critics of semiclosed systems, suggest dire consequences from reducing production per unit of area. Would this cause more land to be cleared and converted to agriculture to maintain gross food production, or an increasing shortage of food in less affluent countries? Neither is likely. Surplus food production in affluent countries is a problem that distorts world trade and food prices in the less affluent countries, and rising land prices for alternative uses will make it increasingly unattractive to convert land to agriculture. With respect to agricultural production in less developed countries, it has been argued for 10 years that conventional agronomy is depleting soil nutrients and structure (Pearson et al. 1995), and re-

Table 4. Selected best management practices for regenerative systems.

Farm aspect	Expected results once practices or changes are implemented	Best practices to achieve results
Livestock facility management and infrastructure	All facilities leakage free; tolerable but minimal odor and dust	Watertight and certified manure storage; filter strips/fields around potential sources of contaminated water and windbreaks around facilities
Nutrient management	Method and timing of application, and speed of incorporation, to minimize the risk of nutrient runoff and leaching	Applying and incorporating nutrients such that the mineralization of nutrients and crop uptake are synchronized and the application of nutrients does not compromise the physical health of the soil
Energy efficiency	Generating true carbon credits (the energy efficiencies achieved are at least such that if the harvested biomass from a farm was to be converted into ethanol, the amount of energy in the ethanol would exceed the energy expenditure used for the production, transport, and treatment of the raw biomass)	Optimizing nutrient management; minimizing soil tillage; selecting crops that will be dry or require minimal treatment before storage; installing energy-efficient technology in buildings
Biodiversity	Protection of wetlands, highly sensitive lands, and forested lands that are inadequate for agriculture; use of restored watercourses as a corridor for wildlife shelter and as routes for animal migration	Leaving existing wetlands intact; installing vegetated/treed buffer strips along permanent watercourses

Source: Maynard and Nault 2005.

quirements for expensive inorganic fertilizers and pesticides make agriculture less profitable than it might be if farmers practiced regenerative agronomy.

Advocacy of, and research into, regenerative systems will require a shift in mind-set. Urban-based voters in the United States are already accustomed to funding programs for farming and farmers, either through taxation or through environmental cooperatives. The next, essential step is to accept the opportunity to create government programs and private philanthropy that leverage change in agronomic systems. Philanthropy will achieve this directly and through influencing research and government policy.

Regenerative agronomy will, of course, require compromises to balance food production and ecosystem services. Economic valuation of ecosystem services may or may not be necessary to obtain the engagement of policymakers. Two aspects of the valuation issue seem relevant here. First, ecosystem services (e.g., provision of, clean water) have two types of value, relating to efficiency (during linear operations) and to safeguarding the system, and its outputs, from catastrophic or nonlinear change. Faber and colleagues (2002) describe how trees help avert floods, provide visual appeal, and create preconditions for catastrophic fires to illustrate how they can be valued simultaneously for efficiency and for system maintenance. In the context of this overview, a regenerative agronomic system might be valued for its, say, long-term creation of grain (through normal market economics) and of soil organic matter (measuring efficiency through carbon credit trading). What value for ecosystem services will ensure that an agronomic system is maintained rather than overcropped, which leads to degraded soil structure and desertification or salinization, as millions of hectares of Australian cropland testify? To date, estimates of the value of ecological services such as water (Patterson 2002) have worked within the linear system, not considering valuation against catastrophic change.

A second issue regarding valuation is whether it is necessary to create a single value that bundles market economics, ecosystem services, and system maintenance. Creating a single value helps attract the attention of politicians, and economists (e.g., Patterson 1998) generally argue that the valuation of ecosystems, and choosing among different options for their management, requires enumeration (Costanza et al. 1997). By contrast, Gatto and De Leo (2000) argue that creating a single monetary pricing approach is dangerous, concealing the complexities of decisionmaking. Nonmarket valuation is a point of conflict "both within and outside the profession [of environmental economics]" (Bennett 2005). Given the momentum in land-use planning toward participatory decisionmaking, in which trade-offs are achieved mostly through discussion rather than through numerical techniques, it is appropriate to ask whether a thrust in environmental economics toward creating single value systems for market products *and* environmental services is necessary.

Conclusions and suggestions

This overview identifies eight reasons to consider changing agronomic systems. All of these reasons are globally significant, are practically irreversible, and require urgent response. I have used illustrations from industrialized agriculture, where resistance to change will be greatest because of the enormous capital and marketing systems embedded in the way we do things now. This is reinforced by the commitment of mainstream science and technology to further growth in productivity. Nonetheless, the need for regenerative agronomic systems is compelling, and it is equally so in developing countries, where the high costs of importing fertilizers, pesticides, and machinery cause mining of nutrients across large areas (e.g., West Africa) and impoverishment of rural environments and economies. These issues are reviewed by Graves and colleagues (2004), who conclude that "there is no single panacea for the problems faced by subsistence farmers."

To advocate the adoption of new practices raises a question: What needs to be changed to facilitate change? Research on more closed agronomic systems, particularly organic systems, has been ongoing since about 1940, and data describing the benefits and problems of these systems are generally adequate. Inputs (e.g., pesticides) that maintain conventional open, leaky systems have been equally well researched, both in terms of their efficacy within the agronomic system and their impacts and costs to the environment and society at large. There is little need for more of the same research.

Rather, a shift to regenerative agronomic systems might be facilitated by changing the balance within research portfolios and considering new public policy settings. Researchers need to identify what they need to know and determine how to influence public policy to support these research priorities, as well as take actions that will encourage farmers to change. For example, the transition to regenerative agronomy would be facilitated by research into plant biotechnology specifically aimed at improving pest tolerance (thereby reducing chemical inputs), nitrogen fixation, efficiency of uptake of nutrients (e.g., phosphorus) through mycorrhizae, and perennation (to reduce tillage and improve groundwater recharge and, in some areas, combat salination). Prioritizing research into geographic information systems and variable-rate applicators will reduce the leakiness of ineffective applications of pesticides and fertilizers, and the field of robotics offers one way to address the high labor and management needs of regenerative systems, irrespective of farm scale. As an anonymous reviewer of this manuscript offered, "In regenerative agriculture the development of low-cost, reliable robots might trigger a reexamination of agronomic practices that were deemed too labor intensive."

There are three ways for professional bodies and the public to influence the shift toward regenerative agronomy: through encouraging farmers to change the way they manage their private property, through public or common property management, and through legislation. A mix of action in all three domains will most likely produce the best results. "The challenge remains to develop a policy response that combines the strengths of regulation, common property and private property approaches" (Bennett 2005). To illustrate what such a mix might look like, I suggest six possible actions to accelerate the adoption of regenerative agronomic systems:

1. Dialogue between government agencies and certification bodies (e.g., the Soil Association, a UK environmental organization that promotes organic agriculture) should advocate the inclusion of closedness in certification criteria. These national bodies are well positioned to draw attention to the importance of minimizing inputs and negative outputs from open agronomic systems. Similarly, labeling of locally produced food (by region of origin and by "food miles," how far food travels to markets) will emphasize the energy economy of its distribution (Halweil 2002).

2. Life cycle analysis and costing of nonagricultural commodities such as car parts and building materials will stimulate research in plant-derived biomaterials that will result in the use of all plant parts, not just grain.

3. Economic analysis of farming systems should include full costing of farming inputs (e.g., pesticides, fertilizers), which are sometimes poorly used within conventional, open systems. Here the biggest impetus for change might be through governments' introduction of taxes on pesticides to reflect the real cost to society (e.g., the cost of cleaning up waterways). Taxes are but one method of discouraging unwanted externalities and creating semiclosed systems, but they have been implemented effectively in several European countries, as Pretty and colleagues (2001) discuss.

4. Encourage the shift to regenerative systems through government funding to support the transition period. A theme emerging from research into organic farming systems is that in the first five years or so, these systems have lower yield and more management problems than do conventional systems, and for some of this time there are no price premiums. Allocating incentive payments during this period (as in the United Kingdom until 2002) would arguably have a great impact on reducing the long-term costs of farming and the negative environmental impacts from agriculture. By contrast, conventional governmental policy directs payments mostly to large, conventional farms, which have a relatively low benefit–cost ratio, and long-term benefits, if they exist, are not tangible (see, e.g., analyses of 20 years of the USDA Conservation Reserve Program [Ribaudo et al. 2001] and of European Union policies [Kleijn and Sutherland 2003]).

5. Changes in research management will assist the shift, although these are only touched upon, not argued for, in this article. It would be helpful for researchers to focus a greater percentage of their work on transitions to regenerative systems, management of soil–organism–plant interactions, targeted plant biotechnology, robotics, and full economic analyses.

6. Finally, members of affluent urban societies might engage more in agriculture either directly, by participating in farming activities as a recreational pastime (e.g., *Selbsternte;* Vogl et al. 2004) or joining environmental cooperatives, or indirectly, through philanthropic or tax support. Agriculture will also be maintained, and regenerative systems encouraged, by purchasing local products, organic products, products that are certified as having been produced with few food miles, or those associated with environmental service outcomes.

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References cited

Appleby M, Aylard R, Jones J. 2004. Organic Farming Study. Independent Research on the Duchy of Cornwall's Home Farm at Highgrove. Milton Keynes (United Kingdom): Mayfly Consultancy/City Print.

Balmford A, et al. 2002. Economic reasons for preserving wild nature. Science 297: 950–953.

Bennett J. 2005. Australasian environmental economics: Contributions, conflicts and "cop-outs." Australian Journal of Agricultural and Resource Economics 49: 243–261.

Berry PM, Stockdale EA, Sylvester-Bradley R, Philipps L, Smith KA, Lord EI, Watson CA, Fortune S. 2003. N, P and K budgets for crop rotations on nine organic farms in the UK. Soil Use and Management 19: 112–118.

Bromm J. 2002. An economic and productivity comparison of organic and conventional farming in Saskatchewan. Undergraduate honors thesis. Lakehead University, Thunder Bay, Canada.

Brown LR. 2003. Plan B: Rescuing a Planet under Stress and a Civilization in Trouble. New York: Norton.

Butler LJ. 2002. The economics of organic milk production in California: A comparison with conventional costs. American Journal of Alternative Agriculture 17: 83–91.

Constanza R, et al. 1997. The value of the world's ecosystem services and natural capital. Nature 387: 253–260.

Dalgaard T, Halberg N, Porter JR. 2001. A model for fossil energy use in Dutch agriculture used to compare organic and conventional farming. Agriculture, Ecosystems and Environment 87: 51–65.

[DEH] Department of the Environment and Heritage, Australian Greenhouse Office. 2005. Australia's Fourth National Communication on Climate Change. Canberra (Australia): Commonwealth of Australia.

Edwards-Jones G, Howells O. 2001. The origin and hazard of inputs to crop protection in organic farming systems: Are they sustainable? Agricultural Systems 67: 31–47.

Environment Canada. 2006. Canada's 2003 Greenhouse Gas Inventory: Overview 1990–2003. (5 February 2007; *www.ec.gc.ca/pdb/ghg/inventory_report/2003_factsheet/2003Factsheet_e.cfm*)

Faber SC, Constanza R, Wilson MA. 2002. Economic and ecological concepts for valuing ecosystem services. Environmental Economics 41: 375–392.

Flessa H, Ruser R, Dorsch P, Kamp T, Jiminez MA, Munch JC, Beese F. 2002. Integrated evaluation of greenhouse gas emissions (CO_2, CH_4, N_2O) from two farming systems in southern Germany. Agriculture, Ecosystems and Environment 91: 175–189.

Francis CA. 2004. Greening of agriculture for long-term sustainability. Agronomy Journal 96: 1211–1215.

Gatto M, De Leo GA. 2000. Pricing biodiversity and ecosystem services: The never-ending story. BioScience 50: 347–355.

Graves A, Matthews R, Waldie K. 2004. Low external input technologies for livelihood improvement in subsistence agriculture. Advances in Agronomy 82: 473–557.

Halweil B. 2002. Home grown: The case for local food in a global market. Worldwatch Institute Paper no. 163. (6 February 2007; *www.worldwatch.org/pubs/paper/163/*)

Hanley N, Oglethorpe D. 1999. Towards policies on externalities from agriculture: An analysis for the European Union. American Agricultural Economics Association 5: 1222–1227.

Hanson B, Alroe HF, Steen KE. 2001. Approaches to assess the environmental impact of organic farming with particular regard to Denmark. Agriculture, Ecosystems and Environment 83: 11–26.

Kleijn D, Sutherland WJ. 2003. How effective are European agri-environmental schemes in conserving and promoting biodiversity? Journal of Applied Ecology 40: 947–969.

Kuminoff NV, Wossink GA. 2001. A Statistical Overview of Organic Agriculture in the United States. (12 March 2007; *www.organicaginfo.org/upload/statisticaloverview.pdf*)

Leach G. 1976. Energy and Food Production. Guilford (United Kingdom): IPC Science and Technology Press.

Loake C. 2001. Energy accounting and well-being: Examining UK organic and conventional farming systems through a human energy perspective. Agricultural Systems 70: 275–294.

Mahoney PR, Olson KD, Porter PM, Huggins DR, Perillo CA, Crookston RK. 2004. Profitability of organic cropping systems in southwestern Minnesota. Renewable Agriculture and Food Systems 19: 35–46.

Maynard H, Nault J. 2005. Big Farms, Small Farms. Ottawa (Canada): Agricultural Institute of Canada.

Morison J, Hine R, Pretty J. 2005. Survey and analysis of labour on organic farms in the UK and Republic of Ireland. International Journal of Agricultural Sustainability 3: 24–43.

Oberholtzer L, Dimitri C, Greene C. 2005. Price Premiums Hold On as U.S. Organic Produce Market Expands. Washington (DC): US Department of Agriculture, Economic Research Service. Outlook Report VGS30801.

Olewiler N. 2004. The Value of Natural Capital in Settled Areas of Canada. Canada: Ducks Unlimited and Nature Conservancy of Canada. (22 March 2007; *www.ducanada.ca/aboutduc/news/archives/pdf/ncapital.pdf*)

Pacini C, Wossink A, Giesen G, Vazzana C, Huirne R. 2003. Evaluation of sustainability of organic, integrated and conventional farming systems: A farm and field-scale analysis. Agriculture, Ecosystems and Environment 95: 273–288.

Patterson M. 1998. Commensuration and theories of value in ecological economics. Ecological Economics 25: 105–125.

———. 2002. Ecological production based pricing of biosphere processes. Ecological Economics 41: 457–478.

Pearson CJ. 2003. Sustainability: Perceptions of problems and progress of the paradigm. International Journal of Agricultural Sustainability 1: 3–13.

Pearson CJ, Ison RL. 1997. Agronomy of Grassland Systems. New York: Cambridge University Press.

Pearson CJ, Norman DW, Dixon J. 1995. Sustainable Dryland Cropping for Soil Productivity. Rome: Food and Agriculture Organization of the United Nations.

Pimentel D, Hepperly P, Hanson J, Douds D, Seidel R. 2005. Environmental, energetic, and economic comparisons of organic and conventional farming systems. BioScience 55: 573–582.

Popp J, Hoag J, Ascough J II. 2002. Targeting soil-conservation policies for sustainability: New empirical evidence. Journal of Soil and Water Conservation 57: 66–74.

Pretty J. 1998. The Living Land: Agriculture, Food and Community Regeneration in Rural Europe. London: Earthscan.

Pretty JN, Brett C, Gee D, Hine RE, Mason CF, Morison JIL, Raven H, Rayment MD, van der Bijl G. 2000. An assessment of the total external costs of UK agriculture. Agricultural Systems 65: 113–136.

Pretty JN, Brett C, Gee D, Hine RE, Mason CF, Morison JIL, Rayment MD, van der Bijl G, Dobbs T. 2001. Policy challenges and priorities for internalising the externalities of modern agriculture. Journal of Environmental Planning and Management 44: 263–283.

Pretty JN, Ball AS, Lang T, Morison JIL. 2005. Farm costs and food miles: An assessment of the full cost of the UK weekly food basket. Food Policy 30: 1–19.

Reganold JP, Glover JD, Andrews PK, Hinman HR. 2001. Sustainability of three apple production systems. Nature 410: 926–930.

Ribaudo MO, Hoag DL, Smith ME, Heimlich R. 2001. Environmental indices and the politics of the Conservation Reserve Program. Ecological Indicators 1: 11–20.

Schultz TW. 1954. The Economic Organization of Agriculture. New York: McGraw-Hill.

Shadbolt N, Kelly T, Holmes C. 2004. Organic dairy farming: Cost of production and profitability. AFBM Journal 2: 136–146.

Smith CS, McDonald GT. 1998. Assessing the sustainability of agriculture at the planning stage. Journal of Environmental Management 52: 15–37.

Trewavas A. 2004. A critical assessment of organic farming-and-food assertions with particular respect to the UK and the potential environmental benefits of no-till agriculture. Crop Protection 23: 757–781.

Trohimovich T. 2002. The Growth Management Act (GMA) after More than 10 Years: Another Look and a Response to Criticisms. (12 March 2007; *www.futurewise.org/resources/publications/GMA_another_look.pdf*)

Tzilivakis J, Warner DJ, May M, Lewis KA, Jaggard K. 2005. An assessment of the energy inputs and greenhouse gas emissions in sugar beet (*Beta vulgaris*) production in the UK. Agricultural Systems 85: 101–119.

[USEPA] US Environmental Protection Agency. 2005. Inventory of US Greenhouse Gas Emissions and Sinks: 1990–2003. (5 February 2007; *http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissions.html*)

van Straaten P. 2002. Rocks for Crops: Agrominerals of Sub-Saharan Africa. Nairobi (Kenya): International Center for Research in Agroforestry.

Vogl CR, Axmann O, Vogl-Lukasser B, 2004. Urban organic farming in Austria with the concept of *Selbsternte* (“self-harvest”): An agronomic and socio-economic analysis. Renewable Agriculture and Food Systems 19: 67–79.

Wackernagel M, Rees WE. 1996. Our Ecological Footprint: Reducing Human Impact on the Earth. Gabriola Island (Canada): New Society.

Welbaum GE, Sturz AV, Dong Z, Nowak J. 2004. Managing soil microorganisms to improve productivity of agro-ecosystems. Critical Reviews in Plant Sciences 23: 175–193.

Wendell Cox Consultancy. 2005. Source Book of World Urbanization. (12 March 2007; *www.rentalcartours.net/uza.pdf*)

Wossink A, Kuminoff N. 2005. Valuing the option to switch to organic farming: An application to U.S. corn and soybeans. Paper presented at the 11th Congress of European Association of Agricultural Economists; 23–27 August 2005, Copenhagen, Denmark.

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