Published online February 6, 2007

Reconsidering Integrated Crop–Livestock Systems in North America

Michael P. Russelle,* Martin H. Entz, and Alan J. Franzluebbers

ABSTRACT

Although integrated crop–livestock systems have been employed globally for millennia, in the past century, farmers in North America have tended toward increased specialization. There is renewed interest in reintegrating crops and livestock because of concerns about natural resource degradation, the profitability and stability of farm income, long-term sustainability, and increasing regulation of concentrated animal feeding operations. Integrated crop–livestock systems could foster diverse cropping systems, including the use of perennial and legume forages, which could be grown in selected areas of the landscape to achieve multiple environmental benefits. Integrated systems inherently would utilize animal manure, which enhances soil tilth, fertility, and C sequestration. Integration of crops and livestock could occur within a farm or among farms. Both scales of integration rely on farmers' knowledge, motivation, and resources. Despite the numerous benefits that could accrue if farms moved toward on-farm or among-farm integration of crops and livestock, the complexity of such systems could constrain adoption. However, farmers should expect that adoption of integrated crop–livestock systems would enhance both profitability and environmental sustainability of their farms and communities. The combination of system complexity and potential for public benefit justify the establishment of a new national or international research initiative to overcome constraints and move North American agriculture toward greater profitability and sustainability.

Humans developed agricultural systems that combined crop production with animal husbandry 8 to 10 millenia ago (Smith, 1995; Halstead, 1996). These integrated systems provided a greater variety of products to a farm family than did either enterprise alone and offered a means of utilizing crop residues or noncultivated land to produce meat, milk, and associated products, while generating manure to improve the fertility and quality of cultivated soil. In the past 60 yr, however, agriculture in many industrialized countries has become increasingly specialized, resulting in a separation of crop and livestock enterprises (Ray and Schaffer, 2005).

Although direct consumption of crops provides more protein and energy to humans than when crops are processed by livestock (Spedding, 1988), and although some livestock production systems have contributed to environmental degradation (Durning and Brough, 1991), livestock can utilize crops and residues not suitable as food and fiber for humans. In addition, crop–livestock systems that are appropriately integrated and intensified *for the location* can provide multiple benefits (Mearns, 1996; Schiere et al., 2002).

Four modes of agriculture have been described (Schiere et al., 2002): (i) low external input agriculture (in which demand is adjusted to resource availability and greater labor and skills are necessary to increase production); (ii) expansive agriculture (where land is abundant); (iii) high external input agriculture (in which demand for output or profitability determines input levels, sometimes leading to environmental degradation); and (iv) new conservation agriculture (in which production goals are matched with the resource base to achieve both profitability and environmental benefits).

It is within this last agricultural mode that we suggest integrated crop–livestock systems have the largest role to play in industrialized countries.

An FAO report concluded that "cheap resources lead to specialization, [whereas] restricted use of resources leads to mixing" of crop and livestock enterprises (Anonymous, 2001). In an analysis of agricultural systems in the Great Lakes Basin of North America, Clark and Poincelot (1996) concluded that cheap fossil fuel energy was responsible for "marginalization of pasture". By de-emphasizing pasture in beef and dairy production, we "have abandoned the one real advantage that ruminants have over other animal classes, namely their ability to convert cheap, environmentally benign, scale-neutral feedstuffs into human usable products" (Clark and Poincelot, 1996, p. 15). With decreasing economic margins, higher energy and fertilizer N costs, declining soil organic matter levels, increasing concerns over the long-term sustainability of many contemporary agricultural systems, and greater regulation of agricultural practices, it is time to reconsider the potential benefits of integrating livestock and crop production. Current interest in this topic is evidenced by a number of research trials and programs that examine various facets of integrated systems, a small selection of which are listed in Table 1. Such studies can be used to develop improved farming systems that integrate crop productivity, manure use, animal health, soil and water quality, and economic returns.

Our objective is to provide a general review of some of the benefits and challenges associated with these integrated systems. This paper is meant to complement the other regionally focused papers from the symposium titled "Integrated Crop–Livestock Systems for Profit and Sustainability" at the 2005 International Annual Meeting of ASA-CSSA-SSSA.

Improved Cropping Systems

Integration of livestock and crop enterprises generally entails changes in crop rotations. About 80% of the

M.P. Russelle, USDA-ARS Plant Sci. Res. Unit and U.S. Dairy Forage Res. Center (Minnesota Cluster), 1991 Upper Buford Cir., Room 439, Univ. of Minnesota, St. Paul, MN 55108; M.H. Entz, Dep. of Plant Sci., Univ. of Manitoba, 222 Agriculture Bldg., Winnipeg, MB Canada R3T 2N2; and A.J. Franzluebbers, USDA-ARS J. Phil Campbell, Sr., Nat. Res. Conserv. Center, 1420 Experiment Station Rd., Watkinsville, GA 30677-2373. Received 3 May 2006. *Corresponding author (russelle@umn.edu).

Published in Agron. J. 99:325–334 (2007).
Symposium Papers
doi:10.2134/agronj2006.0139

677 S. Segoe Rd., Madison, WI 53711 USA

Abbreviations: DM, dry matter; LTER, long term ecological research.

Table 1. A small selection of programs and research sites in North America that currently (2006) conduct integrated crop–livestock systems research (websites accessed 5 Sept. 2006; verified 22 Nov. 2006).

Name	Year initiated	Location/website
Wisconsin Integrated Cropping Systems Trial	1990	Wisconsin, USA www.cias.wisc.edu/wics.php
Integrated Farm	1992	Nebraska, USA www.ianr.unl.edu/ianr/csas/integrated-farm.htm
Biologically Integrated Farming Systems	1994	California, USA www.sarep.ucdavis.edu/bifs/
Center for Environmental Farming Systems	1994	North Carolina, USA www.cefs.ncsu.edu/
Ley Farming Systems	1998	North Dakota, USA www.ag.ndsu.nodak.edu/dickinso/agronomy/leyfarming.htm
Integrated Crop/Livestock System	1999	Texas, USA www.orgs.ttu.edu/forageresearch/Sustainable.htm
Integrated Forage, Crop, and Livestock Systems for the Northern Great Plains	2000	North Dakota, USA www.ars.usda.gov/research/projects/projects.htm?ACCN_NO=406526
Dudley Smith Farm	2002	Illinois, USA www.aces.uiuc.edu/DSI/
Four-State Ruminant Consortium	2003	Montana, South Dakota, North Dakota, Wyoming, USA http://sdaes.sdstate.edu/multistate/fourstate/update.htm
Multi-State Project to Sustain Peanut and Cotton Yields by Incorporating Cattle into a Sod Based Rotation	2003	Alabama, Florida, Georgia, USA http://nfrec.ifas.ufl.edu/sodrotation.htm
National Centre for Livestock in the Environment	2005	Manitoba, Canada www.umanitoba.ca/afs/ncle/

Corn Belt region of the USA is in a simple two-species, corn (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.] rotation (Sulc and Tracy, 2007). In the northern Great Plains of North America, typical farms produce either winter wheat (*Triticum aestivum* L.) in rotation with fallow or a limited number of other grain crops (Peterson et al., 1993; Anderson et al., 1999). Multiple agronomic and environmental benefits can be realized when land is converted from annual cropping to rotations that include perennial forages. Introduction of perennial crops into previous annual crop systems has reduced the risk of environmental damage during the perennial cropping phase by decreasing nitrate leaching by up to 96% (Randall et al., 1997) and nearly eliminating soil erosion by water (Shiftlet and Darby, 1985). For the entire rotation, soil erosion by wind was lowered by at least 20% by including a perennial cropping phase on sandy soils (Padbury and Stushnoff, 2000). Perennial cropping also has increased soil organic C levels by over 400 kg C ha^{-1} annually during a 15-yr period in northeastern USA (Drinkwater et al., 1998). Improvements in soil organic matter content are correlated with improved soil tilth, water holding capacity, nutrient supply, and higher grain yield potential (Russell et al., 2006). Simply changing crop rotations, however, does not necessarily alter soil C levels, as reported in corn-based cropping systems in the high yield environment of the midwestern USA when comparisons were made at optimal fertilizer N rates (Russell et al., 2006).

One of the keys to environmental protection with perennials is reduction of N losses. Alfalfa (*Medicago sativa* L.) in crop rotations, for example, has utilized excess soil N and reduced nitrate leaching compared to annual crops (Entz et al., 2001a; Russelle et al., 2001). In one study at a fertilizer spill site, alfalfa removed 970 kg N ha^{-1} over 3 yr, more than threefold that of annual grain crops (Russelle et al., 2001). Perennial legumes, like alfalfa, also add large amounts of available N to the farm in feed and soil organic matter (Peoples et al., 1995; Russelle and Birr, 2004). Estimates of fixed N in harvested alfalfa ranged from 45 to 450 kg N ha^{-1} in the Mississippi River Basin, depending on yield and soil N availability (Russelle and Birr, 2004), and estimates of net soil N addition ranged from 100 to 150 kg ha^{-1} from a 3-yr alfalfa hay crop (Andrén et al., 1990; Goins and Russelle, 1996; Kelner et al., 1997). For this reason, legumes like alfalfa have reduced fertilizer N requirements for succeeding nonlegume crops by up to 100% (Lory et al., 1995; Ma et al., 2003; Russell et al., 2006), thereby reducing input costs, energy demands (Hoeppner et al., 2006), and environmental impacts of farming.

Another improvement from diversifying cropping systems is that they reduce yield losses from insects and diseases (Altieri, 1999). For example, two serious diseases of peanut (*Arachis hypogaea* L.); stem rot (*Sclerotium rolfsii* Sacc.) and limb rot (*Rhizoctonia solani* Kuhn), were reduced following bahiagrass (*Paspalum notatum* Flueggé) compared with continuous peanut, resulting in a peanut yield increase of 30% (Johnson et al., 1999). A commonly reported outcome of including forages in rotation with annual grain crops is reduced weed populations (Harvey and McNevin, 1990). More than 80% of farmers surveyed in Manitoba and Saskatchewan observed fewer weeds after the forage phase of the rotation (Entz et al., 1995). The types of weeds that were controlled by the forage–grain crop rotation varied among the agroclimatic regions (Entz et al., 1995). More than 70% of respondents reported improved grain yields following a forage crop and beneficial effects were more pronounced in wetter areas of these regions (Entz et al., 1995).

These multiple mechanisms have contributed to improved resilience of cropping systems with forage legumes (Stinner et al., 1992), but are not obtained without risk. Reduction of soil erosion during perennial establishment on sloping land requires companion cropping and/or conservation tillage (Wollenhaupt et al., 1995). Similarly, to minimize runoff of dissolved P, farmers need to limit P accumulation in perennial vegetation and soils and application of P fertilizer and dung in grazed systems near surface water (Schuman et al., 1973; Haygarth et al., 1998; Nash and Halliwell, 2000). In a study on the effect of alfalfa stand length on subsoil N content, Entz et al. (2001a) found that after 4 yr, alfalfa reduced soil nitrate concentrations more than annual crops for soil depths between 120 and 270 cm. Because soil nitrate concentrations increased under alfalfa by 250% after the 4th year, the risk of nitrate leaching was lower in a 2-yr wheat phase rotated with 4 yr of alfalfa than with 6 yr of alfalfa (Entz et al., 2001a). Increased N availability after legume stands are terminated requires thoughtful management to reduce risk of N losses (Campbell et al., 1994; Mohr et al., 1999; Huggins et al., 2001).

Integrating livestock into cropping systems is perhaps most critical in organic crop production. Long-term organically managed commercial farm fields are showing signs of P deficiencies (Entz et al., 2001b) and hence nutrient recycling via ruminants may be critical to long-term sustainability of these soils. While nutrient recycling and also weed control benefits of forage crops are well known to organic farmers (Macey, 1992), a high proportion (75%) of northern Great Plains organic farms do not include forage crops in their rotations (Entz et al., 2001b).

Fixed annual crop rotations can suffer from weaknesses that are expressed under stressful weather conditions and pest infestations (Zentner et al., 2001). Building on the flex-cropping approach of Zentner et al. (2001) and the opportunity cropping concept of Peterson et al. (1993), Tanaka et al. (2002) suggested the use of a dynamic cropping system approach to achieve long-term goals. This approach is based on a fundamental understanding of agroecosystem behavior in the context of landscape and weather. Although these three groups focused on optimizing cropping scenarios, livestock could be integrated into these systems to further stabilize farm income.

Just as crop selection is dictated by climate, edaphic conditions (slope, past erosion, soil depth, and soil texture, drainage status, etc.) should be considered in the selection, sequence, and placement of crops. Alfalfa provides significant protection for water quality and enhances subsequent crop yields in humid environments, but can reduce subsequent crop yield 1 yr out of 2 because of excessive subsoil moisture depletion in semiarid environments (Pikul et al., 2005). For this reason, annual legumes may be superior to perennial legumes in drier regions (Biederbeck and Bouman, 1994). Maximum environmental and economic benefits from diverse cropping systems may accrue when a well-adapted forage crop is placed strategically in the landscape. For example, Burkart et al. (2005) evaluated the likely environmental impacts if land use in western Iowa were converted from primarily corn–soybean cropping (70% of the current land area) to integrated crop–livestock farming. The alternative land use scenario involved a 2-yr corn–soybean rotation limited to slopes $< 5\%$, a 6-yr corn–soybean–corn–oat (*Avena sativa* L.)/forage–forage–forage rotation on 5 to 14% slopes, and permanent pasture on steeper land. They estimated that annual soil erosion loss would decrease to < 6 Mg ha^{-1} from 22 Mg ha^{-1} under current cropping practices. Median annual N load in streams also would decrease by 28% and leachable N would decline from 32 to 11 kg N ha^{-1}.

Integrating Livestock

Economic and environmental benefits are enhanced when crop rotations with forages include livestock enterprises. Of primary importance is economic return. Farmers already have integrated beef cattle production onto cropland in the Great Plains to improve profitability (Small and McCaughey, 1999). In North Dakota, for example, net worth was nearly $9000 greater for farms with crops and beef cows compared with crops only (Anderson and Schatz, 2003). Crop residues represent a large source of biomass for ruminant feed or energy in areas where utilization would not increase the risk of environmental degradation (Beauchamp, 1990; Smil, 1999). Beef cows have been able to utilize both forage and crop residues, whereas calves have been fed grain during preconditioning and finishing. A year-round grazing system based on grass–legume pastures and corn crop residues reduced the need for hay by 900 kg dry matter (DM) cow–stocker pair^{-1} and offered the additional benefit of supporting August- and April calving (Janovick et al., 2004). Lower on-farm feed costs more than compensated for the smaller rate of gain during the cold winter, resulting in breakeven costs of at least $2.40 kg^{-1} gain lower than the traditional feeding system (Anderson et al., 1996).

Adding cattle to a legume–grain crop rotation doubled the rate of soil C accumulation, because of the manure additions (Drinkwater et al., 1998). Recycling of crop C through manure and decomposing residues improves soil C sequestration (Singh et al., 1998; Mäder et al., 1999; Soussana et al., 2004). For example, the annual increase in topsoil C was faster by 2300 kg ha^{-1} yr^{-1} under grazed smooth bromegrass (*Bromus inermis* Leyss.) and by 1200 kg ha^{-1} yr^{-1} under grazed switchgrass (*Panicum virgatum* L.) than under a corn–soybean–3-yr–alfalfa rotation (Al-Kaisi et al., 2005). As a consequence, depleted soil C stocks from annually cropping have been 90% restored after 9 yr of pasture (Römkens et al., 1999). It is notable that perennial forages placed sequestered C deeper in the soil profile than annual crops (Gentile et al., 2005). Too much or too little fertilizer N decreased soil C storage and increased greenhouse gas emissions (Soussana et al., 2004). These authors highlighted the idea that newly sequestered C accumulated at a slower rate during the perennial grassland phase of a rotation than the C that disappeared during annual cropping. During 40 yr of continuous cropping, soil C declined by 540 kg ha^{-1} annually, whereas a 3-yr perennial grass phase followed by 3 yr of annual cropping maintained soil C (García Préchac et al., 2003; La Manna et al., 2005).

In semiarid rangelands, properly managed grazing may increase soil C levels slowly (mean 160 kg C ha^{-1} annually, $\pm$120 kg ha^{-1}), presumably by favoring perennial grass populations with high root-to-shoot ratios, stimulating vegetative growth, improving tillering and rhizome production, enhancing return of aboveground

C to the soil as plant litter and dung, and increasing C exudation by roots (Liebig et al., 2005). Grazing effects on soil C storage may vary with grazing intensity (Reeder et al., 2004), grassland type, or precipitation gradient. Derner et al. (2006) found a 24% increase in soil C after long-term grazing in a short-grass prairie, but a slight decline in soil C in mid- and tall-grass prairie. Liebig et al. (2005) emphasized the critical role that livestock management plays in both organic and inorganic C balance in these fragile ecosystems. They found no data on C balance in systems in the region where livestock graze crop residues. Liebig et al. (2005) also cautioned that the net effect on global warming due to greenhouse gas (principally CO_2, N_2O, and CH_4) emission is largely unknown, because increased N_2O emission from grazed or manured land and increased CH_4 emission from ruminant livestock could offset lower net CO_2 emission from grassland.

In two dissimilar watersheds in Minnesota, Boody et al. (2005) reported that implementing a variety of conservation practices could reduce stream sediment loads by 35 to 84%, N loads by 51 to 74%, and P loads by about 70%. Conservation practices included extensive pastures on slopes > 3%, perennial cropping, cover cropping, conservation tillage, and vegetated buffer strips along streams. The net effect of greater integration of crops and livestock was not indicated per se, but a potential increase in methane production of 125% from dairy and beef herds needed to consume the forages would likely be offset by greater C storage in land converted from annual cropping to pastures.

Improved Manure Use

The importance of manure as a source of recycled nutrients has been recognized for millennia. The economic value of manure, though significant, has not overcome the convenience and relatively low cost of inorganic fertilizers, and the lower confidence farmers have in nutrient supply from manure. Larger, more specialized livestock production operations that import nutrients from distant sources have resulted in greater nutrient concentration in localized areas (Powers and Van Horn, 2001; Slaton et al., 2004). These factors have contributed to excessive manure (or total nutrient) application and subsequent degradation of water resources, which in turn has stimulated regulations (Jongbloed and Lenis, 1998; Saam et al., 2005).

With the advent of laws that regulate manure application rates and methods, ad hoc siting and expansion of concentrated animal feeding operations has been curtailed. Manure transport from concentrated animal feeding operations has become more expensive because of increased attention on achieving appropriate nutrient application rates. Both N and P are causes for environmental concern when applied excessively. There have been several technological solutions developed for manure-generated problems, including use of phytase in nonruminant diets to increase P use efficiency (Bosch et al., 1998) and lowering the P levels in ruminant diets (Powell et al., 2001) to reduce P excretion. These solutions would reduce manure P concentration and therefore allow greater manure application rates. Other approaches, such as altering dietary N, composting, secondary treatment, and methane generation are also possible, but will not be discussed here. These technologies, however, may apply as well to integrated crop–livestock systems as to specialized operations.

Feces contain partially digested and transformed plant-derived N and C, which contribute to soil organic matter maintenance and accumulation. In addition, bedding included in solid manure or litter increases the C application rate. Apparent recovery of poultry litter C in soil under bermudagrass (*Cynodon dactylon* L.) pastures averaged 14% over 5 yr (Franzluebbers et al., 2001). The value of manure for C sequestration, however, may have declined with a reduction in organic bedding used in barns and contained in manure slurries. Manure slurries are easier to move and apply (Ghafoori et al., 2005), but may contribute less to soil organic matter levels than solid manures (mixed with bedding) when compared on the basis of equal C loading (Beauchamp and Voroney, 1994). However, there is a lack of quantitative information about the stability of manure C, which limits our ability to predict soil C response (Velthof et al., 2000).

The main limitation to manure distribution from concentrated livestock facilities may be unwillingness of other farmers to accept the manure; the second most important limitation is the energy requirement, and therefore the economic cost (Ribaudo et al., 2003). With higher fossil fuel prices, the cost of transport increases, but other farmers are more likely to accept manure as a means of reducing their payments for commercial fertilizer. Under an N-based application standard in the Chesapeake Bay watershed on the eastern seaboard of the USA, average hauling distance for manure-producing farms was estimated at 37 km when 100% of farms without livestock were willing to accept manure, but 120 km if only 20% of such farms were willing to accept manure (Ribaudo et al., 2003). Given 100% willingness to accept manure, but changing from a N-based to a P-based standard, average hauling distance increased from 37 to 64 km. In a Manitoba study using N-based manure application rates, the fossil fuel energy costs associated with application of pig slurry (agitation, pumping, and field injection) 1.6 km from the barn required 60% as much energy as using inorganic N fertilizer (Entz et al., unpublished data, 2006). The energy cost of applying this manure would increase further if: (i) the distance from the barn increased; and (ii) as the basis for manure application changed from N to P. Thus, substantial energy savings can be realized by reducing the distance that feed and manure are transported, and this can be achieved by integrating crops with livestock on individual farms or by integrating operations among local farms.

Nature and Scale of Integration

During the past several decades, most literature on crop–livestock integration has come from developing countries where integration is linked to improved soil fertility, and hence crop yield, and animal power (e.g., Powell et al., 2005). While the principles of integration, especially nutrient cycling, are similar among countries, the nature of crop–livestock integration in industrialized countries is different mainly because the drivers for change are different. Two main drivers for integration in North America are environmental problems associated with excess nutrients from intensive livestock operations and the high cost of energy needed to sustain monoculture grain production systems.

There are two practical scales of integration of crop and livestock farming enterprises: (i) within-farm integration; and (ii) among-farm integration. Steinfeld (1998) argued that with time and sophistication of agricultural systems, crop–livestock integration would move from a local (within-farm) to a regional (among-farm) scale. The notion that all integration eventually ends up at the regional level is attractive to large-scale agribusiness and national policymakers who often prefer large, industrial-scale systems with fewer stakeholders. Entz et al. (2005), however, provided examples confirming that crop–livestock integration is dynamic and that both within-farm and among-farm integration are practiced and worthy of scientific exploration.

Within-farm and among-farm integration have advantages and challenges (Entz et al., 2005). A list of information required in these systems indicates the high degree of management skill required, at either scale of integration (Table 2). Individual farmers differ in knowledge and management skills, so integrated systems need to be appropriately designed and adapted (Files and Smith, 2001).

Table 2. Information required for decision making in integrated crop–livestock systems (adapted from Pannell, 1995; Ewing and Flugge, 2004).

Consideration	Information required
Short-term profit	crop yield crop residue and feeding value amount and distribution of pasture yield input costs output value (market, government program payments, other payments, such as C trading)
Multiyear factors	rotation benefits (reduced need for N and pesticides, improved soil condition) symbiotic N_2 fixation residual fertilizer weed populations
Whole-farm factors	farm size and spatial distribution of fields (rented and owned) machinery size and availability for different enterprises labor availability, ability, and cost financing (availability, flexibility of banker, cost) livestock feed (requirements, availability, cost)
Risk factors	yield variability (edaphic, climatic, and biotic constraints) price variability (market, hedging opportunities, price stabilization programs, covariance with yield, insurance) risk acceptance or aversion responsiveness (flexibility, willingness to adopt new practices)
Sustainability factors	persistence of perennials (reseeding and purchased feed costs) weed populations (herbicide resistance and herbicide residues) soil condition and sensitivity (erosion, soil organic matter content, salinity, acidification) off-site impacts (water quality, total maximum daily load limits, salinity, wildlife, aesthetics)

Within-Farm Integration

Many of the regionally specific considerations required for on-farm integration of crops and livestock have been presented in the associated papers of this series (Allen et al., 2007; Franzluebbers, 2007; Sulc and Tracy, 2007). One of the key attributes of these systems is the potential for more stability. Because of complementary interactions such as nutrient “sharing” and biological pest control, integrated systems can exhibit better physical and financial stability than specialized enterprises (Ewing and Flugge, 2004). Market signals require rapid response from specialized producers, whereas managers of integrated systems can take more time to determine whether economic trends are persistent, and if so, to alter the mix of enterprises accordingly.

In areas previously dominated by perennially based crop–livestock systems, optimum cropping strategies may involve more annual cropping. This is best exemplified in other countries, where perennial pastures have played a larger role in modern livestock production. In response to market signals, the past decade has seen a shift toward less perennial pasture and a greater proportion of annually cropped land on mixed crop–livestock farms in much of southern and eastern Australia (Ewing and Flugge, 2004). Integrated systems have included leys, where pastures are regenerated after each cropping cycle, or were characterized by “phase” farming, where pastures are reseeded after the cropping cycle. In the case where crop residues were grazed, however, no sown pasture component was necessarily present. On highly permeable soils near Hamburg, Germany, Rotz et al. (2005) reported that conversion of some grass silage and grazed land to corn silage would reduce N loss by 17%, while improving net economic return to management by 11%. Increased economic return largely was due to improved milk production from adding corn silage to the ration and reduced N losses because a better balance between degradable protein and energy in the ration reduced N excretion. Ewing and Flugge (2004) shared the view of Rotz et al. (2005) that the balance between grain and forage crops depends on economic and environmental drivers, as well as specific characteristics of the farm. A mix of short-term pastures and annual silage crops also has been increasingly adopted for ruminant finishing and dairying operations in New Zealand (Woodfield and Easton, 2004).

Within-farm integration with ruminants often includes grazing for part of the year. Examples of such systems are grazing winter wheat in early spring in the southern Great Plains (Redmon et al., 1995), and extended grazing with late-season grain crops (e.g., swath grazing) in the northern Great Plains (Tanaka et al., 2005). Grazed dairy systems appear to have similar profitability as confined systems (Gloy et al., 2002), suggesting that farm management skills play a major role in both systems. Although grazed dairy cattle may have lower somatic cell count in milk and relatively high reproductive success than cattle in confinement systems (Goldberg et al., 1992), breed differences will affect system performance. Better performance of Jerseys than Holsteins with regard to conception success may make Jerseys the better choice for seasonal calving operations (Washburn et al., 2002). Milk and meat produced on pasture may be suitable for market niches (such as "Free Range" labeling) that can improve product value because of perceived or actual improvements in animal welfare (Honeyman, 2005; Nielsen and Thamsborg, 2005). Human health benefits from ruminant animal products in forage-fed systems, especially pastures, are related to higher levels of omega-3 fatty acids and conjugated linoleic acids (Scollan et al., 2005; Clancy, 2006).

Integration of livestock on crop farms would likely increase the complexity and rapidity of N cycling (Russelle, 1992). Just as in fertilized crops (Kolenbrander, 1981), N losses increase rapidly when inputs exceed the level required for maximum production (Rotz et al., 2005). This means that farmers on integrated crop–livestock farms need to be more cognizant of nutrient flows on the farm, and in particular need to recognize and appropriately credit nutrient availability from manure (Schmitt et al., 1999). Additionally, the heterogeneity of nutrient distribution in pastures due to animal behavior (Peterson and Gerrish, 1996) may require management approaches that encourage more random distribution of excrement to prevent adverse environmental outcomes (Gourley, 2004; Kratz et al., 2004).

Examples from other countries provide ideas for further integrating crop and livestock with other enterprises (Kirschenmann, 2007). In describing systems that involve livestock and fish, Little and Edwards (2003) emphasized the concept of intensification, rather than concentration, of production. The idea of integrating crop and livestock production—of adopting more complex crop rotations, a wider array of equipment, more restricted crop protection chemical programs, greater workload through the year, increased skills in crop, soil, and animal management, and detailed knowledge marketing a broader range of products—may not be palatable for everyone. Nor does it need to be. Another means of achieving some of the synergies provided by integrated crop–livestock systems is by integrating across farms.

Regional (Among-Farm) Integration

Where government regulations for nutrient management exist, growth in concentrated animal feeding operations has required partial integration among farms to distribute the manure on cropland or pasture (Schmitt et al., 1999). These arrangements have been and largely remain unidirectional—manure moves from the feeding operation to other farms, but nutrients do not necessarily return as feed. Furthermore, farmers who receive the manure often do not adequately account for its nutrient supply (Schmitt et al., 1999).

On dairy farms in Wisconsin, the average area of land available for manure spreading was 1.0 ha animal unit^{-1} for farms with $<$ 50 cows, but only 0.6 ha animal unit^{-1} for farms with $>$ 200 cows (Turnquist et al., 2006). The area available has dropped by 27% between 1997 and 2002 for the larger farms. Furthermore, a majority of Wisconsin dairy farmers spread all manure on fields within a 5-min driving distance from the barn. The median proportion of land that received manure to total available cropland ranged from 23 to 44% (Saam et al., 2005). They also reported that less land received manure as the relative amount of rented land increased, presumably because farmers did not want to invest this resource on land they might not be allowed to utilize in the future.

A variety of planning approaches for integrating manure management among farms are being pursued. Expanding the idea of using a GIS approach to manure allocation within a farm [e.g., the Missouri Spatial Nutrient Management Planner (www.cares.missouri.edu/snmp/)], one group used data from several sources to classify land that is suitable for manure application (based on slope, land cover, soil characteristics, and distance from surface water) and categorize the parcels into priority acres (little or no restrictions except soil nutrient levels), cautionary acres (runoff or leaching concerns), and acres that are unsuitable for manure application (e.g., Wagner and Posner, 2005). Such map products can be used to help farmers or agricultural consultants locate manure producers or potential acceptors.

There are, however, examples of more fully integrated neighborhoods of farms, two of which are described here. Entz et al. (2005) described how beef cattle, swine, pastures, and grain crops were integrated among farms by Hytek Ltd., a company formed by specialized farmers in Manitoba. Manure was used to fertilize annual grain crops and pasture, grains were processed and utilized by livestock, and cow–calf pairs with replacement heifers were supported on pastures. In 2005, the company consisted of 40 000 sows, 100 000 finishing and young, segregated piglet sites, 600 cow–calf pairs, and 300 yearling heifers, supported by 180 ha of cropland, 800 ha of hay, and 4000 ha of pasture (Entz et al., 2005). In this situation, the majority of grain (about 70%) was imported, because most of the land in the immediate area is of low quality for grain cropping, and traditionally is used as pasture.

In Maine, a number of regionally integrated potato (*Solanum tuberosum* L.)–dairy farm operations have developed, in which land and other resources are shared and manure is applied to land that had not received it earlier (Files and Smith, 2001). There were three common outcomes noted by the farmers: (i) increased soil quality (i.e., improved friability and water holding capacity); (ii) increased proportion of marketable potatoes; and iii) improved crop yield. Farmers emphasized the need for trust between partners that was based on a handshake rather than formal contracts (Files and Smith, 2001). They also showed little interest in assigning an explicit economic value to exchanged goods and services. Key issues limiting broader development of these relationships were distance between farms (ideally $<$ 25 km), basic trust between individuals (which required lengthy relationships or references from other farmers), and a willingness to begin slowly with modest exchanges (Files and Smith, 2001). An advantage in these among-farm collaborations would be that more people have a stake in assuring successful and mutually acceptable outcomes. Questions remain as to whether these collaborations might achieve the same range of synergies as within-farm integration.

At either scale of integration, farmers' goals must be met at least as well as they would be in other systems. These goals will vary according to cultural background, but a recent list from Australia (Scott, 2006) reveals deep interest in achieving environmental goals, a clear need to improve and stabilize profitability, and a desire to have weekends off and annual vacations (Table 3). There is growing realization that agriculture can contribute not only to food and fiber production for society, but also to environmental services, such as water quality protection, wildlife habitat, landscape scenery, flood control, nutrient cycling, and C storage (Batie, 2003), and to the quality of life on farms (Scott, 2006).

LARGE-SCALE RESEARCH INITIATIVE NEEDED

Despite numerous challenges for integrating crop and livestock production, synergies in these systems would provide significant benefits in profitability and environmental sustainability, and do not necessarily involve tradeoffs between profitability and improved environmental outcomes. For example, greater profits may accompany declines in soil erosion and improvements in soil organic matter, as shown in a number of long-term integrated crop–pasture and crop–livestock experiments (La Manna et al., 2005).

There is a need for more advanced research on crop–livestock systems within the climatic and edaphic conditions and policy environments in which they will be employed (Entz et al., 2002). A challenge will be to integrate crop and animal researchers, most of whom now work separately and have different experimental requirements. Because animal scientists require many animals per treatment, the labor and land-base requirements for these integrated field experiments will be larger than what most crop scientists have used. On the other hand, adequate assessment of economic and environmental outcomes will require longer-term experiments than are typical in animal science research. A few examples of integrated systems are presented in Table 1, and some have been described in the literature (e.g., Karn et al., 2005; Tanaka et al., 2005).We suggest that a coordinated national or international program will produce better results than regional and local efforts, even considering the high quality of those listed in Table 1. The program would require: (i) in-depth analysis to determine what combination of crops, livestock, and inputs to test (Schiere et al., 2002); (ii) large research and extension teams to examine various aspects of system performance; (iii) patience on the part of researchers and funding entities to collect data over a sufficient time period to understand behavior with varying weather conditions (Allen et al., 2007); and (iv) sufficient funding to support the required staff, facilities, equipment, and analyses. Problems raised in these systems would be similar to those in the Long Term Ecological Research (LTER) studies that have been undertaken in the USA and elsewhere over the past quarter century. Much of the experience, methods, and knowledge developed in the LTER program could be used to develop a new, competitive, integrated agricultural systems grant program producing fundamental knowledge with immediate application in agriculture.

While simulation models could be an important first step in exploring climatic, edaphic and management scenarios and could be useful in determining "best-bet" integrated systems (Kingwell and Pannell, 1987; Rotz et al., 2005), the complexities of integrated systems might limit the reliability of models. Moreover, practitioners will want to see real data. Integrated crop–livestock systems are fundamentally knowledge intensive, and experienced extension personnel likely will be more valuable than simulation models as farmers and agricultural consultants design their systems. In any case, human resources would be a critical part of the package and would complement model output.

Current research and extension are not sufficient and changes in agricultural policy likely will be needed to help achieve the environmental benefits that integrated crop–livestock systems offer. It appears that in the United Kingdom and Western Europe, a switch from production- or area-based payments to stewardship payments has diversified agricultural practices (Dobbs and Pretty, 2004). A similar change in farm subsidies in the USA from commodity support to adoption of conservation practices should lead to agricultural diversification through the Conservation Security Program (Mausbach and Dedrick, 2004). With increasing costs for inputs like diesel fuel, natural gas, and fertil-

Table 3. Major goals articulated by farmers at a workshop in New South Wales, Australia (adapted from Scott, 2006).

Outcome	Goals
Economic	annual return of 10% after living expenses vertical integration will provide additional benefits to the farm family, including long-term profitability high-quality products will lead to higher prices and better market access
Diversification	integrated crop–livestock systems must be innovative and flexible
Integration	land use should be matched with land capability results should satisfy the needs of farmers, the community, and consumers ability to manage the synergies among enterprises
Environmental	both the farms and watersheds will be environmentally sustainable farmers will be rewarded for meeting environmental targets healthier soils and high quality water will support improved productivity of crops and livestock
Social	key indicators of system performance will be standardized an economically viable and diversified agriculture in the region will enable social support structures (e.g., artistic, cultural, and health) to flourish farm families will need to work only 5 d wk^{-1} and will be able to afford 4 wk of vacation annually

izer, it can be anticipated that North American farmers also will be seeking alternative practices to help them achieve their short- and long-term goals.

ACKNOWLEDGMENTS

This manuscript was motivated in response to the many excellent presentations made by invited speakers at the Integrated Crop–Livestock Symposium during the ASA–CSSA–SSSA meetings in Salt Lake City, UT, 6–10 Nov. 2005. Symposium organizers were MPR and AJF. Support was provided in part by the USDA–National Research Initiative Competitive Grants Program (Agric. No. 2001-35107-11126) to AJF.

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