Benefits of Re-integrating Livestock and Forages in Crop Production Systems

E. Ann Clark

SUMMARY. Specialization is the foundation of contemporary agriculture, yet until the early decades of the 20th century, enterprise diversity was the norm. As agriculture has become more specialized in the intervening years, yields have increased dramatically, but so too have a range of economic, environmental, and health problems. This contribution presents evidence that specialization is an ecologically dysfunctional design for food production, a thesis which is supported by the predominance of problem-solving research in the contemporary literature. As demonstrated by Louis Bromfield in the 1940's and by organic and sustainable farmers today, the strategic integration of crops and livestock/forage enterprises avoids many of the problems of specialization, while also capturing economic and ecological synergies denied to specialist producers. In addition to providing human foodstuffs, forage-based livestock production also offers a range of novel opportunities to channel natural processes to the service of humanity, from carbon sequestration and site remediation to non-chemical vegetation management.

KEYWORDS. Specialization; soil management; pasture; grazing; environment; organic agriculture

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INTRODUCTION

Contemporary agriculture is characterized by a high degree of specialization or '*dis*-integration' of crop and livestock production, both on individual farms and among regions. Grain and hay exported from specialized crop operations are utilized in confinement feeding operations which are ecologically disconnected with the crop operations, whether within the same region or thousands of kilometers away.

Specialization has afforded us a bountiful and seemingly cheap food supply partly by externalizing costs in the form of adverse impacts on human, livestock, and environmental health. Scientific literature relating to production agriculture focuses increasingly on rectifying such problems as manure nutrient and pathogen loading around confinement facilities (Davis, Young, and Ahnstedt, 1997; Entry et al., 2000a, b; Kovacic et al., 2000; Taylor and Rickerl, 1998; Whalen and Chang, 2001), soil degradation under continuous row crop agriculture (Gordon, Fjell, and Whitney, 1997; Nelson, 1997; Wheeler et al., 1997); surface- and groundwater contamination by biocides, fertilizers, and manure (Barbash et al., 2001; Karr et al., 2001; Russelle et al., 2001; Sharpley and Rekolainen,1997; Troiano et al., 2001), and animal health and welfare in confinement (Mellon, Benbrook, and Benbrook, 2001).

This contribution explores the thesis that specialized agriculture is an ecologically dysfunctional design for food production because it widens opportunities for pests to proliferate, pollution to occur, and health to be compromised. It will be argued that re-integrating crop and livestock agriculture has the capacity to avoid these increasingly intractable problems, while also capturing useful synergies among enterprises.

The historic roots of specialization will first be reviewed, followed by consideration of contemporary problems created by the polarity of crop and livestock enterprises. Focusing primarily on soils, it will be proposed that livestock are, in fact, an essential prerequisite to ecologically sustainable farming practice. I will conclude with an overview of the largely untapped potential for using forages and livestock for environmental enhancement.

HISTORICAL CONTEXT

It is said that those who refuse to heed the lessons of history are condemned to repeat them. Nowhere is this better demonstrated than in the question of integrating crop and livestock enterprises to sustain agriculture.

As far back as 1947, Louis Bromfield argued in *Malabar Farm* that the "general" highly diversified farm of his grandparents had "outlived its usefulness and its economic justification" in favor of "reasonably" specialized farming. By 'general' farm, he meant a self-sufficient farm, producing a few of each class of livestock as well as all the necessary crops, fruits, and vegetables to sustain the farm family. He reviewed the lessons derived from his 9 years of experience at Malabar Farm to conclude that specialized grass and small grain farming to support meat and milk production was the most efficient and profitable use of his rolling Ohio farmland.

What he called 'reasonably specialized' is archetypical mixed farming, with livestock and especially the grass consumed by the livestock fully integrated into the farming system. Perennial grass, clover (*Trifolium* sp.), and alfalfa (*Medicago sativa* L.) featured prominently in the prescription developed by Bromfield to return to health land which had been degraded by years of specialized, arable cropping. In a series of highly influential books (*Pleasant Valley*, 1945; *Malabar Farm*, 1948; *Out of the Earth*, 1950; *From My Experience*, 1955), along with farm tours attended by thousands, Bromfield provided dramatic evidence that grass - and hence, the livestock to convert the grass into profit - was essential to arable agriculture in the Midwest.

Yet, he then went on to conclude in the same text that the traditional three-or-four-year crop rotation was no longer necessary on productive farms. At the dawn of the modern synthetic chemical and fertilizer era, Louis Bromfield argued that the grass and livestock manure which he himself had shown to be indispensable could in fact be replaced with "lime, green manures, and humus", or more broadly, fertilizers and plowdown crops. He was impressed by Faulkner's *Plowman's Folly* (1943), which advocated conservation tillage coupled with heavy use of green manure crops. Despite his own extensive experience with integrated farming, Bromfield predicted that plowdown crops and chemical fertilizers would become the tools of preference for the next generation of specialized grain farmers.

That a visionary of the stature of Bromfield would have made such a prediction is testament to the allure of new technology - in this case, relying on fertilizer and conservation tillage to displace integrated agriculture and enable specialization. His prediction is all the more remarkable because these same forces of specialization starting earlier in the century had actually created the barren, rundown land which became Bromfield's canvas at Malabar Farm.

Although synthetic biocides did not become commercially available on a large scale until after World War II, farm enterprise specialization began much earlier in the 20th century. Gregson (1996) traced the forces driving enterprise specialization in the US from the mid 1800's to the present day. She cited evidence that diversified agriculture was the norm in the midwestern US (and in Ontario; see below) through the first quarter of the 20th century. From then onwards, however, developments in everything from farm equipment to fertilizer formulations supported increased specialization. Gregson (1996) showed, for example, that rate of synthetic fertilizer application accounted for two-thirds of the variation in specialization in Illinois between 1925 and 1969. She theorized that fertilizer served to homogenize growing conditions, allowing farmers to respond uniformly to market signals, regardless of the inherent suitability of their land for specific crops. More recently, Duvick (1989) emphasized the homogeneity of corn (*Zea mays* L.) genetics, stating:

> "...there has been a change over the past 20 years toward widespread plantings of a relatively small number of single-cross hybrids...This change has probably increased Corn Belt-wise uniformity of reaction to climatic variables."

Increasing reliance on production inputs, including genetics, had the effect of standardizing both growing conditions and response to management and climate, removing the buffering effect of individual producer diversity in cropping method and cultivar/hybrid choice and increasing vulnerability to the market.

Ready access to effective chemical fertilizers also encouraged the perception that farmers were no longer dependent on biological nitrogen (N) fixation and nutrient cycling through livestock to maintain soil health. It took only a few decades for such thinking to produce the impoverished farmland which Bromfield purchased in 1939 as Malabar Farm. Paradoxically, the program of *revitalization through integration* which he chronicled so persuasively in his popular books was prematurely curtailed when government and academia as well as industry became proponents of specialization (Nelson, 1997).

The integral role of livestock in sustainable agriculture was widely known prior to the advent of chemical fertilizers and biocides. Leitch (1920) reported on a detailed economic survey of 385 beef farms in western Ontario focussing on the northern half of Middlesex County, which at that time was heavily devoted to grazing beef cattle. Although the primary product was beef, farms were ‘mixed’, growing both clover *(Trifolium pratense* L.) and timothy (*Phleum pratense* L.) hay, wheat (*Triticum aestivum* L.), oats (*Avena sativa* L.), barley *(Hordeum vulgare* L.), corn, and potato (*Solanum tuberosum* L.). Most of the coarse grains were fed on the farm, while some grain crops, and specifically wheat, as well as alsike clover (*Trifolium hybridum* L.) seed were also sold as cash crops.

One of the practical questions addressed by the survey was ‘should crops be sold or fed?’ Farms were placed in 6 categories, according to the fraction of total income that came from crop sales, ranging from 0-10% (#1) to >50% (#6). Over this range, total income increased with the fraction of income from crops (Figure 1).

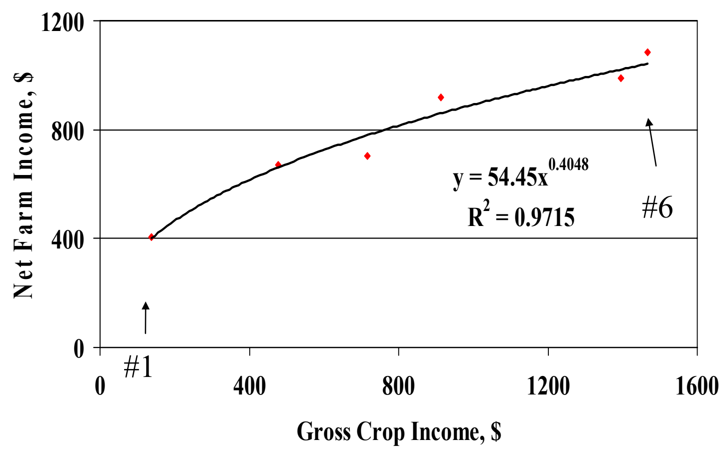

Figure 1. Net farm income as a function of gross crop income on Middlesex County beef operations in 1918 (adapted from Leitch, 1920)

The author's interpretation of this relationship reflected the perceived importance of grass in that era. He noted that while the evidence might suggest that the best thing to do would be to sell off the stock and just go cash crop entirely:

a) the line was curvilinear, not linear, with each additional increase in gross crop income producing disproportionately smaller increases in net farm income, and

b) about one-third of crop sales for the highest crop income group (#6) were from alsike clover, and 1918 was an unusually favorable year in that both yield and price were high.

He concluded that recognizing year-to-year variations in the weather and crop prices, the most profitable operations were those with 30-40% of their gross income from crops, with the balance from livestock, because *"maintaining of this live stock insures the keeping up of soil fertility, which is a factor of no small consideration"* (Leitch, 1920).

Within the same dataset, he asked "how much tillable land should be in pasture" for highest profit? Surveyed farms demonstrated that the answer varied with farm size (Figure 2). Small farms [<100 acre (ac)] were most profitable with no more than 20% of tillable land in pasture. For medium to large farms, however, the most profitable fraction ranged from one-third to one-half of tillable land in pasture.

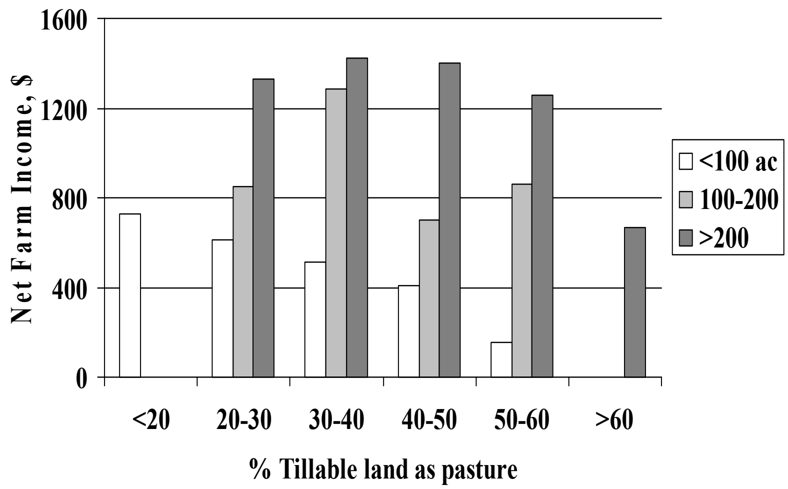

Figure 2. Net farm income as a function of the fraction of tillable land that was under pasture, as affected by farm size (<100, 100-200, and > 200 ac) (adapted from Leitch, 1920).

Clearly, prior to the arrival of synthetic fertilizers and other production inputs, both sustainability and profitability depended on the integration of livestock with crops. Neither crop nor livestock alone maximized profit in the long term. Too much of either crops or livestock reduced net income. Thus, in that era, farmers realized the benefits of integrating crops and livestock. With input costs rising much faster than the value of the commodities, this may be a lesson for contemporary farmers as well.

THE PROBLEMS OF POLARITY IN LIVESTOCK-DOMINATED AGRICULTURE

Livestock and the feedstuffs they consume dominate the agricultural landscape of North America and much of the developed world. Worldwide, the proportion of grain that is grown specifically for livestock feed is 40%, increasing with per capita income to as high as 90% in North America (Cox and Atkins, 1979). Baker and Raun (1989) reported that half of all agricultural receipts in the US came from the sale of livestock. Two-thirds of the feed grains and half of the soybeans (*Glycine max* (L.) Merr.) produced in the US were also absorbed in feeding livestock. Much of the remainder is destined for livestock feed in importing nations. Thus, the fortunes of the livestock sector are already intertwined with those of the grain crop sector. The strengths and weaknesses one sector affect the viability of the other sector.

Despite their interdependence, crops and livestock have become increasingly disconnected - spatially and functionally - in contemporary agriculture. Farmers and ranchers have been urged to specialize, to become experts at growing corn and soybeans or weaned calves and nothing else. Economies of scale are the cited argument, yet dis-economies of scale are becoming increasingly evident, particularly as society becomes increasingly unwilling to absorb the externalized costs of large scale agriculture. Thus, one argument for re-integrating livestock and forages into crop production systems is to avoid the economic, environmental, and health problems that have been incurred by specialization.

Economic

As reflected in declining farm populations and plummeting enrolments in agricultural majors, agriculture is no longer gainful, full time employment for most North American farmers. Bird, Bultena, and Gardner (1995) documented the inverse relationship between farm population and farm size in the upper Midwest and plains states. In Iowa, Minnesota, North Dakota, and Montana, for example, farm population declined by 72, 77, 82, and 74% between 1940 and 1990, while farm size increased by 88, 89, 123 and 121%, respectively.

John Ikerd, an agricultural economist, has written extensively about the broader economic implications of large scale agriculture, using swine in Missouri as a case example.

One justification for large scale production is lower per unit cost of production, and hence, cheaper food for consumers. Ikerd argues that while cost of production is indeed slightly lower in large scale than in conventional hog operations, the impact on consumer costs is almost undetectable, because the cost of live hogs is less than 35% of the price paid by consumers (USDA Market
Price Statistics). The remainder goes to processors, transportation, retailers, and other intermediaries.

Large scale hog production also employs a fraction of the people required to produce hogs in more conventional systems. In Missouri, for example, a composite farrow to finish contract operation would employ just 4.25 people to produce $1.3 million in sales of hogs (Ikerd, 1998). Producing roughly the same dollar value on independently operated hog farms would employ 12.6 people. Assuming a multiplier of 2.22, which reflects related jobs created in the feed business, construction, pharmaceutical, veterinary, and other suppliers, as well as jobs created through retail purchases of goods and services by new employees, then producing $1.3 million in hog sales under contract would 'employ' 9.4 people, compared to almost 28 people on conventional, independent hog farms (Ikerd, 1998). In this example, contract growing would displace 18.5 people, with ripple effects throughout the farm economy and rural community.

Specialization has generated a bountiful food supply, while driving farmers out of business. In an era of specialization, a farmer who can 'feed 128 of his fellows' has to take off-farm employment to put food on his own table. It is difficult to conclude that specialization has benefited either farmers or farm communities.

Environmental

The lack of integration of crop and livestock production amplifies the ecological footprint of agriculture. The unidirectional movement of feedstuffs from specialized cropland to specialized livestock feeding facilities, as is currently occurring with the installation of very large scale dairies based on imported feed in Kings and Tulare counties in California, depletes soil fertility at one end while concentrating nutrients to excess at the other. Decades of experience with manure and disease management on beef feedlots would predict future problems with large scale dairying.

Taylor and Rickerl (1998) compared statewide feedlot averages on the density of fed livestock per unit of available cropland to receive manure. Feedlots in the big four cattle states - Texas, Nebraska, Kansas and Colorado - were 3.3 to 5.6 times as concentrated as those in South Dakota. Yet even so, the manure returned to cropland in the vicinity of 78 South Dakota feedlots exceeded recommended levels of N 41 and 51% of the time, and recommended levels of phosphorus (P) 52 and 71% of the time, for corn and wheat respectively. Furthermore, due to economic disincentives for long distance hauling of manure, per hectare application of N and P in manure varied directly with feedlot size. The fraction of sites with cropland receiving in excess of 100 lb N ac^{-1} was 16% in the <1000 head category, but increased to 33 and 75% in the 1001-2000 and >2000 head categories, respectively. In effect, livestock capacity in feedlots has increased faster than the capacity of the landbase to receive the manure. As a result of agricultural practice, 98% of South Dakota lakes smaller than 5000 ac no longer meet standards for fishing and swimming (Taylor and Rickerl, 1998).

Colorado supports a cattle population of approximately 1 million head on feed at any point in time. Davis, Young, and Ahnstedt (1997) assessed nutrient status of 41 Colorado corn fields, each of which was within 8 km of a feedlot and had been receiving manure for several years. Nitrogen balance in excess of crop needs averaged 521 and 292 kg N ha^{-1} for sandy and clayey soils, respectively, with the difference due primarily to greater use of N-contaminated groundwater on the sandy soils. With one exception, all samples from both soil types were in the 'Very High' range of soil P. Repeated application of feedlot manure to corn land in Colorado has produced land at risk of both nitrate leaching and P runoff adsorbed to soil particles.

Whalen and Chang (2001) reported that Alberta has a 1.2 million head feedlot capacity, distributed among 4800 feedlots ranging in size from 1000 to 50,000 head. They examined P dynamics on experimental unirrigated and irrigated plots which had received a predetermined range of manure rates for 16 years. Solid manure was applied in the fall of each year after barley harvest, and immediately incorporated. They found that even using the provincially recommended rates of 30 and 60 Mg ha^{-1} provided 5-6 times as much P as is recommended for unirrigated and irrigated barley, respectively. They also documented that total and available P concentrations were higher, particularly at the higher rates of application, at every measured depth in the soil (down to 150 cm), when compared to unmanured controls. Whalen and Chang (2001) found that repeated applications of manure in excess of demand can result in risk of P leaching to groundwater even in calcareous soils. Evidence that soil P has reached the level of an environmental risk within confinement feeding zones in the Netherlands, Belgium, the northeastern USA, and Florida was reviewed by Sharpley and Rekolainen (1997).

Farming systems impacts on the environment may also include greenhouse gas production, and effects on global warming, eutrophication, and acidification (Haas, Wetterich, and Kopke, 2001). For example, in on-farm comparisons in Germany, up to half of the total energy cost per unit milk produced on intensively managed grass dairies came from purchased N fertilizer. Although not yet commonplace, these types of alternative indices of environmental impact appear likely to assume greater prominence in the future.

In sum, production systems which adopt cyclical rather than linear nutrient flows, and which rely more on biologically fixed N and less on fossil fuels impose a smaller‘ecological footprint.’

Health

Direct health risks associated with specialized agriculture may accrue from the fertilizers and biocides used in crop production and from the antibiotics, growth stimulants, and other products routinely used in confinement housing of livestock. Pathological risks associated with livestock manure, including cryptosporidia and *E. coli*, have assumed increasing prominence in recent years. Additional indirect risks can occur when biocides, manure, or fertilizer nutrients contaminate surface or groundwater. For example, a 5-year study by Porter, Jaeger, and Carlson (1999) compared endocrine, immune, and nervous system responses to aldicarb, atrazine, and nitrate - alone or in combinations - at the maximum allowable groundwater concentrations for these chemicals. Binary combinations of these chemicals elicited responses not seen with individual chemicals. Indices of aggression and thyroid activity as well as immune system function, measured as antibody production when challenged with a foreign protein, responded to combinations of either or both herbicides with nitrate.

Crops

Perennial forages keep the soil covered year-around, enhancing infiltration and reducing surface runoff. In addition, a perennial sward establishes and maintains net nutrient uptake capacity earlier and later in the year, better accommodating natural cycles in mineralization and reducing leaching risk. In contrast, row crops are particularly prone to runoff and off-site contamination, both because the land is poorly covered for much of the year, and because timing of nutrient uptake is out-of-phase with soil mineralization (Staver and Brinfield, 1990). In Iowa, Schilling and Libra (2000) showed a positive linear relationship between the fraction of row crop land in a watershed and the concentration of nitrate in the watercourses draining the watershed, for both large and small watersheds:

Large watersheds: $y = 0.108x - 0.812$ ($r^2 = 0.65$)

Small watersheds: $y = 0.11x + 0.217$ ($r^2 = 0.94$)

In both types of watersheds, increasing the fraction of the land occupied by row crops increased nitrate in the watercourses at a rate of 0.11 units of nitrate (mg L^{-1}) per unit land area (%). The life cycle of the annual grain crops grown for confinement feeding, and particularly those which are heavily fertilized with N, predetermines risk of both leaching and off-site contamination.

Many of the annual crops used for livestock feed in North America are dependent upon biocides to control weeds, insects, and diseases. At present, almost a billion pounds (lbs) of biocide active ingredient (a.i.) are applied annually to US crop and rangeland (Benbrook, 1996), with the rates of application varying among crops. Kegley, Orme, and Neumeister (2000) reported that in 1998, California corn for grain and for silage received 2.7 and 4.9 lb a.i.ac^{-1}, respectively, in comparison with pasture and range, which received just 0.67 and 0.16 lb a.i. ac^{-1}, respectively.

According to Troiano et al. (2001), it was originally assumed that biocides were unlikely to leach to groundwater due to “dilution effects, low water solubility, high vapor pressure, rapid degradation, and binding to the soil." This belief has now been challenged by the ubiquitous finding of biocide contamination in both ground and surface water in large scale surveys, as reviewed by Barbash et al. (2001). The US National Water Quality Assessment program, sampled 2227 sites (surface and groundwater) distributed in 20 major hydrologic basins, between 1993 and 1995 (Barbash et al., 2001). Frequency of detection correlated positively with adjoining land usages for urban non-agricultural use (atrazine, cyanazine, simazine, alachlor, and metolachlor) and for rural agricultural use (atrazine, cyanazine, alachlor and metolachlor).

In California, 16 biocide active ingredients and breakdown products have now been detected in groundwater as a result of legal agricultural use (Troiano et al., 2001). More than 50 biocide active ingredients have been classified as potential leachers. Well water surveys have identified Pesticide Management Zones (PMZs) which are vulnerable to leaching. When no mitigation measures are available and sampled concentrations are near the maximum contaminant level allowed in the state, use of specific biocides can be prohibited, as occurred with bentazon on rice (*Oryza sativa* L.).

Because California began testing wells in the mid to late 1980's, a considerable database has now evolved. Using the section (2.6 km^2) as the sampling unit, testing was designed to sample wells in 10% of the sections surrounding each PMZ. Detection of a previously detected a.i. in a section adjacent to a PMZ resulted in the sampled section being submitted for addition to the PMZ list. Thus, the number of adjacent sections to be monitored increased over time. For example, in an area covering parts of Fresno and Tulare Counties, biocides were detected in 74 sections in 1988, 163 in 1990, 253 in 1992, and 409 in 1995 (excluding DBCP; 1,2-dibromo-3-chloropropane).

Increasing detection reflected increased biocide dependence. According to Kegley, Orme, and Neumeister (2000), usage of biocide active ingredient[1] increased from 22.1 to 39.9 million lb in Fresno County and from 11.0 to 18.3 million lb in Tulare County between 1991 and 1998. On an area basis, active ingredient averaged 29 and 26 lb ac^{-1} for these two counties in 1998.

The trend is clear. Increasing biocide dependence manifests itself in increasing detection in groundwater. The health implications remain uncertain, however, due to limited, independently validated testing, single residue testing, and lack of testing of newly identified risks.

California and other jurisdictions have documented biocide exposure due to concerns about human health. For example, some 70 biocide active ingredients are known to cause cancer in animals (Benbrook, 1996). Among the best studied is 2,4-D and other chlorophenoxy herbicides, which have been linked with non-Hodgkin's lymphoma (Zahm and Blair, 1992; various in Steingraber, 1997). Schreinemachers (2000) associated the incidence of cancer with use of chlorophenoxy herbicides in selected agricultural counties in Minnesota, North Dakota, South Dakota, and Montana. Most US wheat is grown in these states, with 90% of spring and durum wheat and 30% of winter wheat being treated with chlorophenoxy herbicides. Age-standardized cancer mortality (1980-1989) increased with acres sown to wheat for various types of cancer.

Thus, whether due to nitrate or biocide contamination of groundwater or risk of other biocide exposure, contemporary methods of growing crops on specialized grain farms, for

[1] Gross active ingredient includes all pounds of biocides, both agricultural and non-agricultural

feeding on specialized livestock operations, increases potential health risks.

Livestock

Large-scale confinement feeding systems foster potential human health risks, both from the manure they generate and from the pharmaceuticals that are required to keep stock healthy in high density confinement. In North Carolina, hog numbers grew from 3.7 to 9.8 million between 1991 and 1997, largely in a 5 county region around the world's largest slaughterhouse - which processes 24,000 hogs a day, 365 days a year (Nowlin, 1997). Agriculture - and primarily swine operations - accounted for 56 to 76% of the nutrient pollution of two major surface water systems, causing serious problems with eutrophication and with *Pfiesteria piscicida*, a dinoflagellate which is lethal to fish (Nowlin, 1997). More than 50% of the manure lagoons tested in North Carolina exhibited severe seepage losses, exposing groundwater to contamination. Karr et al. (2001) cited evidence that manure N produced in some North Carolina counties exceeds 500% of crop need for N, yet commercial fertilizers are widely used.

Antibiotic use has increased in confinement feeding systems, particularly for hogs and chickens (Mellon, Benbrook, and Benbrook, 2001). Fully 80% of the antibiotics used in contemporary farming are prophylactic in nature or growth promotants - not to cure animal illness. The US livestock industry annually consumes 24.6 million lbs of antimicrobials, such as tetracycline, penicillin, and erythromycin for non-therapeutic uses (in the absence of disease). Of these, hogs and poultry are the most dependent, consuming in excess of 10 million lbs each, compared to cattle at 3.7 million lbs. Pretty et al. (2000) cited evidence that resistant strains of *Salmonella, Campylobacter, Enterococci,* and *E. coli* resulted from use of these antimicrobials in farm animals.

There is diminishing societal tolerance for farm practices which externalize costs of production involuntarily to society and environment. Pretty et al. (2000) estimated the externalized costs of UK agriculture, many of which are a direct result of the functional isolation of crop from livestock enterprises. Just those which relate in one way or another to nutrient management, including N and P in drinking water, emissions of ammonia, and emissions of nitrous oxide from N fertilizer, account for over one-third of the externalized costs. Total value to 1996 UK agriculture of costs currently excluded from farm budgets was £2343 million or £208 ha^{-1} of arable land and permanent pasture. This conservative estimate of externalized costs amounts to 89% of average net farm income, reducing the benefit:cost ratio of UK agriculture to virtually 1:1.

Examples of diminishing societal tolerance of externalized costs are numerous. Neeteson (2000) described current regulations on nutrient management in Dutch agriculture, including a ban on winter-spreading of manure, obligatory cover for manure storage facilities, compulsory injection or immediate incorporation to reduce emissions during spreading, and fines for exceeding permissible levels of N and P surpluses. Troiano et al. (2001) reviewed the California legislation which mandated systematic water quality testing and constrained biocide use in 'PMZ'.

Whether economic, environmental, and health-related, specialized agriculture has engendered problems of increasing societal concern. In response, society appears to be moving toward a 'full cost accounting' approach, which would oblige farmers and others to more fully internalize their costs of production. Such a development may help to profile some of the potential positive synergies of integrated crop:livestock agriculture.

CAPTURING THE SYNERGIES OF LIVESTOCK-BASED AGRICULTURE

Historically, livestock were viewed as tools of production. Livestock were integrated into farm operations specifically to capture positive synergies among enterprises - to perform tasks and supply services to other enterprises - not just as a marketable commodity. As shown in the survey by Leitch (1920), livestock only made ecological and economic sense as part of a larger whole. And of course, the same could be said for grain or any other enterprise. In the traditional view, the value of a ewe or a corn field was more than just the saleable product. The economic value of their contributions to other enterprises, whether for weed control or nutrient cycling or animal health, was recognized.

Contemporary agriculture has been operating under the premise that farmers no longer *need* to make enterprises 'fit' together to accomplish tasks - they can just *buy* the services formerly achieved through integration. So long as costs of inputs were low, relative to the value of the commodities, this strategy appeared to work well. Now the cost of inputs is rising one or even two orders of magnitude faster than the value of the commodities produced, contributing to the economic crisis facing farmers today. For example, one of the newest inputs to production is genetically modified (GM) crops, such as Roundup Ready (RR) soybeans[2]. Benbrook (1999; Table 7) documented that compared to growing non-GM soybeans, the cost of growing RR soybeans consumed an additional 2.3 to 12% of gross income per acre across 8 midwestern

[2] RR is Roundup Ready, engineered to be tolerant to the herbicide glyphosate

states[3].

Indeed, valuing crops and livestock simply as marketable commodities, as in specialized agriculture, not only creates costly and intractable problems (see above), but furthermore, blinds farmers to the potential for economic, agronomic, and environmental *synergies* between livestock and crop enterprises. Thus, enterprise integration has merit not simply to avoid generating problems, but also, to harness natural processes to human ends.

For example, crop rotation and associated management are known to influence perennial weed communities, the soil weed seed bank, and the soil reservoir of pests, pathogens, and nutrients as well as deleterious and beneficial soil microbes (Bezdicek and Granatstein, 1989; Dick, 1993; Reganold, 1995; Sturz et al., 2001). Entz, Bullied, and Katepa-Mupondwa (1995) surveyed 253 Manitoba and Saskatchewan farmers who were known to include forages in their crop rotations. Over 80% reported a reduction in weed pressure for 1, 2, or more years (11, 50, and 33%, respectively) following forages. Inclusion of forages in the rotation afforded good control of several of the most problematic weeds in western Canada, wild oat (*Avena fatua* L.), Canada thistle (*Cirsium arvensis* L.), wild mustard (*Sinapis arvensis* L.), and green foxtail (*Setaria viridis* (L.) Beauv.). The utility of forages in controlling wild oat and green foxtail is noteworthy, because both are already resistant to several common herbicide families. Over two-thirds of the farmers surveyed by Entz, Bullied, and Katepa-Mupondwa (1995) also reported higher grain yields following forages, particularly in the zones with higher moisture. Thus, this

[3]costs calculated as US$8/ac in technology fee plus the yield drag at US$5.25/bu; RR soybeans yield less than their non-GM counterparts

survey data corroborated the research findings that forages benefit the performance of subsequent crops in the rotation.

Likewise, Drinkwater et al. (1995) reviewed literature showing that soils managed for high soil organic matter (SOM) content in the absence of biocides showed higher microbial activity and lower levels of instantaneous mineral N pools, despite having higher levels of potentially mineralizable N. In a 2 year trial involving 20 California organic and conventional tomato (*Lycopersicon esculentum* Mill.) farms, low available soil N and high microbial activity were associated with lesser incidence and severity of corky root (*Pyrenochaeta lycopersici*). Thus, integrating crops and management practices conducive to maintaining high levels of SOM, such as perennial forages (see below), may enhance soil health for other crops in the rotation.

The contribution of livestock to ecologically sustainable farming is still recognized by organic and sustainable agriculturalists. The position statements of organic farming organizations such as the *International Federation of Organic Agriculture Movements (IFOAM)* include principles such as "to encourage and enhance biological cycles within the farming system, involving micro-organisms, soil flora and fauna, plants and animals" and "to create a harmonious balance between crop production and animal husbandry."

A survey of 2450 'sustainable' (based on a calculated sustainability index) and conventional producers in four states of the US found that 76 to 93% of the sustainable farms had livestock, compared with 37-58% for conventional (Bird, Bultena, and Gardner, 1995). The rationale for keeping livestock varied among regions, with intensively managed grazing preferred in the higher rainfall areas, compared with extensive grazing of range land in Montana. Some producers integrated grazed or hayed forages in their crop rotation, in part for weed control. Others valued livestock as a buffer, to convert weather damaged grain into income that would otherwise have been lost. On sustainably managed farms, livestock perform functions apart from simply production of a marketable commodity.

Although agroecosystems differ from natural ecosystems, integrating forages and livestock into a cohesive whole most closely mimics nature. By affording access to the synergies of a natural ecosystem, integrated systems minimize economic, environmental, and health problems, and hence, the need to purchase problem-solving inputs. In other words, integrated systems help to internalize costs of production. For example:

a) Forage swards typically consist of multiple rather than a single species, utilizing biotic diversity to exploit diverse ecological niches (Clark, 2001), retain nutrients, maintain soil cover and productivity throughout the year, and discourage weed and pest proliferation.

b) Withholding land from cultivation avoids the periodic disturbance characteristic of arable systems, which promotes SOM breakdown and exposes the land to erosion (see below).

c) Vigorous perennial swards resist weed encroachment. Simple swards sown to 1 or 2 species can be vulnerable to weed encroachment, as shown in UK surveys by Morrison and Idle (1972) and Hopkins et al. (1985). However, weed contribution to sward yield was just 10 to 20% in a 9 year old pasture sown to a complex mixture in Ontario (Clark, 2001). In contrast, tillage and/or herbicides applied to annual crops set back succession, ensuring that pioneer invaders - weeds - will be an ongoing problem.

d) Perennials establish and maintain a nutrient sink throughout a greater portion of the year, better diluting leaching risk in spring and fall. Studies cited by Pearson and Ison (1987) suggest that N leaching can be considerable under highly productive grazed legume pastures in regions of high rainfall. They conclude, however, that losses under permanent grassland are typically minor, perhaps 3% of what is taken up by the herbage, in contrast to losses of 10-30% of uptake under annual forages.

In contrast, annual crops introduce a periodicity in nutrient uptake capacity which is out-of-phase with soil mineralization cycles, creating vulnerability to nutrient loss. In Maryland, Staver and Brinfield (1990) documented the ability of fall rye (*Secale cereale* L.) following corn to immobilize an additional 118 kg N ha^{-1} which would otherwise have been vulnerable to loss from corn land fertilized at the recommended rate. Aside from off-site contamination, nutrients lost due to the asynchrony between crop demand and nutrient supply must be replaced.

e) Nutrient export in livestock products (meat, milk, or wool) is low, relative to that of grain or whole plant crops (hay or silage), as most ingested nutrients are excreted. Spedding, Walsingham, and Hoxey (1981) reported implied nutrient exports from grain and potato crops to range from 80 to 360 kg N ha^{-1}, from 12 to52 kg P ha^{-1}, and from 17 to 230 kg K ha^{-1}, compared with 12 to 35 kg N ha^{-1}, 0.7 to 6 kg P ha^{-1}, and 0.1 to11 kg K ha^{-1} in livestock products. Marketing feedstuffs as livestock in an integrated operation, rather than as feed in a specialized operation, promotes cyclical rather than linear nutrient flows and reduces dependence on purchased nutrients.

f) Perennial swards can also serve as a reservoir for natural pest control agents. Langer (2001) cited evidence that clover:grass leys facilitated parasitoid control of cereal aphids (*Sitobion avenae* (F.)) in adjoining arable croplands. In Denmark, Langer (2001) found that an undersown grass/clover ley supported a population of aphids as well as parasitoids, thus maintaining a population of aphid-controlling parasitoids year-around.

g) Livestock manure has been shown to be superior to chemical fertilizer, as shown in long term studies by Baldock and Musgrave (1980). The beneficial effect appears to exceed what could be attributed to nutrients alone, suggesting that manure affects other yield enhancing processes, perhaps through soil structure or soil biotic diversity. For example, activity of the soil enzymes urease and amidase was shown to be much higher in soils amended with livestock manure than chemical N fertilizer (Dick, 1993). Both of these soil enzymes facilitate N cycling, and hence, the ability of soils to supply N to crops.

Thus, inclusion of forages and/or livestock within an integrated production system permits synergies which diminish dependence on both processes and purchased products which have become problematic in specialized agriculture.

Conserving/Improving Soil Health

Forages and livestock promote soil health, which is considered to be "...the capacity of soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health" (Deng, Moore, and Tabatabai, 2000). Central to soil health is SOM status, which is an integrative index of the balance between organic matter (OM) input and breakdown. Soil organic matter is the energy which fuels the biotic processes which sustain soil health, as manifested in tilth, structure, water holding capacity, and resistance to both compaction and erosion. However, since the start of cultivation, SOM has declined exponentially to a new, lower plateau which is characteristic of specific management environments (Beauchamp and Voroney, 1994).

Soil organic matter can be replenished from the roots and stubble of sown crops or from green manure crops, or from pastured or applied livestock manure. The magnitude of root biomass that accumulates in perennial leys was reported by Eriksen and Jensen (2001). They assessed the effect of spring cultivation on 3-year old swards of perennial ryegrass *(Lolium perenne* L.) (PRG) or PRG-clover. Under Danish conditions, root residues to a depth of 20 cm were 11.5 and 8.8 t ha^{-1} in the PRG vs. PRG-clover swards, respectively. Root tissues accounted for 95% of total plant residual dry matter. From early April to late June, cultivated swards evolved 2.6 t C ha^{-1} compared to 1.4 t C ha^{-1} in the uncultivated swards. Much of the N released through mineralization occurred within the first 4 weeks after cultivation. Conclusions which may be drawn from this study are a) that root tissues are a prominent source of the OM which enriches the land in grassland leys, b) cultivation promotes C loss, and c) capturing the N mineralized from incorporated swards requires rapid establishment of an effective nutrient sink, directly after cultivation.

In Norway, Breland and Eltun (1999) compared indices of soil microbial activity in 8-year arable vs. forage-based rotations. The forage-based rotations integrated a 3-year grass ley into the original arable crop rotation. After 5 years, total soil C in the arable vs. forage-based systems was 2.4 vs. 2.7%, while microbial biomass C was 242 vs. 303 mg C kg^{-1} soil and microbial biomass N was 41.1 vs. 51.4 mg N kg^{-1} soil, respectively. The metabolic quotient was also lower in the forage than in the arable rotation, 0.472 vs. 0.553 μg CO_2-C h^{-1} mg^{-1} biomass C. The metabolic quotient is inversely related to the maturity and species-diversity of soil microbial communities, and hence, to the efficiency with which OM is cycled. Greater root biomass and the addition of animal manure accounted for improved soil health in the forage-based vs. arable rotations (Breland and Eltun, 1999).

Deng, Moore, and Tabatabai (2000) compared soil health parameters in several 4-year crop rotations at long-term sites established in Iowa. When measured in 1996, soils with 1 or 2 years of alfalfa in the rotation were higher in microbial biomass C (380 and 429 mg C kg^{-1} soil, respectively) than soils under continuous corn or corn-soybean rotations (326 and 335 mg C kg^{-1} soil, respectively). Parallel trends were evident in microbial biomass N, with 60 and 66 mg N kg^{-1} soil in rotations with 1 or 2 years of alfalfa, respectively, compared to 57 and 58 mg N kg^{-1} soil in continuous corn or corn-soybean rotations, respectively. Microbial biomass is considered a sensitive indicator of the capacity for OM breakdown and nutrient cycling. Similar trends were shown for dehyrodrogenase activity, which is an index of microbial activity, and amidase activity, which relates to N mineralization. They concluded that including alfalfa in a crop rotation served to increase soil bioactivity compared to continuous arable cropping.

At the same sites in Iowa, Deng and Tabatabai (2000) demonstrated that N mineralized during 24 weeks of aerobic incubation was higher on soils from rotations including 1 or 2 years of alfalfa (175 and 208 mg N kg^{-1} soil, respectively) than in continuous corn or corn-soybean rotations (132 and 140 mg N kg^{-1} soil, respectively). Parallel trends were observed when N mineralization was expressed relative to organic N content, namely, 8.25 and 9.48% for rotations with 1 or 2 years of alfalfa, respectively, vs. 6.97 and 7.57% for continuous corn or corn-soybean, respectively. Including alfalfa in crop rotations not only conserved soil C and N, but also served to strengthen the active N pools in soils and increase N availability (Deng and Tabatabai, 2000) for subsequent crops.

Land which had been under continuous arable cropping for 11 years provided the site for a New Zealand (NZ) comparison of microbial responses to grass vs. arable cropping (Haynes, 1999). After 5 years of treatment, responses to various grass and arable treatments were compared with those from a nearby longterm (LT) pasture. Throughout the 15 cm profile, soil organic C was highest under LT pasture and lowest under LT arable with the other treatments intermediate. The range between these two extremes was greatest in the 0-2.5 cm layer - 65 vs. 30 g C kg^{-1} soil - declining to 40 vs. 30 g C kg^{-1} soil in the 10-15 cm layer. Just 5 years under grass, however, improved soil organic C in the 0-2.5 cm layer by 50%, compared to LT arable usage.

As noted by Brelund and Eltun (1999), Haynes (1999) found the metabolic quotient of LT arable land (stable at more than 80 µg CO_2-C mg^{-1} biomass day^{-1}), was clearly distinguishable from that of other treatments. The greatest contrast was that in the LT pasture, which increased from 45 to 55 µg CO_2-C mg^{-1} biomass day^{-1} with depth in the profile. Evidence from this and other studies led Haynes (1999) to infer an adverse effect of cultivation on the efficiency of use of C substrate. He concluded that the beneficial effect of including a grass-clover ley in an arable rotation was due not simply to the addition of C and N to the soil, but primarily to withholding the land from cultivation.

Weil, Lowell, and Shade (1993) compared 5 cropping systems in Maryland, of which one was continuous grass, while the others were rotations involving corn, soybean, and wheat, with varying intensities of both tillage and chemical use. Over 5 years, SOM in the surface 15 cm was significantly higher in the grass than the other treatments (2.28 vs. 1.68-1.95%), with parallel effects on total C (1.11 vs. 0.7-0.85%) and bulk density (1.15 vs. 1.29-1.38 g cm^{-3}). Consistent with effects on bulk density, infiltration rate was 10 times faster in the grass than in the continuous corn, with the other treatments intermediate. Total N was also significantly higher in grass than in the other rotations (0.1 vs. 0.07-0.08%), with the exception of an organic treatment (0.09%). The authors concluded that "Most dramatic improvement in porosity, OM accumulation and N mineralization ability came from 5 years continuous growth under grass sod, underscoring the potential role of grass in sustainable cropping systems..."

The effectiveness of plowdown crops as an OM source in stockless crop rotations was evaluated by Bulson et al. (1996). They compared the effect of 3, 4-year stockless rotations on agronomic performance and edaphic variables in the UK. In each rotation, 1 of 4 years was devoted to red clover for plowdown, to add N and OM to the system, with the remaining 3 years in combinations of cereals, potatoes, and beans. Over an 8 year period, SOM declined linearly from over 3% to about 2.5% in all three rotations. The authors observed that the decline in SOM occurred despite allocating 1 year in 4 to a plowdown crop, as well as incorporating all crop residue. They concluded that imported OM may be needed just to sustain existing levels of SOM. However, they also noted that initial SOM may have been unusually high, owing to having been in a 5-year grass ley prior to the trial.

Saviozzi et al. (1999) contrasted the utility of imported farmyard manure (FYM) and sewage sludge (SS) as C and nutrient sources in Italy. Both amendments were applied at a rate of 5 t ha^{-1} $year^{-1}$ to land in a long term corn-wheat rotation. The control was undisturbed native grass. Total organic C was more than twice as high in the control as in the FYM and SS treatments (5.13 vs. 2.33 and 2.00 g 100 cm^{-3}, respectively). Biomass C was reduced in both the FYM and SS treatments, relative to the control (2340 and 2282 vs. 3541 mg 100 cm^{-3}, respectively). Similar trends were evident for other chemical and biochemical parameters, suggesting an overall deleterious effect of cultivation which was not compensated for by annual addition of FYM or SS at this rate.

Posner, Casler, and Baldock (1995) used 8 system descriptors to develop an integrative Agroecological Index to compare 6 crop rotations. Descriptors included a) aboveground productivity; b) %DM recycled; c) energy out:in ratio; d) N fixation; e) biodiversity index (# species planted); f) energy subsidy; g) cover crop factor (from USLE); and h) frequency of disturbance. The rotations compared were R1 continuous corn, R2 OM-corn, R3 soybean-wheat/red clover-corn, R4 3 year alfalfa-corn, R5 oat/alfalfa-alfalfa-corn, and R6 grazing. Over these six rotations, the Agroecological Index ranged from 1 to 7.69, with the biggest jump between R3 and R4. The R3 rotation exemplifies continuous arable cropping including a plowdown crop, while R4, 5, and 6 integrated perennial swards into the production system. Thus, forage-based systems and especially the grazed system (R6) were clearly advantageous in most descriptor categories.

In effect, livestock provide the economic justification for inclusion of perennial forages in crop rotations, and perennial forages in turn confer multiple benefits to the system. Thus, in many cases, livestock provide the missing element needed to develop sustainable systems, particularly in terms of soil health.

FORAGES AND LIVESTOCK FOR ENVIRONMENTAL ENHANCEMENT

Apart from food production, forages and/or livestock have the potential to supply a range of additional services, both to farmers and to society at large.

Carbon Sequestration

Withholding land from cultivation under perennial crops, including forages, is the only known way to produce a net increase in SOM, effectively reducing the levels of carbon dioxide, a greenhouse gas, in the atmosphere. Beauchamp and Voroney (1994) developed a simple model to quantify OM addition from crop rotations typical of swine and dairy operations in Ontario. Crop C returned to the soil varied with crop type, depending on the harvest index, the C fraction contained in the roots and exudates, and the C fraction voided by the fed livestock. Estimates of crop C returned to the soil in a corn-soybean-wheat rotation for swine varied from 2.3 to 4.6 t C ha^{-1} for soybean and grain corn, respectively. For a dairy rotation of corn-corn silage-cereal-3 years of alfalfa-grass, the range in crop C returned to the soil was 3.5 to 4.6 t C ha^{-1} for silage and grain corn, respectively, compared with 4.7 to 6.8 (mean of 5.8) t C ha^{-1} $year^{-1}$ among the 3 alfalfa-grass years. Therefore, as a source of SOM, perennial forage swards averaged more than twice as much C per year as soybean, and 25% more than grain corn (Beauchamp and Voroney, 1994).

The proportion of fed C recovered in manure varies among classes of livestock, from 10% in broilers to 40% for non-lactating cattle, and from 20% for grain to 40% for perennial forages (Beauchamp and Voroney, 1994). In addition to contributing more C as roots and stubble, perennial swards also supported classes of livestock that void a larger fraction of fed C, and hence, return a larger fraction of C in the manure. Higher levels of C input, together with simply withholding land from cultivation (Haynes, 1999), are the cause of the net increase in SOM which has been routinely observed under sod in LT research plots.

Soil Erosion

Perennial forages directly advantage sustainability by providing feedstuffs without exposing the soil to erosion. Rayburn (1993) compared pasture vs. recombinant bovine somatotropin (rBST) for increasing milk production in the Northeast. Using New York State as the example, he contrasted the acreage needed for pasture-based and confinement-based feeding systems at two levels of milk production - 16,402 lb milk/cow x 687,000 producing cows - versus 18,370 lb milk/cow x 613,000 producing cows - with each scenario designed to produce 11.3 billion lb of milk projected for 1998. Each ration, whether pasture or confinement-based, was balanced using NRC nutrient requirements.

He concluded that more acreage would be needed to support the pasture option, particularly at the higher level of per-cow output, but that the type of crop grown would also change toward a larger proportion of soil conserving crops. The "C" value - an index of the crop rotation effect on soil erosion from the Universal Soil Loss Equation - for the pasture and confinement options was 0.108 and 0.178, respectively. Thus, while pasture-based systems required more total acreage, total potential soil loss was 33 and 27% less under the moderate and high production scenarios. Grass-based livestock production systems reduce soil erosion, as compared to confinement feeding dependent on annual grains.

Remediation

Contamination of aquifers is an increasingly prominent byproduct of specialized agriculture. Deep-rooting perennials, such as alfalfa, have the potential to intercept and capture labile nutrients which have leached below the rooting depth of annual crops. The perennial growth habit confers an additional advantage, in that it broadens the duration of effective 'sinkness' or nutrient extraction capacity to better correspond to the spring and fall leaching risk intervals which pertain in the humid temperate zone (Dinnes et al., 2002). Russelle et al. (2001) demonstrated the capacity of alfalfa to cleanse groundwater contaminated by a 1989 fertilizer spill in Minnesota. Over a 3 year period, Ineffective (non-N-fixing) Agate alfalfa removed 972 kg N ha^{-1}, compared to 287 kg N ha^{-1} in grain from corn (424 kg N ha^{-1} if all aboveground matter had been harvested from the annuals).

Potential for removal of fecal coliforms from surface applied hog manure was tested on several combinations of grass and forest vegetation (Entry et al., 2000a, b). Depletion of coliforms from the soil was unaffected by vegetation type, and responded primarily to soil moisture and temperature. Persistence of pathogens, including pathogenic *E. coli*, in surface applied manure may be prolonged in cool, humid climates.

Kovacic et al. (2000) tested the effectiveness of constructed wetlands based on native mesic species in removing nutrients from agricultural tile drainage. Subsurface tiles rapidly convey drainage water, including solutes and effluent from agricultural land, into surface water systems. Almost 50% of the arable land in southern Ontario is tile-drained (Barton, 1996), compared to 37% of Cornbelt and Great Lakes cropland (Kovacic et al., 2000). Over a 3-year period, artificial wetlands and adjoining 15 m buffer strips consisting of reed canary grass (*Phalaris arundinacea* L.), hop sedge (*Carex lupulina* Muhl. Ex Willd.), barnyard grass (*Echinochloa crus-galli* L. Beauv.), prairie cordgrass (*Spartina pectinata* Bosc ex Link), lady's thumb (*Polygonum amphibium* L.) and other native mesic species effectively removed 46% of the N and 2% of the P from effluent draining from tiled land growing corn and soybeans. Thus, herbage species were effective in cleansing N but not P from tiled land effluent.

Anthelmintic Properties

Forage species may have medicinal or behavioral effects which can be utilized to reduce dependence on synthetic worming agents. Increasing resistance to anthelmintics has encouraged a global search for alternatives (Niezen et al., 1996). Recent studies in NZ , Sweden and the UK have shown that a range of forage and herb species, including chicory (*Cichorium intybus* L.), birdsfoot trefoil (*Lotus corniculatus* L.), lotus (*L. pedunculatus* Cav.), sulla *(Hedysarum coronarium* L.), meadow brome (*Bromus biebersteinii* Roem. & Schult.), dock (*Rumex obtusifolius* L.), and plantain (*Plantago lanceolata* L.) may act to reduce the degree of parasitic infestation in sheep (Moss and Vlassoff, 1993; Niezen et al., 1996, 1998; Robertson et al. 1995; Scales, Knight, and Saville, 1994;). In a 2-year NZ study, Fraser, Rowarth, and Knight (1997) reported that ram lambs grazing chicory, white clover (*Trifolium repens* L.), or birdsfoot trefoil grew faster and had a significantly lower adult nematode burden than lambs grazing perennial ryegrass or plantain. The anthelmintic properties of these species may involve a) secondary compounds (e.g. condensed tannins); b) improved health of the livestock; or c) a pasture canopy which morphologically limits larval development, survival, and mobility.

Windbreaks

Windbreaks can enhance water use efficiency and reduce physical damage from scouring of eroded soils. Bilbro and Fryrear (1997) compared the performance of rows of annual and perennial plants vs. slatted-fence in controlling wind erosion in Texas. When measured 10 m downwind, a single row of switchgrass (*Panicum virgatum* L.) reduced wind velocity to 39% of that upwind. In contrast, wind velocity downwind was 43% for two rows of slatted-fence, 48% for one row of slatted-fence, and 60% for 3 rows of grain sorghum (*Sorghum bicolor* L.). Thus, switchgrass may be used in place of slatted-fence for some wind abatement applications.

Steppuhn and Waddington (1996) monitored alfalfa yield and water conservation behind windbreaks created by double rows of tall wheatgrass (*Thinopyrum ponticum* L.) at 50 feet (15 m) intervals. Over a 7 year interval, alfalfa yield was 40% greater within the windbreak area than in adjoining open fields, not adjusted for the 8% area occupied by the wheatgrass. Water storage in the upper 1.2 m of soil was 78% greater in the windbreak area than in open fields. Thus, a hardy perennial utility species, tall wheatgrass, sufficiently improved the growing environment to improve yield in a valued hay species, alfalfa.

Biomass Plantations

Switchgrass may also have application as a source of biomass fuel. Vogel (1996) reviewed the historical replacement of pasture/hay land with grain crops in the US, and the associated increase in soil erosion. He presented evidence that 1.5 ac of switchgrass producing 6 to 7 t ac^{-1} could produce as much ethanol as 1.8 ac of 150 bu/ac corn. He estimated that 20 to 40 million ac of land could be sown to switchgrass biofuel plantations, essentially retiring grain crops from marginal land analogous to the Conservation Reserve Program but without large federal subsidies.

Vegetation Management

Grazing livestock can also enhance the environment by displacing herbicides for weed control. Baker and Raun (1989) noted that prior to WW II, sheep were used to graze weeds in corn. Wurtz (1995) reviewed the use of domestic geese as biological control agents in agriculture, including for Christmas tree plantations and tree nurseries. Reid (2002) reported on the use of free-range laying hens to weed commercial-scale raspberry (*Rubus idaeus* L.) and vegetable fields. The chickens rotated among 14 separately fenced paddocks. Raspberry fields were grazed virtually year-around, apart from in spring, to allow development of primal canes, and during the picking season from late June to mid August. Vegetable fields were grazed over the winter months, from November to April. The scratching and pecking action of chickens was particularly effective for both within-row weeding of the raspberries, eliminating a difficult and costly manual operation, and preparing the land for spring vegetables.

Cattle, sheep, and goats can also be used to graze out undesirable species during reforestation and on rangelands. Foster (1998) reviewed practical experience with employing grazing livestock to manage competing vegetation in forests. He referenced research starting in the 1950's, which proved commercially feasible in the western US starting in the early 1960's, and in B.C. since 1984. Experience in Ontario is more limited, starting in 1991.

The preference of most grazing livestock for herbaceous rather than woody vegetation is the key to releasing young trees from herbaceous weed pressure. Foster (1998) compiled a table of sheep grazing preferences in northeastern Ontario, identifying species considered to be high, medium, and low in palatability, as well as those unpalatable or poisonous. Species which are good candidates for removal by sheep include aster (*Aster* spp.), black bindweed (*Polygonum convolvulus* L.), honeysuckle (*Lonicera* spp.), and pin cherry (*Prunus pensylvanica* L.). Species of low palatability include balsam fir (*Abies balsamea* L. Mill.), blueberry (*Vaccinium* spp.), Labrador tea (*Ledum groenlandicum* Oeder), and sweetfern (*Comptonia peregrine* L. Coult.). Foster (1998) thoroughly discussed the managerial factors influencing the utility of grazers for vegetation management, including compliance with regulations, predator risks, and effective grazing management.

In sum, forages and the livestock that consume them have the potential to perform a range of services to society, in addition to food production. Some functions are remedial in nature, to rectify problems created by enterprise specialization and byproducts of modern society, while other applications channel natural processes to the service of humanity.

CONCLUSIONS

William McDonough stated that "regulations are an indication of design failure", and that the more we need to develop regulations, monitor for compliance, and test "to keep from killing each other too quickly," the more we should reconsider the fundamental design itself. By that definition, the design of specialized agriculture is fundamentally flawed and needs reconsideration. Ample evidence has been presented to support the thesis that specialization is ill-designed to meet the multiple needs of society for abundant, healthy foodstuffs, produced in accord with ecologically sound practices, combined in economically remunerative systems.

We are faced with two choices. We could continue to devote scarce scientific resources and government regulatory infrastructure to combat the diminished ecosystem integrity and collateral human losses caused by pursuing ecologically dysfunctional production systems. Alternatively, we could recognize that the root cause of these increasingly widespread problems is a fundamentally flawed system design and embrace a proven solution - the reintegration of crop and livestock agriculture.

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Tables and Figures

FIGURE 1. Net farm income as a function of gross crop income on Middlesex County beef operations in 1918 (adapted from Leitch, 1920)

FIGURE 2. Net farm income as a function of the fraction of tillable land that was under pasture, as affected by farm size (<100, 100-200, and > 200 ac) (adapted from Leitch, 1920).