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AGROECOLOGY: INTEGRATION WITH LIVESTOCK

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Abstract

Livestock systems are a large global asset contributing to food security and poverty alleviation, but livestock supply chains have major environmental impacts at global scale. The scientific literature on agroecology has not yet integrated livestock systems; only 5 percent of the indexed studies concerning agroecology deal with livestock. Following Dumont *et al.* (2013), we review five principles for integrating livestock systems within the agroecology debate: (i) adopting management practices that aim to improve animal health; (ii) decreasing the inputs needed for production; (iii) reducing emissions; (iv) enhancing diversity within animal production systems to strengthen their resilience; and (v) preserving biodiversity by adapting management practices. Through a number of case studies from different world regions, we show that the key features underpinning agroecological livestock systems are an increased use of biodiversity, the integration of crops and livestock within a diversified landscape and a recoupling of the major element cycles. For intensive landless systems, we discuss how recycling principles derived from industrial ecology could complement those from agroecology. We conclude that performance criteria far beyond annual productivity are required when assessing agroecological livestock systems.

INTRODUCTION

Livestock systems occupy approximately 35 percent of the global ice-free land area: 3.4 billion ha of grasslands and rangelands, and 350 million ha of feed crops (Foley *et al.*, 2011). These systems are a significant global asset with a value of at least US$1.4 trillion, and are also important for livelihoods. More than 800 million poor people depend on livestock farming for their survival and the sector contributes to the employment of at least 20 percent of the world's population (Herrero *et al.*, 2013). Ruminants are able to produce food on non-arable lands (because of slope, elevation and climate) and to transform resources not used for human consumption, such as grass and fodder, into edible products. However, using highly productive croplands to produce animal feed, even efficiently, reduces the potential world supply of food calories (Foley *et al.*, 2011). Keeping livestock acts as insurance and is an essential risk reduction strategy for vulnerable communities, while also providing nutrients and traction for growing crops in smallholder systems. Meat, milk and eggs provide 18 percent of calories for human consumption and close to 35 percent of essential proteins and micronutrients (e.g. vitamins, minerals, unsaturated fatty acids) (Herrero *et al.*, 2013). However, there are large differences in meat and milk consumption between rich and poor countries.

Extensive grazing systems occupy the largest fraction of the land used by livestock. Such systems help maintain ecosystem services, biodiversity and carbon stocks, but may also contribute to land degradation, especially in dry areas. The production from grazing systems in the developing world is modest, mostly because of low productivity, low feed availability and poor quality of feed resources in predominantly arid regions (Herrero *et al.*, 2013).

Livestock plays an important role in the smallholder farming systems of sub-Saharan Africa (Vall *et al.*, 2006). Rangeland-based systems cover a large area of the continent, but mixed crop-livestock systems support the majority of rural and urban livelihoods and contribute significantly to food security. Farmers often sell livestock to buy food when crop harvests fail. In many cases livestock are kept primarily to support crop production, with milk and meat considered as useful by-products of livestock keeping. Crop residues constitute an important part of the livestock diet in mixed systems, with the remainder provided by rangelands, which are often communally managed. In industrialized countries and increasingly in developing countries, part of the demand for meat and milk products is now met through industrial systems that rely on feed markets rather than the local land base for feed inputs (Herrero *et al.*, 2013).

Drivers such as population increase, changes in diets, urbanization, changing policy and institutional contexts, and expanding markets exert a strong influence on livestock systems. While meat consumption has started to decline in some western European countries, the demand for animal products is projected to rise further in developing countries. The FAO projects a large increase in demand for both dairy products and meat products (Alexandratos and Bruinsma, 2012). Even though continuing improvements in feeding efficiency within each production system are assumed, the shift in production from developed to developing countries implies that overall animal feeding efficiencies are likely to progress at a slower pace in the future than in the past (Gerber *et al.*, 2013).

Global greenhouse gas (GHG) emissions caused by whole livestock supply chains currently account for nearly 15 percent of the total anthropogenic GHG emissions (Gerber *et al.*, 2013). Livestock production systems emit 37 percent of anthropogenic methane (CH_4), mostly from enteric fermentation by ruminants. Moreover, livestock systems cause 65 percent of anthropogenic nitrous oxide emissions, the great majority from manure, and 9 percent of global anthropogenic carbon dioxide (CO_2) emissions. The largest share (7 percent) of these CO_2 emissions are derived from land-use changes – especially deforestation caused by the expansion of pastures and arable land used for feed crops (Gerber *et al.*, 2013). Nevertheless, the global soil organic carbon sequestration potential is estimated to be 0.01-0.3 Gt C year^{-1} on 3.7 billion ha of permanent pasture (Lal, 2004). Therefore, soil carbon sequestration by the world's permanent pastures could potentially offset up to 4 percent of global GHG emissions. This could be achieved through improved grazing land management and the restoration of degraded lands. Reducing excessive nitrogen fertilization and the substitution of mineral nitrogen fertilizers by biological nitrogen fixation (BNF), as well as avoiding fire in savannahs, improving animal nutrition to reduce CH_4 from enteric fermentation and improved manure management are other factors that could also play a significant role (Lal, 2004; Gerber *et al.*, 2013).

By 2050, the global consumption of animal products could increase by up to 70 percent, leading to a further rise in livestock GHG emissions (Herrero *et al.*, 2013). Livestock-based farming systems are affected by climate change through impacts on feed quantity and quality, and through the direct effects of heat and water availability on animal production, fertility and survival. Whereas animals are generally less vulnerable to drought than crops, extreme droughts can wipe out regional herds (Morton, 2007).

As the negative externalities associated with current animal production systems are increasingly questioned, it is timely to ask what agroecology could suggest for the redesign of livestock production systems. There are an increasing (but still relatively small) number of scientific studies combining “livestock” and “agroecology” as keywords (650 indexed studies since the 1970s across all databases). Most of these studies are indexed in three research areas: agriculture, environment/ecology and veterinary sciences. In comparison, there are five times more indexed studies about livestock and environmental sustainability and this number is further multiplied by nine when counting all studies addressing environmental issues for livestock, with a substantial subset (ca. 10 000) of these studies addressing ecology and biodiversity. Therefore, despite a wealth of studies in ecology and environmental disciplines dealing with livestock, few have adopted the agroecology perspective. Likewise, only 5 percent of the indexed studies concerning agroecology include the keyword “livestock”. Hence, integration with livestock has not been achieved by the scientific literature on agroecology, nor has agroecology been a mainstream paradigm in environmental studies concerning livestock.

Other approaches in the literature deemed that the optimization of livestock systems could be based on eco-efficiency (e.g. Wilkins, 2008); that is the maximization of animal products per unit of inputs or natural resources. This approach emerged through studies that aimed to reduce the consumption of energy and raw materials in the industry. However, animal production is nested into ecological and social processes, with ecosystem goods and services supporting the technological activities of husbandry. Moreover, because of their organic nature, animal products and their associated by-products are ultimately recycled in multiple loops within biogeochemical cycles such as the carbon and nitrogen cycles. Therefore, the simple paradigm of eco-efficiency (i.e. ‘producing more with less’) may be too linear as a concept and not sufficient to optimize ecologically grounded livestock production systems.

In his influential book on agroecology and food systems, Gliessman (2007) stated that:

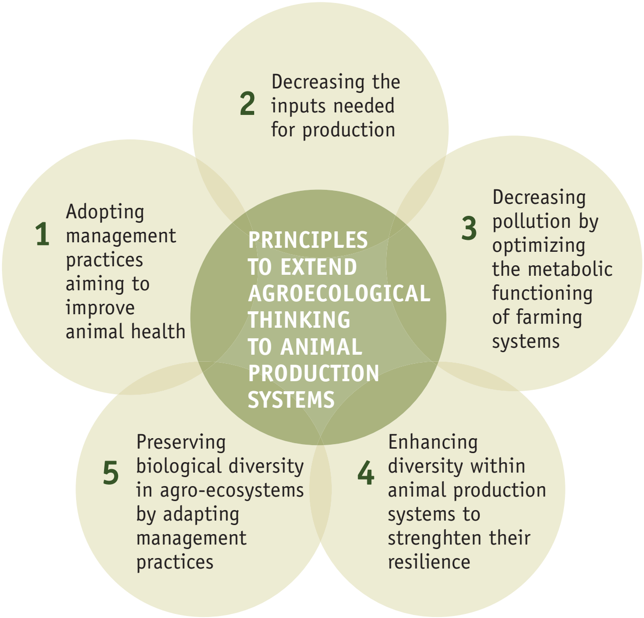
> *“the problems lie not so much with the animals themselves or their use as food as they do with the ways the animals are incorporated into today’s agroecosystems and food systems. Animals can play many beneficial roles in agroecosystems, and therefore make strong contributions to sustainability.”*

Numerous studies in grazing ecology, animal behaviour and farming systems have addressed the integration of farm animals in agriculturally managed ecosystems, but not through the lens of agroecology.

It is only recently that a review has addressed for the first time the prospects for agroecology in the animal production sector (Dumont *et al.*, 2013). This review covers a large diversity of livestock systems (i.e. grazing, mixed and industrial systems) and shows how agroecological principles can be applied to most, but possibly not all, systems. For intensive systems where animals are kept in farm buildings, recycling principles derived from industrial ecology could complement those from agroecology.

Dumont *et al*. (2013) have proposed five principles to be optimized in animal production systems: (i) adopting management practices that aim to improve animal health; (ii) decreasing the inputs needed for production; (iii) decreasing pollution by optimizing the biogeochemical functioning of farming systems; (iv) enhancing diversity within animal production systems to strengthen their resilience; and (v) preserving biodiversity in agro-ecosystems by adapting management practices (Figure 1). Each of these principles (or objectives) is based on ecological processes. Therefore, animal husbandry is viewed through a paradigm which is derived from ecology. In the following sections we review each of these five principles and discuss how they can be applied to animal production systems along a large intensification gradient.

Figure 1. **Five ecological principles for the redesign of animal production systems**



Source: Dumont *et al.*, 2013

INTEGRATED ANIMAL HEALTH MANAGEMENT

Applying agroecology to the question of animal health implies focusing on the causes of animal diseases in order to reduce their occurrence. Major attention will therefore be given to choosing animals adapted to their environment and using a set of management practices that favour animal adaptations and strengthen their immune systems. Animals express morphological (small body size, little hair or feathers, etc.), physiological (urea recycling, compensatory growth, etc.) or behavioural (night feeding, selection for less fibrous diets, etc.) adaptations to hot or other types of harsh environments. Local species or breeds that have been selected in tropical environments are more resistant to trypanosomes, gastrointestinal parasites and ticks.

Adapting management practices can also strengthen animal immune systems and reduce sensitivity to pathogens. This is crucial for pigs, poultry and rabbits. For instance, mixing animals has been shown to suppress, as a result of increased stress, the immune response to a viral vaccine in pigs (de Groot *et al.*, 2001), and should thus be avoided as much as possible. In poultry, susceptibility to dietary stress is genetic strain dependent, which further emphasizes the importance of choosing genotypes adapted to particular environments and production objectives. In pigs, stringent hygienic conditions altered the development of digestive microflora and stimulated inflammatory response genes (Mulder *et al.*, 2009). Removing newly borne animals from their mothers very early can weaken the development of immunity. Conversely, experiments have shown that adoption of rabbits at one-day of age by reproductive females permits the early implantation of a functional and diverse microbiota, which increases their resistance to pathogens (Gidenne *et al.*, 2010). For all these species, managing the size and genetic structure of animal groups, and the way they are housed (e.g. systems allowing sick animals to be isolated from their group), coupled with tools for the early detection of diseases will limit the need to use chemical drugs (Dumont *et al.*, 2014).

In grassland-based systems with rotational grazing, mixed farming of several species on the same farm limits the contact that each species has with its specific pathogens by clearing pastures of parasites using a non-susceptible species. An integrated health management practice in organic sheep farming systems uses a preventive anthelminthic treatment with tannin-rich plants before ewes are turned out to pasture. This system benefits from rotational grazing, as nematode larvae numbers decline in temporarily ungrazed plots. Lambs are grazed on newly-sown pastures or on highly nutritive areas of regrowth in cut meadows in order reduce the risk of nematode infestation. When no other measures are available, the targeted treatment of highly infected sheep using chemical drugs is used, based on individual indicators such as anaemia and diarrhoea (Cabaret, 2007).

Some legume species offer opportunities for improving animal health using less medication through the presence of bioactive secondary metabolites (Lüscher *et al.*, 2014). In addition to a direct antiparasitic effect, tannin-rich plants might also have some indirect effects by increasing host resistance. The observation that sick ruminants are able to consume substances that are not part of their normal diet, containing active ingredients capable of improving their health, supports the hypothesis that animals can self-medicate. Lambs infected with parasites also slightly increased their intake of a food containing tannins while experiencing a parasite burden (Villalba *et al.*, 2010). Therefore, the self-selection of plant secondary metabolites provides a potential source of alternatives to chemical drugs in pastoral systems.

In Kenya, the additional forage resources of the push-pull system, using native grasses and legumes, have been shown to contribute to the sustainability of livestock systems by improving animal health (Hassanali *et al.*, 2008). In Madagascar, essential oils are used as alternatives to antibiotics and may also repel biting insects attacking livestock (e.g. geranium oil against *Stomoxys calcitrans* and *Jatropha* spp. extracts as anthelmintic). This may help prevent the harmful effects on soil macrofauna from the use of veterinary products (Ratnadass *et al.*, 2013).

Aquaculture is quickly growing as an animal production sector. While the sector is still dominated by shellfish and herbivorous/omnivorous pond fish, either entirely or partly utilizing natural productivity, rapid growth in the production of carnivorous species such as salmon, shrimp and catfish has been driven by globalizing trade and favourable economic incentives for large-scale intensive farming. Most aquaculture systems rely on environmental goods and services that are provided freely or at a low cost (Bostock *et al.*, 2010). In aquaculture, controlling water quality is pivotal for health management. In intensive systems, an alternative to antibiotics is the use of probiotics and prebiotics for modulating gut microflora, delivered through the feed or directly into the water (Balcázar *et al.*, 2006). Probiotics and prebiotics can improve fish health, resistance to diseases, growth performance and body composition. For instance, feeding turbot larvae (*Scophthalmus maximus*) with rotifers enriched in lactic acid bacteria provided protection against a pathogenic *Vibrio* sp., and increased mean weight and survival rate compared with control turbot larvae (Gatesoupe, 1994).

REDUCED USE OF EXTERNAL INPUTS FOR FEED PRODUCTION

A high proportion of global arable land is devoted to animal feed production (including grains, oilseeds, pulses and fodder), which reached 208 million tonnes of proteins per year in 2005, that is 38 percent of global arable protein production[1]. As a comparison, grasslands contributed an estimated 300 million tonnes of proteins per year towards the nutrition of ruminants in 2005 (Soussana *et al.*, 2013). Crop feed production requires a variety of inputs including chemical fertilizers, pesticides and, in some regions, large quantities of water for irrigation. Additionally, livestock has large direct and indirect impacts on land use, primarily through the expansion of pastures and arable crops into tropical forested areas.

Thus, a major challenge is to reduce the inputs required for production and increase the efficiency of animal production systems to minimize direct and indirect environmental impacts. This can be done by increasing the feed conversion efficiency of livestock and by using feed sources (e.g. crop residues, agricultural by-products, backyard wastes, grasslands, rangelands, browsing) that do not compete with the human food supply, thereby increasing food security and reducing environmental damages.

Improving the efficiency of nutrient utilization by animals can help reduce the import of nutrients from outside the farm and decrease emissions. Research has initially focused on pigs and poultry, as these species compete directly with human food supply. The low digestibility of phosphorus in pig feeds was partly alleviated by a diet supplementation with natural microbial phytase, an enzyme solubilizing immobilized form of phosphorus (Dourmad *et al.*, 2009). Nitrogen and phosphorus excretion and GHG emissions per animal can be manipulated through diets (e.g. for mitigating CH_4 emission in ruminants) or through appropriate feeding practices

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[1] Calculated from FAOSTAT in 2012 (see: http://faostat3.fao.org/home/E).

(e.g. phase feeding for reducing nitrogen and phosphorus excretion in pigs) (Dourmad *et al.*, 2009; Martin *et al.*, 2010).

The benefits of improving the efficiency of feed utilization can be extended by applying appropriate feeding practices. For example, in laying hens, sequential feeding of wheat grain and protein–mineral concentrate can improve feed conversion, and facilitate the use of local feedstuffs introduced as whole grains, thus reducing feeding costs (Faruk *et al.*, 2010). In organic egg production systems, stimulating the hens to exercise natural foraging behaviour reduced the import of nutrients into the system. High-producing layers were able to forage on crops consisting of grass/clover, pea/vetch/oats, lupine and quinoa without negative effects on health or performance (egg weight and body weight) (Horsted and Hermansen, 2007). In another example, geese that grazed on unfertilized grass growing between tree rows in a walnut plantation increased walnut production by 26 percent and tree growth by 6 percent (Dubois *et al.*, 2008). There was no microbial contamination (e.g. *Escherichia coli*) of the fruits if geese were removed at least two months before harvesting.

Feeding systems based on natural resources and agricultural by-products enable resources to be spared for human food supply. Permanent pastures and rangelands are cheap natural resources. On the other hand, the major limitations of rangeland-based feeding systems are the large areas required to compensate for low forage productivity and quality, which increases farm work (e.g. construction of fences, shepherding), and the seasonal and year-to-year variability in the amount and quality of forage resources (Jouven *et al.*, 2010). This reduces the feeding efficiency within grazed systems, leading to high enteric CH_4 emissions per unit of meat or milk produced (Gerber *et al.*, 2013). Nevertheless, extensive grazing systems have low GHG emissions per unit of area, and emissions from livestock are partly compensated in such systems by soil carbon sequestration (Lal, 2004).

There are many examples of cheap, alternative feed resources (e.g. millet, wheat, oats, barley straws) that are used as supplemental feed for ruminants, horses and donkeys in many agro-ecosystems around the world. Food crop by-products, such as waste vegetables and fruit residues after juice extraction, can be used to supplement grazing animals or forages (Gliessman, 2007). Various tropical forages make a viable alternative to soybean meal in the diets of lambs (Archimède *et al.*, 2010) or growing pigs (Kambashi *et al.*, 2014). Close to 1 400 worldwide livestock feed sources are indexed in the open access information system *Feedipedia* jointly developed by INRA, CIRAD, AFZ (Association Française de Zootechnie[2]) and FAO.[3] This information system shows that many unconventional sources can be integrated into feeding systems, including multiple by-products from plant production and plant food processing. Because agroecology usually enhances the diversity of crop species produced and processed within the farm, it opens many options for the design of livestock feeding systems using less energy, fertilizer and irrigation water inputs. Draft animal power for land preparation and transport further reduces energy use in extensive tropical farming systems.

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[2] French Association for Animal Production

[3] Available at: www.feedipedia.org

Because of competing demands for water for drinking, hygiene and energy, it is urgent to improve water management in aquaculture. A variety of technologies have been developed to offer solutions to limited water resources and degradation of water quality. These include recirculating aquaculture systems (RAS) (Martins *et al.*, 2010), and integrated intensive aquaculture installations that can take place in coastal waters, offshore environments or in ponds, and are adaptable for various combinations of fish, shrimps, shellfish, sea urchins, plankton and seaweeds (Neori *et al.*, 2004; Gilles *et al.*, 2014). These systems serve to decrease some of the inputs needed for production (e.g. water, nutrients, land) but they are energy demanding. As pointed out by Martins *et al.* (2010), a small water exchange rate in RAS can also create problems resulting from the accumulation of growth-inhibiting factors coming from fish (e.g. cortisol), bacteria (metabolites) and feed (metals).

OPTIMIZING THE BIOGEOCHEMICAL FUNCTIONING OF FARMING SYSTEMS

Recoupling C-N-P cycles in grasslands

Within extensive grasslands, the carbon, nitrogen and phosphorus cycles are naturally coupled by plant autotrophy and by soil organic matter (SOM) stabilization. This coupling is tightly regulated through a host of biological and ecological processes including plant plasticity, plant and soil community functional diversity and root symbioses driving BNF and phosphorus mobilization. Therefore, the stoichiometry[4] of these major cycles is controlled, resulting in converging element ratios in SOM. However, ruminants tend to uncouple the carbon and nitrogen cycles by releasing digestible carbon as CO_2 and CH_4, and by returning digestible nitrogen in high concentrations as reactive nitrogen in urine patches. Phosphorus from animal excreta becomes bound to soil particles, which reduces its mobility provided that soil erosion is low. Since the 1950s, grassland intensification has mostly been based on mineral and organic nitrogen and phosphorus fertilization, controlled grazing (and mowing), and vegetation improvement through the introduction of productive and high quality grasses. Grassland intensification has led to increased pasture productivity and to an increased animal stocking density. While this may have been initially beneficial for soil carbon sequestration, it has also favoured increased enteric CH_4 and reactive nitrogen emissions.

The environmental impacts of grassland intensification are controlled by a trade-off between increased C–N coupling by vegetation and increased C–N decoupling by animals. Stimulation of vegetation productivity by the adequate application of nitrogen and phosphorus fertilizer raises carbon uptake and storage, while increasing stocking density reduces mean carbon residence time within the ecosystem (Soussana and Lemaire, 2014). Hence, a threshold level of grassland

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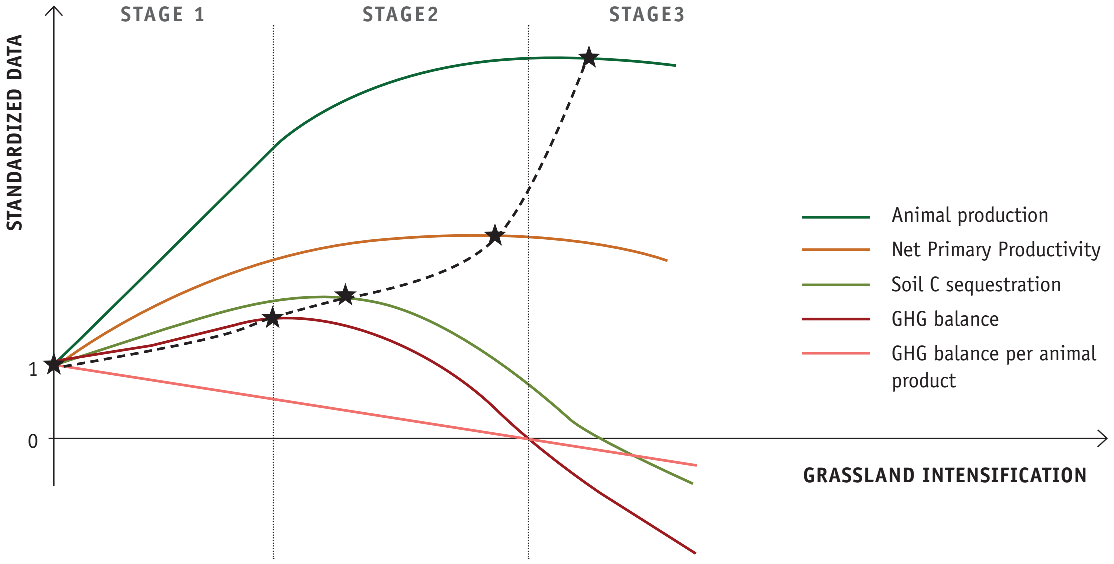
[4] Stoichiometry indicates the mass ratio in which elements involved in chemical reactions stand. This mass ratio analysis can also be used for biogeochemical cycles.

Figure 2. **Effects of grassland intensification by grazing and cutting, and N fertilizer application on animal production, net primary productivity, soil C sequestration and GHG balance per unit of land and per unit animal production**



Responses are standardized to one for an un-intensified control pastoral system prior to modernization of animal agriculture. Star symbols connected by a dashed line show the maximum value for each variable. Grassland intensification combines inorganic N fertilization and an increase in animal stocking density following a step change in management.

Source: Soussana and Lemaire, 2014

intensification can be determined above which any additional animal production would be associated with large environmental risks (Figure 2).

Agroecology provides a number of specific pathways to ensure greater environmental sustainability for pasture intensification. Agroecologically focused breeding programmes, animal nutrition initiatives and improved animal health by the means mentioned above can increase pasture productivity and herbage quality, thus raising animal protein conversion efficiencies. Replacing inorganic nitrogen fertilizer inputs by BNF and recycling efficiently the organic nitrogen from animal excreta within integrated arable-livestock systems can increase the carbon flows in animal products and soils, while recoupling the C-N-P cycles and reducing losses to the environment.

Managing grasslands with less mineral nitrogen fertilizers and with an increased reliance on BNF is a desirable objective in order to reduce the costs of inputs, avoid GHG emissions caused by the process of industrial synthesis and by the transport of mineral nitrogen fertilizers, and to increase the digestibility and protein content of the herbage (Frame, 1986). In contrast with inorganic fertilizers, BNF allows the introduction to the ecosystem of quantities of nitrogen already coupled with corresponding carbon, which reduces overall N_2O emissions (IPCC, 2006). The symbiotic interaction between legume plants and *Rhizobium* bacteria offers the unique possibility to allow the host plant access to the unlimited source of atmospheric nitrogen. Legumes have a distinct competitive advantage in nitrogen-limited systems. However, where

nitrogen is abundant, N_2 fixation is energetically costly and N_2-fixers tend to be competitively excluded by non-fixing species (Soussana and Tallec, 2010).

Legume-based grassland systems have often been shown to be difficult to manage, as the proportion of pasture legumes in sown mixtures and in permanent grasslands fluctuates both from year-to-year and within single growth periods. The benefits of legumes for ruminant systems are most effective in species-diverse mixed swards with a legume proportion of 30-50 percent, resulting in lower production costs, higher productivity and increased protein self-sufficiency (Lüscher *et al.*, 2014). Sown legumes may also contribute to the restoration of degraded pastures, providing a win-win solution combining increases in plant productivity, soil carbon stocks and animal production. Such a scheme has been successfully applied in Portugal through the use of phosphorus fertilization and species rich grass–legume mixtures.[5] Forage nitrogen-fixing trees also offer an interesting alternative (e.g. *Acacia* spp., *Faidherbia* spp., *Gliricidia* spp.) as they can be used to restore degraded pastures and to provide forage during seasonal droughts, while offering shade to herds.

The maintenance of a wide range of grazing intensities at the landscape level can be used for conserving a diversity of pasture species at this scale (McIntyre *et al.*, 2003). Managing grassland communities to obtain a desirable mix of plant traits and plant functional types helps to recouple the carbon and nitrogen cycles and to match seasonal fluctuations in feeding demands by domestic herbivores (Pontes *et al.*, 2007). Moreover, functional diversity enhances the resistance of temperate grasslands to weed invasion in both extensively and intensively managed swards (Frankow-Lindberg *et al.*, 2009). In permanent pastures, grassland diversity may reduce risks of nitrate leaching through an increased complementarity between species in nitrogen uptake and water uptake (De Deyn *et al.*, 2009).

Integrated livestock systems

An integrated farm is one in which livestock is incorporated into farm operations to achieve synergies among farm units and not just as a marketable commodity (Gliessman, 2007). These systems demonstrate complementarity in resource use when livestock are fed with crops or forages (including trees) that are being produced on-farm, while farm manures improve crop production and income from the cropping system. Through spatial and temporal interactions among farm units, livestock integration contributes to the regulation of biogeochemical cycles and environmental fluxes to the atmosphere and hydrosphere. Adding herbivores mimics further ecosystem functions, which can help increase the stability of the agro-ecosystem. Excreta from one species can even be directly used as components of formulated diets for another species. For example, West African dwarf goats can be sustained on diets including poultry excreta, resulting in improved liveweight gains, feed conversion ratios, carcass yields and ultimately better economic returns to farmers (Alikwe *et al.*, 2011). The main synergy from mixing crops and animals is derived from animal manure becoming a resource that is rich in nutrients and provides soil micro-organisms with a key source of energy. Self-sufficient, low-input dairy

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[5] For more information see: www.terraprima.pt

farms in Brittany illustrate how cost-cutting management practices (part of the arable crops are used as home-grown feeds and grass–legume mixtures are integrated in crop rotations) can lead to a win-win strategy combining good economic and environmental performances (Bonaudo *et al.*, 2014).

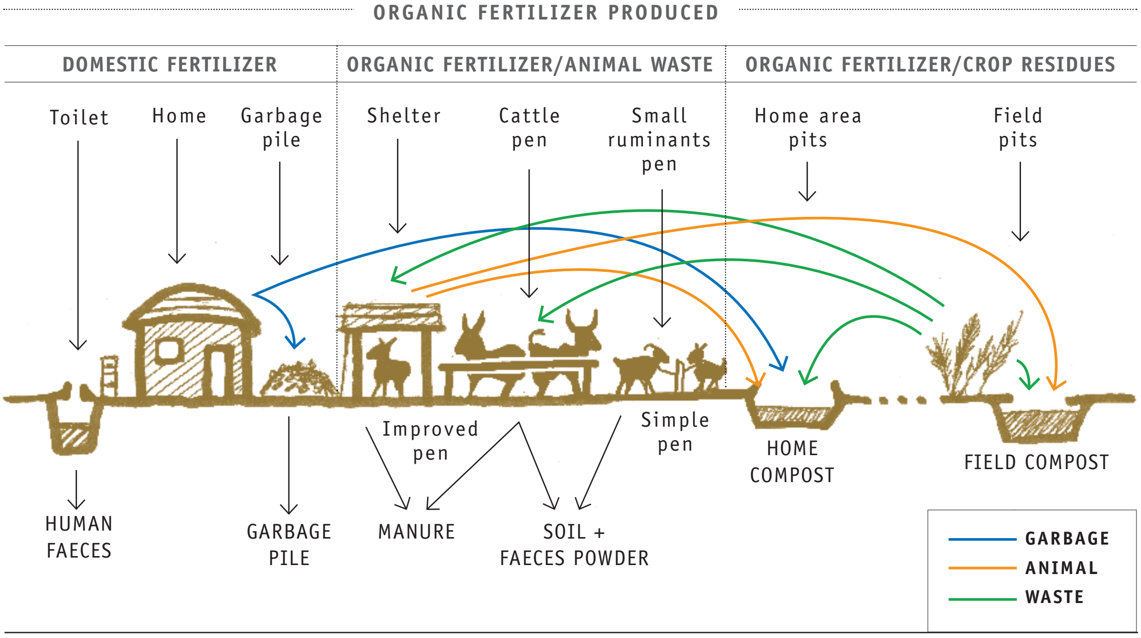
In sub-Saharan Africa, garbage piles containing domestic waste, daily sweepings and faeces from small ruminants, along with some soil, can be produced in the homestead area. Confining animals to facilitate manure collection helps produce organic fertilizer in significant amounts. Some farmers add bedding material and feed leftovers to the pen or animal shed, which further increases the quantity and nutrient content of manure, as the nutrients in urine are trapped by the litter. Household compost can be produced in pits near the homestead area combining the animal faeces, feed and crop residues, and domestic waste. Farmers may choose to irrigate the pit, turn the compost and use a cover to limit nitrogen losses and promote decomposition.

Nutrient cycling and losses associated with the management of manure have been estimated for farms with 10-75 tropical livestock units (TLU) in southern Mali (Blanchard *et al.*, 2013). Between 38 and 50 percent of animal faeces (6-40 tonnes farm^{-1} year^{-1}) are deposited during grazing on common pastures. Deposition of faeces during transhumance represents up to 25 tonnes farm^{-1} year^{-1}. This indicates that in West Africa, 46 percent of the nitrogen in crop residues and manure is returned to the soil of common pastures or areas of transhumance, whereas 13 percent is lost in gaseous form at the time of excretion (Figure 3). Organic manure produced on the farm represents 24 percent of the nitrogen in animal waste, while 17 percent is lost through leaching or in gaseous form during handling and storage of manure and compost. In this study the nitrogen-cycling efficiencies of animal waste varied between 13 and 28 percent, indicating large margins for progress in the complex agroecological management of such systems (Blanchard *et al.*, 2013).

With the rising price of mineral fertilizers and reduction in fertilizer subsidies and programmes promoting organic manure quality, there is an increasing focus on the efficient use of nutrients in livestock manure. To increase nutrient conservation, it is recommended to compost under roofs and on floors, and to limit storage time. Where improved forage is available, farmers often tend to keep animals longer in confinement. On-farm biodigesters providing energy for light and cooking are another innovation in Mali that have been used to deliver a new type of manure. In African conservation agriculture, the use of plant cover through the early mowing of *Brachiaria* spp., *Stylosanthes* spp. and *Vicia* spp. produces fodder with very high protein contents. In Burkina Faso and Madagascar, the managed grazing of crop cover and/or the making of silage or hay from part of the biomass cover adds further value to the ‘no-till cover crop’ innovation (Naudin *et al.*, 2012).

Agroforestry arrangements that combine fodder plants, such as grasses and legumes, with shrubs and trees are often used for animal nutrition. They include scattered trees in pastureland, live fences, tree-based fodder banks and cut-and-carry systems. The restoration of extensive silvopastoral systems in arid and semi-arid areas of Africa is an option that can be used to regenerate rangeland productivity once stocking density rates are well managed. In these systems, trees and shrubs have been observed to enhance carbon sequestration in soils through their root systems while also providing the benefits of bird habitat and shade (Akpo *et al.*, 1995). Moreover, in the dry season trees and shrubs increase the quality of diets for ruminants,

Figure 3. **Crop-livestock integration and diversity of organic fertilizer management in Mali**



Source: adapted from Blanchard *et al.*, 2013

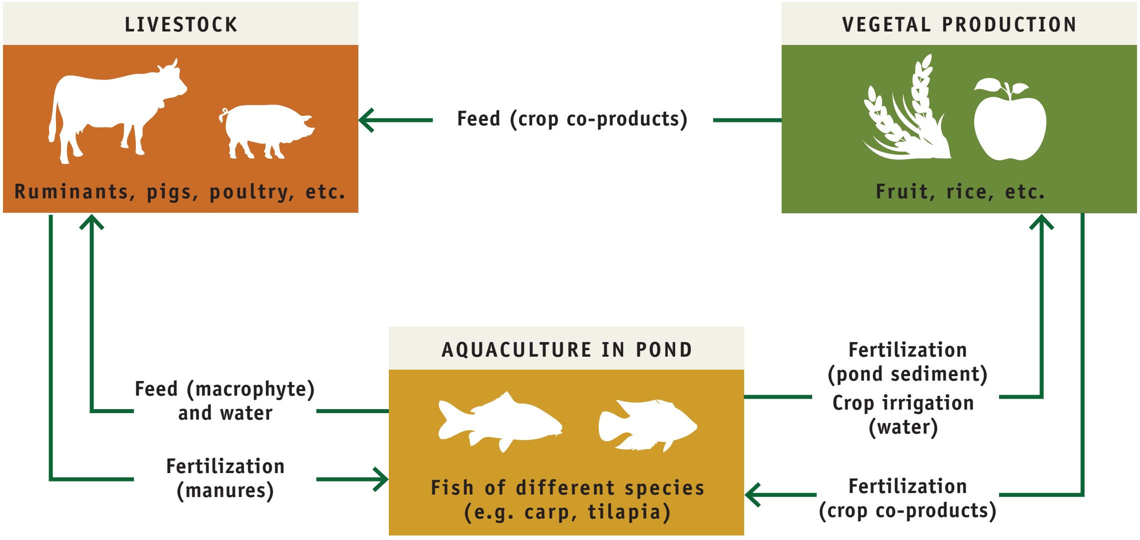
contributing up to 50 percent of dry matter intake for cattle and 80 percent for small ruminants, with protein contents at least four times that of grasses.

Intensive silvopastoral systems in Latin America can be directly grazed by livestock and also include fodder shrubs (e.g. *Leucaena* spp.) and productive pasture species. These systems produce high milk yields and can be combined at the landscape scale with connectivity corridors and protected areas (Murgueitio *et al.*, 2011). Silvopastoral systems that integrate trees, crops and pastures are becoming more common in the Brazilian savannah and have also been associated with increased soil fertility through the continuous supply of organic matter and better land management practices (e.g. avoiding erosion) (Tonucci *et al.* 2011). They also provide a large carbon sequestration potential and shading to livestock, and are likely to be more resilient to heat waves and to droughts. However, many barriers to the adoption of silvopastoral practices still exist. High initial costs, slow returns on investment, and an overall unawareness of the benefits suggest that efforts are needed on behalf of the scientific community and stakeholders towards building capacity and financing.

Integrated aquaculture

In intensively managed wetlands in Southeast Asia, farmers are adding an aquaculture component to already integrated crop-livestock systems. These integrated agriculture-aquaculture systems are based on the recycling of nutrients between farm components: livestock manure and other farm wastes fertilize fish ponds, pond sediments fertilize crops and crop co-products feed livestock (Figure 4). Different fish species and combinations of species are commonly reared in ponds (Rahman *et al.*, 2006). Not only fish yields, but also livestock growth performance, biomass production relative to inputs and economic benefits can all be substantially increased in these systems. For instance, introducing tilapia (*Oreochromis niloticus*) into existing integrated farming systems increased gross margins from US$50-150 to US$300 per household in peri-urban areas of Bangladesh (Karim *et al.*, 2011). However, fish grown under waste-fed conditions can become contaminated with pathogens from human or animal excreta, antibiotics or antibiotic-resistant bacteria. Therefore, reducing sanitary risks is a priority, as outlined in the WHO (2006) guidelines for fish farming.

Figure 4. **Simplified diagram of the interactions within integrated agriculture-aquaculture systems in Southeast Asia**



Source: Dumont *et al.*, 2013

In such aquaculture systems, pond productivity can also be increased by introducing submerged substrates in water to naturally stimulate fish productivity. This principle is based on traditional fishing methods known as *acadjas* in Africa (Bene and Obirih-Opareh, 2009), and *Samarahs* and *Katha* fisheries in Asia (Shankar *et al.*, 1998), where the periphyton – a complex assemblage of all sessile biota attached to the substratum, including associated detritus and micro-organisms – grows and can constitute a natural food for fish. Submerged substrates also offer shelter, while their associated microfauna helps to improve water quality through the trapping of suspended solids, organic matter breakdown and enhanced nitrification. The control of the C:N ratio in pond water through the addition of carbohydrates offers another alternative to enhance microbial development, protein recycling and biomass production. According to Bosma and Verdegem (2011), manipulating the C:N ratio (e.g. by adding tapioca starch) doubled protein input efficiency in ponds, while substrate addition (e.g. bagasse, molasses) increased production by two to three times.

Industrial ecology for intensive livestock systems

Compared with agroecological systems *sensu stricto*, systems based on industrial ecology have a highly controlled composition and a much looser link to the land. These systems make it possible to treat and make productive use of waste from other agricultural or non-agricultural systems (Takata *et al.*, 2012), and will add quantitatively to production, while reducing pollution and competition for land, energy and water. It is noteworthy that the first three principles that have already been discussed can also be applied to these systems. Pig farming systems provide a classic example in which most of the environmental impact is associated with the production of feed ingredients, animal housing and manure storage. An ecologically sound pig farming system optimizes metabolic functioning by using manure from sows to produce biogas for heating and, after treatment, to fertilize cereals, oilseeds and peas grown on the farm to feed the pigs. Biodigesters produce biogas from liquid and solid pig manure (and silage of intercrops), which is the most effective way to avoid environmental losses of CH_4 from liquid manure while also reducing the biological activity of drug residues (Petersen *et al.*, 2007). Biogas can be used for electricity production and heat for pig housing, thus reducing farm energy costs and decreasing piglet mortality. Marked annual variations in the price of pig meat can be strongly buffered by sales of crops produced on the farm. The system is efficient both economically and for the management of manure collection, treatment and use to increase nutrient cycling while reducing pollution. However, it requires a major initial investment for biodigester installation. This example shows that industrial systems can readily be reconnected to a land base by applying industrial ecology principles which form a subset of the broader concepts used in agroecology.

SYSTEMS DIVERSITY AND RESILIENCE

Agricultural intensification has drastically reduced diversity – that is the variety of both plant and animal species and the variety of management practices and production factors. Recent empirical evidence has underlined the potential of diversity in animal production systems for increasing resilience through mechanisms that operate at different levels (Tichit *et al.*, 2011).

At the herd level, diversity in both animal species and management practices secures pastoral systems. Rearing different animal species provides a risk-spreading strategy against drought, disease outbreaks and market price fluctuations (Tichit *et al.*, 2004). Adapting management practices to the biological characteristics of each species is also a key lever to ensure resilience (e.g. by modulating breeding practices according to female longevity and climate sensitivity). Combining several herbivore species in free-grazing systems enables higher overall vegetation use and liveweight gains (D'Alexis *et al.*, 2014). The guiding principle of these systems is the use of multiple spatial niches and feed resources that is also applied in aquaculture. For example, in the popular rohu (*Labeo rohita*) and carp (*Cyprinus carpio*) combination found in Southern Asia, while browsing the sediment for food, carp oxidize the pond bottom and suspend nutrients accumulated in sediments, leading to up to 40 percent higher rohu production and almost doubling total pond production (Rahman *et al.*, 2006).

Within a monospecific ruminant herd, there is some variability in animal traits and the diversity of lifetime performance, which is suggested to act as a buffer by stabilizing overall herd production. Managing diversity over time becomes a central issue in large herds where management strategies targeted at different herd segments are expected to increase overall performance (Lee *et al.*, 2009). Diversity in lifetime performance emerges from complex interactions between herd management practices and individual biological responses (Puillet *et al.*, 2010). These interactions generate contrasting groups of females with different production levels and feed efficiencies. The relative size of these groups in the herd is thus a key determinant of overall performance.

A diversity of forage resources also helps to secure the feeding system against seasonal and long-term climatic variability. Grazing animals take advantage of resource diversity to maintain their daily intake and performance, with contrasting effects of selective grazing occurring according to breed morphological and physiological traits. For instance, Salers beef cows with a relatively high milk yield potential maintained daily milk yield at the expense of body condition in the late season, whereas Charolais cows, which have less milk potential reduced milk yield but lost less liveweight (Farruggia *et al.*, 2008).

In agro-pastoral systems, the feeding system is based on complementarities between cultivated grasslands, which are used to secure animal performance in crucial periods such as mating or lactation, and rangelands, which are mostly grazed at times when the animals have low nutrient requirements (Jouven *et al.*, 2010). When the availability of feed resources is low or unpredictable, defining seasonal priorities between animals with high requirements or key production objectives (e.g. improving body condition), which will need to be given priority access to the best resources, and animals with low requirements or secondary production objectives, helps in the design of efficient feeding systems. The diversity of grassland types within a farm has been shown to improve farm self-sufficiency for forage in both dairy (Andrieu *et al.*, 2007) and suckler farms (Martin, 2009). Recent research has also emphasized that a diversity of grazing management practices, in terms of stocking rate and periods, can enhance production stability despite drought events (Sabatier *et al.*, 2012).

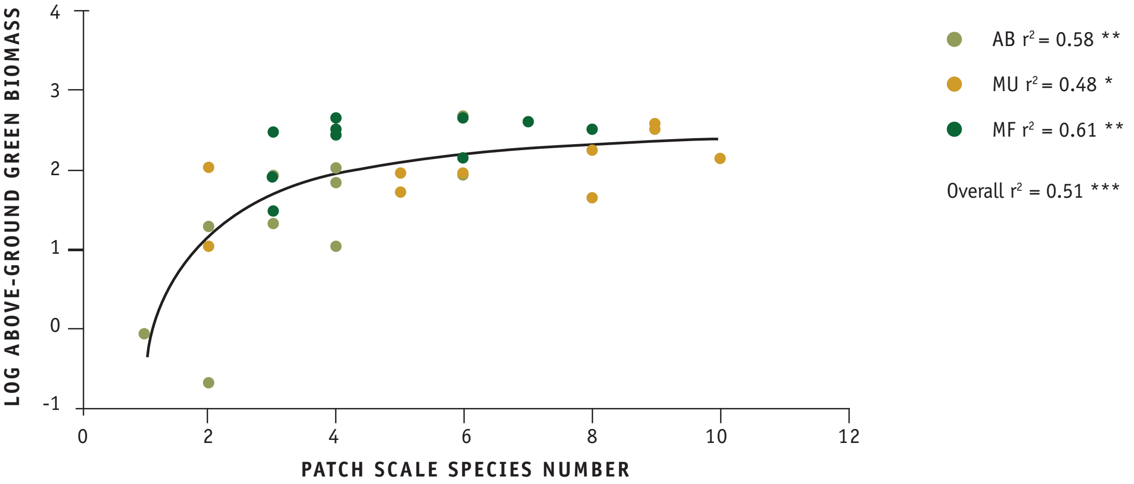
Dumont *et al.* (2014) have pointed out several unresolved challenges involved in understanding whether resilience is a manageable property of animal production systems: (i) to assess the relative weights of biological and decisional processes involved in resilience; (ii) to identify diagnosis and adaptive management indicators, and explore the operational character of early-warning indicators for the anticipation of critical thresholds or "tipping points" (Veraart *et al.*, 2012); and (iii) to understand which management strategies are used by farmers to overcome climatic events and biotic or abiotic stresses. Managing several species or breeds with contrasting adaptive capacities within the same system offers an efficient mechanism to buffer the effects of extreme climate events on herd productivity and farm income (Tichit *et al.*, 2004). The benefits of diversity have also been reported in plant assemblages and at forage system level; the next step is to combine the herd and resource components to identify which level of within-farm diversity could be deployed to benefit several farm performance criteria.

BIODIVERSITY PRESERVATION

In the past decade, concerns over biodiversity loss have spread to domestic biodiversity (i.e. animal genetic resources and local breeds) (Taberlet *et al.*, 2011). Higher performance of commercial breeds means that local breeds tend to be replaced by more productive ones, or at least outcrossed. A loss of genetic diversity has also occurred in commercial breeds via the development of artificial insemination, with only a few males being involved in reproduction schemes. Local breeds have greater abilities to survive, produce and maintain reproduction levels in harsh environments. Therefore, using local breeds is well suited to economically marginal conditions, because of reduced veterinary intervention, ease of breeding and lower feedstuff costs. Animal products from traditional breeds with a strong local identity can fetch premium prices, as consumers identify them as having superior sensory properties (e.g. taste) or nutritional quality, or are attracted by the image of a particular region or tradition. Developing niche markets could help preserve resistance or adaptation traits that would otherwise be rapidly lost and difficult to rescue.

Agricultural intensification and homogenization have been important drivers of losses in the diversity of flora and fauna in grazing lands. In temperate grasslands, plant species diversity tends to reach a maximum at intermediate disturbance and stress levels – which implies that intensively managed grasslands have reduced plant diversity. Maintaining a diversity of local plant species has been shown to increase grassland productivity (Gross *et al.*, 2009) (Figure 5). Therefore, the management of plant functional diversity is a key agroecological strategy that can be applied to grazing systems.

Figure 5. **Above-ground biomass at the patch scale as a function of the number of plant species in a grassland patch (14 x 14 cm)**



Treatment codes are as follows: AB (green circles) = ‘abandonment’ (no mowing or fertilization); MU (orange circles) = mown and unfertilized; and MF (dark green circles) = mown and fertilized. Regressions are linear within each land-use treatment and non-linear for the pooled data set. Levels of significance for regressions are: *$p<0.05$; **$p<0.01$; ***$p< 0.0001$

Source: Gross *et al.*, 2009

Pasture management strategies that preserve biodiversity while ensuring good economic returns to farmers can create win-win outcomes. For example, preserving legume-rich grasslands and introducing sown margin strips at the edge of arable fields favours pollinator abundance and species richness as a result of positive trophic interactions (Marshall *et al.*, 2006). Likewise, manipulating the timing of grazing (through late grazing or grazing exclusion at peak flowering times) can be a powerful conservation tool for flower-visiting insects (Farruggia *et al.*, 2012) and grassland birds (Durant *et al.*, 2008), without impacting stocking rates. However, grazing intensity must be adapted to the livestock type and annual variation of grass growth so that grazing management can meet both production and conservation goals. Jouven and Baumont (2008) modelled grassland-based beef systems and found that meat production could be maintained by deploying biodiversity-friendly practices on up to 40 percent of the farm area. This result is similar to the recommendations of Franzén and Nilsson (2008) for late grazing in Swedish farms. The choice of specific practices that result in the optimal production-biodiversity equilibrium will depend on the particular farming context (e.g. type of grasslands, overall stocking rate, herd management).

To enhance soil biodiversity, management practices such as pasture restoration or land manure spreading contribute to the enrichment and diversification of macrofauna and microflora. Compared with the use of inorganic fertilizers, the application of organic manure in maize or cotton fields has significant positive effects on microbial biomass, the profile of existing species and, consequently, on the enzymes that circulate in the soil and its pool of organic matter (Ratnadass *et al.*, 2013). These interactions promote overall soil fertility. Such changes in the soil ecosystem influence the primary production capacity and floristic biodiversity of the vegetation cover that colonizes the soil in agricultural fields and pastures. In the example of cheese production, interactions also take place between soil micro-organisms, phyllosphere microflora and the microflora used for cheese processing. On temperate mountain pastures, microbial diversity reduced the pathogenicity of *Listeria monocytogenes* in raw milk cheese (Retureau *et al.*, 2010). Moreover, species-rich pastures subjected to extensive management produce a variety of secondary compounds including terpenes that are a key factor for the organoleptic diversity of dairy products (Cornu *et al.*, 2005).

The management of diversity and heterogeneity has to extend beyond farm boundaries to encompass the landscape scale. Ecological processes and services like pest control or pollination are grounded at the landscape scale, stressing the need for collective landscape management among farmers and other land-users, accounting for both farmed and semi-natural elements. Recent research has demonstrated that the proportion of management practices (grazing vs cutting) and their spatial arrangement can affect the long-term dynamics of bird populations in agro-landscapes. While converting some intensive practices into extensive ones affected production, altering the spatial arrangement of practices to increase landscape heterogeneity helped to reconcile production and conservation goals (Sabatier *et al.*, 2014). The selection of temporarily ungrazed plots should take into account not only the ‘habitat value’ of each plot, but also their location so that they can act as dispersal sources or ecological corridors.

Landscape features can exert multiple functions and thus play an important role in biodiversity conservation. In Latin America, high milk yields have been achieved without chemical fertilizers

in intensive silvopastoral systems with trees and palms that provide timber, fruit, green forage for livestock, and root and bark for medicinal uses (Murgueitio *et al.*, 2011). Farmers that participated in the project reported that they perceived a dramatic increase in bird abundance and diversity, including more sightings of endangered species. These systems also facilitate connectivity between tropical forest fragments, providing a further benefit to biodiversity. Farmers received a premium payment for incorporating focal native trees, palms and cacti species into their connectivity corridors – these species were selected for their particular contribution to biodiversity. As the payments did not depend on farm size or capital endowments, they were available to all farmers. Extensive fishponds are another typical example, contributing to food production ecosystems, while providing attractive landscape features and a habitat for wild bird species. In temperate fishponds with a controlled fish biomass (400 kg ha^{-1}), the presence of aquatic vegetation over 10-15 percent of the total area improved water quality, benefited fish reproduction and offered a refuge and nesting habitat for waders (Bernard, 2008). However, the interactions between the biotic and abiotic components of fishponds are complex, and depend on the specific practices used and regional conditions.

PERSPECTIVES

This chapter demonstrates how agroecological principles can be applied to systems incorporating livestock, to promote synergies (rather than trade-offs) between local agro-ecosystems and animal production. Each of the five principles is generic and can be applied to the design of a large range of livestock systems, through options that may vary considerably between agro-ecological zones and according to the social, economic and human dimensions of livestock farming. These options include: (i) the intensification of tropical livestock systems by raising yield outputs through an increased use of biodiversity; (ii) transitions to organic livestock production; and (iii) transformation of intensive systems by encouraging farmers to reduce the use of fertilizers and antibiotics. Therefore, depending on the baseline conditions, agroecological transitions with livestock systems may put more emphasis on a subset of the five principles, in order to achieve specific goals such as maximizing economic returns, conserving biodiversity, mitigating GHG emissions, increasing soil and water quality, and enhancing climatic resilience.

An increased use of both planned and unplanned biodiversity (for animal health and nature conservation purposes), a better crop-livestock integration within a diversified landscape matrix and a recoupling of the major element (C, N and P) cycles are the key features underpinning the five principles discussed in this chapter. All of these features could help balance the supply of animal products and the delivery of supporting and regulating ecosystem services.

Interestingly, the concept of eco-efficiency (the maximization of outputs per unit of inputs/natural resources used) is not promoted as a guiding principle of agroecology, although competition with other uses of land and water resources may necessitate more efficient livestock production. Moreover, the current debate on reduced CH_4 emissions from cattle and sheep per unit of animal production is not at the centre of the debate on livestock within agroecology.

This may question the degree to which agroecology can provide answers to global-scale livestock challenges. Nevertheless, agroecology can offer specific answers, such as how to enhance soil carbon sequestration in herbage-based ruminant systems.

Independently from agroecology, new technologies, such as advanced breeding and precision livestock farming, could play an important role in meeting these challenges. For instance, genomic selection, which enables prediction of the genetic merit of animals from genome-wide markers, has been adopted by dairy industries worldwide and is expected to increase genetic gains for milk production and other traits including feed conversion efficiency (Hayes *et al.*, 2013). Such techniques could evolve (e.g. by considering animal robustness in genetic indices) to become more compatible with the principles of agroecology. In addition, agroecology cannot be applied *stricto sensu* to landless industrial systems which are developing rapidly in both industrialized and developing countries. Hence, agroecology is not a silver bullet. Rather, a dual perspective is needed, grounded in the principles of agroecology and industrial ecology as complementary frameworks for improving the net effects of animal production for sustainable development.

In conclusion, agroecological principles can be applied to a large variety of livestock systems covering extended gradients of soil, climate, farm size and production intensity. Some of the bottlenecks for scaling up agroecological systems pertain to the costs of labour, a relatively weak knowledge basis compared with our detailed understanding of simpler industrial systems, and a lack of training of farmers in applied ecology and farming systems. Moreover, scaling up these systems may require broader changes in markets, industries and food systems (Francis *et al.*, 2003). As illustrated by the examples described in this chapter, it should be emphasized that the principles of agroecology point to performance criteria far beyond annual productivity and call attention to trade-offs between the economic, ecosystem and social dimensions of agriculture.

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