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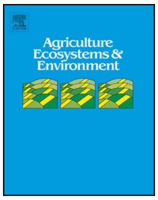

Integrated crop–livestock systems: Strategies to achieve synergy between agricultural production and environmental quality

Gilles Lemaire[a,*], Alan Franzluebbers[b], Paulo César de Faccio Carvalho[c], Benoît Dedieu[d]

[a] Unité Pluridisciplinaire Prairies et Plantes Fourragères, INRA, Lusignan 86600, France
[b] USDA—Agricultural Research Service, Raleigh, NC 27695, USA
[c] UFRGS, Av., Bento Gonçalves 7712, 91540 000 Porto Alegre, Brazil
[d] INRA Sciences pour l'Action et le Développement, Theix, Saint Genès Champanelle 63122, France

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ABSTRACT

A need to increase agricultural production across the world for food security appears to be at odds with the urgency to reduce agriculture's negative environmental impacts. We suggest that a cause of this dichotomy is loss of diversity within agricultural systems at field, farm and landscape scales. To increase diversity, local integration of cropping with livestock systems is suggested, which would allow (i) better regulation of biogeochemical cycles and decreased environmental fluxes to the atmosphere and hydrosphere through spatial and temporal interactions among different land-use systems; (ii) a more diversified and structured landscape mosaic that would favor diverse habitats and trophic networks; and (iii) greater flexibility of the whole system to cope with potential socio-economic and climate change induced hazards and crises. The fundamental role of grasslands on the reduction of environmental fluxes to the atmosphere and hydrosphere operates through the coupling of C and N cycles within vegetation, soil organic matter and soil microbial biomass. Therefore, close association of grassland systems with cropping systems should help mitigate negative environmental impacts resulting from intensification of cropping systems and improve the quality of grasslands through periodic renovations. However, much research is needed on designing appropriate spatial and temporal interactions between these systems using contemporary technologies to achieve the greatest benefits in different agro-ecological regions. We postulate that development of modern integrated crop–livestock systems to increase food production at farm and regional levels could be achieved, while improving many ecosystem services. Integrated crop–livestock systems, therefore, could be a key form of ecological intensification needed for achieving future food security and environmental sustainability.

1. Urgency for renewing agriculture

Everywhere in the world, intensification of agricultural production has been driven by a large use of non-renewable resources that often impair environmental sustainability, as well as by a huge simplification of agricultural systems at all levels of organization, i.e. field, farm, landscape and region. Particularly in industrialized countries, agriculture has become highly specialized in response to political and economic constraints (Russelle et al., 2007; Hendrickson et al., 2008), leading to a large decline in number of farms, despite a large increase in physical and labor productivity (Hanson and Hendrickson, 2009). Intensification and specialization of agricultural systems in industrialized countries has come with increasingly negative impacts on the environment (Tilman et al., 2002), which is now considered unacceptable by society. Consequences of specialization and increasing labor productivity through simplification of crop management and greater external inputs are water contamination, sinking groundwater levels, rising atmospheric greenhouse gas concentrations, soil erosion and dysfunction, and loss of biodiversity (Franzluebbers et al., 2011). Agricultural science must now overcome this apparent contradiction between the necessity to improve productivity of agricultural systems for food security reasons and to urgently prevent degradation and restore the environment.

In developing parts of the world, agricultural systems are evolving very rapidly under demographic pressure, but are confronted by partly similar issues, albeit under unique conditions. Although labor productivity has not increased so much in the past years, because of the important population pressure on land (Paillard et al., 2011), intensive, specialized high-input systems appear to be a goal for modern farming, often in contradiction with the reality and diversity of rural systems and without any deep appreciation

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[*] Corresponding author. Tel.: +33 5 4929 0298.
E-mail addresses: gilles.lemaire@lusignan.inra.fr (G. Lemaire), alan.franzluebbers@ars.usda.gov (A. Franzluebbers), paulocfc@ufrgs.br (P.C.d.F. Carvalho), dedieu@clermont.inra.fr (B. Dedieu).

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for productivity potential of local crop–livestock systems. For example, in Argentina, the cultivated area of crops increased 45% between 1990 and 2006, while use of fertilizers increased 400% (Gavier-Pizzaro et al., 2012). Consequences were loss of habitat heterogeneity, particularly loss of avian diversity and associated ecosystems services that benefit crop production. The Pampa biome in Brazil is experiencing similar threats, in which soybean production is expanding at the expense of natural pasture areas (Carvalho and Batello, 2009). This intensification process based on less diverse specialized systems has occurred not only with cash crops, but with sown pastures as well. Brazil has around 117 million hectares of sown pastures, of which 70% are of one grass genus—*Brachiaria* spp. This process has occurred mainly in the Cerrado, which now has <20% of the original vegetation. According to Zimmer et al. (2011), ~80% of pasture areas have some level of degradation, reflecting the low sustainability of non-diverse farming systems.In both industrialized and developing regions, increasing uncertainties with climate and commodity prices put into question the “specialization—higher productivity” path of development (Evans, 2009). Farmers are deeply concerned by the vulnerability of their systems, notably in developing countries without subsidies, but also more and more in industrialized countries, such as with price controls declining in Europe. Diversified systems such as crop–livestock systems appear then to be an interesting alternative and path forward for agricultural development in the face of climate change and volatility of commodity and input prices. Farming systems need to be robust to overcome hazards (Milestadt et al., 2012), therefore diversity should be a major lever of that flexibility, whether that be through activities such as crops and livestock for sale or resources such as crop, fodder, intercrop cultures, permanent grasslands, etc. (Andrieu et al., 2007).

Livestock production is strongly increasing worldwide because of the increase in demand for animal protein by people in developing countries. Greater income per capita also plays a role in demand for animal products, such as occurring with dairy products in Asia. Animals have various functions in developing countries other than for food production, such as a source of life saving, production of organic fertilizers, etc. Notably, animals have been considered a sign of wealth for the poor, because of these multiple functions (Duteurtre and Faye, 2009). Increasing size of herds is not the only trend (Bouwman et al., 2005). Due to the low energy efficiency of converting plants to animal products, it may be untenable to develop large and very specialized intensive livestock production systems in developing countries. Moreover, these highly intensive and concentrated livestock production practices are generating highly specialized and uniform land use systems, which can be the source of high concentrations of water pollution and emission of greenhouse gases, as well as greater sensitivity to climate change. However, domestic herbivores are not necessarily in competition with humans for food, since they can utilize plant material unsuitable for the human diet from grassland ecosystems located on soils/landscapes not suitable for efficient crop production (Lemaire et al., 2011). Therefore, grasslands should continue to play an important role not only as fodder for sustainable animal production, but also to provide landscape space for realizing essential ecosystem services, such as absorbing negative environmental impacts resulting from the intensification of agriculture (Lemaire et al., 2005).

Integrated crop–livestock systems could provide opportunities to capture ecological interactions among different land use systems to make agricultural ecosystems more efficient at cycling nutrients, preserving natural resources and the environment, improving soil quality, and enhancing biodiversity. Moreover, diversifying agricultural production could utilize labor more efficiently at farm and/or regional scales (Hoagland et al., 2010). Integration of crop and livestock production was the basis for enhancing agriculture in Europe in the 17th century. Eventually, intensive use of fertilizers and mechanization reduced the necessity for this integration. Competitiveness in the world market appears to be based on specialization and increasing size of farms. As a consequence, crop and livestock systems in Western Europe and North America developed more and more into separated farms, especially following rapid industrialization post World War II. Moreover these two systems developed separately in different agro-ecoregions, leading to large uniformly intensive landscapes of cereal production without livestock and concentration of livestock production facilities, such as in Brittany France and in the Netherlands.

Therefore, our challenge is not to rediscover or adopt ancestral agriculture systems that would lead unavoidably to a drastic reduction of agricultural production incompatible with increasing food security requirements, but rather to invent modern integrated systems based on available technology capable of providing both high socio-economic outputs and multiple environmental benefits (Schiere et al., 2002; Sulc and Tracy, 2007; Franzluebbers et al., 2011). This necessary coupling between crop and livestock production must be devised at all levels of organization: the field, where biogeochemical processes are operating; the farm, where management decisions are made; the landscape, where ecosystem processes and interactions between land use components are occurring; and the region or the continent, where socio-economic and political constraints are driving forces.

2. Diversity of agriculture: An antidote for intensification?

Reduction of crop diversity within landscape mosaics and within crop rotations due to the disappearance of forage crops and grassland areas reduces the potential attainment of ecosystem services traditionally served by diversified crop–livestock systems, such as improving soil structure, water infiltration, nutrient cycling, soil organic C sequestration, and soil biological diversity; and controlling weed communities, insects, and disease populations (Franzluebbers et al., 2011). This lack of biogeochemical and ecological controls due to the loss of diversity within cropping systems has been partly compensated by the use of synthetic fertilizers and pesticides, yet which can unfortunately generate unacceptable loads of pollutants to air, water, soil, and neighboring native biotic communities. Moreover, biodiversity at a landscape level for a large range of taxa (plants, insects, small animals and birds) within intensive cereal cropping systems is highly dependent on the spatial continuity and diversity of the landscape mosaic (Bretagnolle et al., 2011a). In particular, permanent vegetation within undisturbed fields (i.e. forage and grasslands) plays an important role in landscape biodiversity by controlling meta-population dynamics (Bretagnolle et al., 2011b).

Again, our challenge in agricultural sciences is to replace the old paradigm based on simplification and standardization of production systems for optimizing productivity per unit of human labor with a new paradigm based on emphasis of diversity at field, farm and landscape scale to optimize productivity per unit of natural resource utilization through spatial and temporal interactions among landscape ecosystem components.

3. Coupling C–N cycles for reduction of environmental fluxes

In natural ecosystems such as grasslands or forests, the permanency of soil-vegetation interactions leads to strong coupling among C, N, and P. Such coupling operates: (i) in plants where N and P are linked to C by plant tissue synthesis through light interception, photosynthesis, N and P assimilation, and plant growth processes; and (ii) in soils through the dynamics of organic matter

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with the capacity of microbes to recapture and recycle mineral N and P. Since N and P are linked to C by stoichiometric relations within the different compartments of soil organic matter and by soil microbial activity, C fluxes through an ecosystem determine to a large extent the fluxes of N and P. The relative distribution of C in the atmosphere and biosphere is proportional to the relative mean residence time of C in each compartment (Parsons et al., 2011). Residence time of C in soils is partially dependent on the N and lignin concentrations of fresh organic matter inputs, but also on physico-chemical and biological control mechanisms (Schmidt et al., 2011). Since litter deposition in grasslands is predominantly dead leaf and root material with initially high C:N and lignin:N ratios (Rasse et al., 2005), mean residence time of C in grassland soils is generally long. Moreover, the high biological activity stimulated by plant root exudates and earthworms promotes the formation of micro-aggregates of soil organic matter with soil mineral matrix with a high degree of physical protection (Schmidt et al., 2011, Bossuyt et al., 2005). Therefore, grassland ecosystems are considered a general sink for carbon dioxide (CO_2) (Goudriaan, 1992). Of course temperature and moisture also play pivotal roles in controlling decomposition of organic matter. This strong coupling between C and N in grassland ecosystems avoids accumulation of reactive N in soils, mainly as nitrate (NO_3), as in annually cropped soils. As a consequence, N losses to the hydrosphere through NO_3 leaching and to the atmosphere through denitrification to nitrous oxide (N_2O) are generally low when vegetation and soil are not disturbed in perennial grasslands. Continuous and intensive grazing with or without N fertilizer inputs leads to decoupling of C and N to varying degrees, because of the reduction in photosynthetic capacity with forage removal.

Cultivation of soil for annual crops provokes decoupling of C and N cycles, because the absence of vegetation and C input during inter-crop periods does not allow for C–N coupling between plants and microbes, resulting in accumulation of reactive N in soils that is susceptible to loss by leaching and denitrification. Moreover, when a cropping system is intensified, large quantities of mineral N, uncoupled with corresponding C flows, are added via external fertilizer inputs, thereby potentially increasing the risk for loss of N to the environment. To fight against this risk, it is recommended to include cover crops within a rotation and to reduce the period of bare soils (Hargrove, 1991). Use of cover crops tends to restore the C–N coupling due to more vigorous soil-vegetation interactions. Beneficial effects of cover crops can be further enhanced with the use of reduced or no tillage in a conservation agricultural approach (Franzluebbers, 2007). Moreover, a large part of cover crop biomass production in a conservation system can be used for feeding ruminant livestock (Gardner and Faulkner, 1991; Franzluebbers and Stuedemann, 2007). In this sense, Carvalho et al. (2010) demonstrated that grazing animals *per se* did not jeopardize soil physical quality in a conservation agricultural system, but excessive stocking with low residual forage mass can deteriorate soil quality. Moderate grazing can increase soil C and N stocks and overall soil quality in the long term (Franzluebbers and Stuedemann, 2010).

Sod-based rotations or ley-farming systems represent a possibility for integration of livestock within a cropping system (Katsvairo et al., 2006; Allen et al., 2007; Franzluebbers, 2007). Such systems can capture temporally the benefits of leys for minimizing environmental impacts in combination with periods of intensive cropping. The longer the ley duration within a rotation, the greater is the potential for soil organic C sequestration and mitigation of N losses to the environment. Nevertheless, precautions have to be taken for the period of destruction and re-cultivation of leys. In addition to these direct environmental benefits, ley-crop rotations can provide indirect ecosystem services, such as improvement of soil fertility and biodiversity, control of weed and pest populations, and saving energy due to economy of tillage and N fertilizers.

Environmental benefits of grassland ecosystems can, however, be progressively impaired as intensification of production increases. Grazing animals consume shoot biomass and this can contribute to partial uncoupling of N from C. Approximately 70% of the C ingested by grazing animals is released back to the atmosphere as CO_2 via respiration and as methane (CH_4) via rumen fermentation (Parsons et al., 2011). However for N, 70–80% is excreted to the soil surface as urine and dung in hot spots, which can increase the risk of N leaching (Ledgard et al., 2009) and N_2O emissions (Flechard et al., 2005), especially as stocking rate and fertilizer N inputs increase. As stocking rate increases with level of intensification of grasslands, C–N decoupling by animals can progressively offset the C–N coupling capacity of the soil-vegetation system, leading to a trade-off between production and environmental goals. It can be surmised that each grassland situation (i.e. soil, climate, vegetation) might exhibit a level of intensification, beyond which might exceed the environmental carrying capacity (e.g. soil erosion limit, soil C sequestration, CH_4 and N_2O emissions, NO_3 leaching, etc.) caused by animal grazing activities. A challenge for research is to develop suitable field experiments and process-based models with long-term objectives to evaluate such environmental carrying capacities of grasslands in different situations.

Should grassland utilization exceed environmental carrying capacity for whatever reason, one solution could be to feed animals indoors with hay or silage harvest of forage. Such a system could help regain C–N coupling, as well as reduce environmental fluxes at the field scale, particularly if legume species were utilized for forage, since they do not require high N fertilizer inputs. However, the problem of C–N decoupling by animals would be transferred to the management of the different types of manure. Integration of indoor ruminant livestock systems with cereal cropping systems could allow the re-introduction of C in crop residues as straw bedding for an efficient C–N re-coupling and nutrient recycling system. Some technological possibilities, such as composting or methanization of stored manures, could allow an optimization of the manure chain through treatment and more efficient utilization. Cost-benefit and environmental impact analyses of these different options would have to be conducted at the whole system level using life-cycle assessment methodology.

4. A multi-scale analysis from fields and farms to landscape and regions

Most of the impacts of agricultural systems on the environment can be evaluated only at broader levels of landscape or continent scales, such as for soil erosion, quality of surface and ground water, air quality, population dynamics, and biodiversity. For these problems it is impossible to develop a simple aggregative approach from field to catchment and to landscape levels, because of the explicit spatial and temporal interactions between the different land use systems. Moreover, these interactions are structured by the pattern of distribution of different land uses and management systems resulting from diverse human interests. Farming system approaches are thus required (Darnhofer et al., 2012). The farm unit is the level of organization where management decisions can be explicitly analyzed, including flexibility as well as production costs, productivity and income. However, environmental consequences of farming are often dependent upon topographical, hydrological, and ecological contexts at the territorial or/and regional scale. Therefore, the broader scale is important, but must consider farm diversity, farm dynamics, land use regularities and changes and their consequences on ecosystem services, and at least, the local and global drivers of change (Lambin et al., 2000; Lazrak et al., 2010).Integrated crop–livestock systems typically would have greater work load compared with specialized systems. In a competitive world, physical labor productivity (total

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crop and livestock harvest per labor unit) is a major factor affecting farm decision making. This factor addresses (i) crop and livestock management and biotechnical efficiency (e.g. crop harvest per land area and livestock performance per head) and (ii) work organization and structural labor productivity (livestock unit per labor unit). Work organization relies on the combination and balance among three elements (Madelrieux and Dedieu, 2008; Hostiou et al., 2012): (1) crop and livestock management-tasks to be performed, whether simple or complex, time required for completion, and seasonality requirements; (2) type of equipment and machinery needed to improve working conditions and work efficiency; and (3) labor force management, considering who works (what is delegated outside the family farm, what is shared with other farmers, and what is done by the farmers themselves), who has the skills and when jobs get done.

Various factors can lead to workload simplification, depending upon exposure to labor productivity issues. One of the first steps to simplification is the decrease in number of agricultural operations, e.g. deleting sheep activity from a mixed sheep–beef or dairy cattle farm or deleting livestock or crop activity from a mixed crop–livestock farm). A second step to simplification is through biotechnical management, i.e. reducing management variables connected to animal and/or crop production. An example would be for a farmer to buy feedstuffs for livestock, in spite of existing on-farm production potential for fodder, grains, and pasture. High correlation ($r \geq 0.7$) exists between structural labor productivity and inputs/gross sales ratio in animal production systems (Charroin et al., 2012). In a similar sense, Hostiou and Dedieu (2009) suggested that Amazonian dairy farmers were reluctant to adopt highly sophisticated rules proposed by research and extension for efficient grassland management and long term sustainability due to workload issues. Long-term analysis of farm work organizational structure has shown the complications of seasonal management in diversified crop–livestock farms, in which animal production tasks can conflict with cropping activity workload, e.g. sorting of finished lambs can be delayed in spring when in competition with spring crop seeding tasks and early harvest of haylage (Dedieu and Serviere, 2012). All of these studies lead to the same conclusion that sophisticated management, of which integrated crop–livestock management is one, can be difficult to implement when focused on increasing physical labor productivity alone. To avoid simplification of biotechnical management, solutions can be explored outside of the individual farm through sharing of equipment and labor force organization (e.g. shared employees, delegation of tasks, and shared tasks between farmers).

Specialization of farms as pure cropping or pure intensive livestock production systems might be considered a mainstream path for modernization and development. It is already present in many industrialized regions (Europe, USA, South America), but territorial studies also show diversity in farming systems in many regions (e.g. part-time farms, large specialized farms, mixed farms, etc.) (Gibon et al., 2010). There is also a complexity of drivers influencing decisions on the farm (i.e. global markets, land tenure problems, urbanization, household incomes, environmental problems, etc.) (Ickowicz et al., 2010). Nevertheless, from a planning perspective it could be possible to avoid excessive specialization at a landscape level by encouraging local interactions among specialized farms, i.e. creating a structured meta-agroecosystem at a territory level. This new vision of agriculture could be a way to reconcile the necessity of diversity of land use and management systems to achieve ecological and environmental outcomes and the necessity of specialization and simplification of production systems to achieve efficient socio-economic outcomes. Again, this issue of balancing production with environmental quality represents a huge challenge for developing future agricultural systems based on socio-ecological principles (Holling, 1973) and that are truly sustainable, productive, and resilient.

Therefore, integration of cropping and livestock systems at farm, landscape or regional level must be considered not only as a way of optimizing food provisioning with environmental quality, but also as a means to produce other ecosystem services, such as CO_2 sequestration, soil and water quality preservation, protection of biodiversity, etc. Therefore, deterioration of these services caused by specialized agricultural systems could be reversed with integrated crop–livestock systems. The role of grasslands as a pivotal component of livestock production system is essential to regain more of these ecosystem services, as well as for pollination, biotic regulation and stability or resilience of productivity. Moreover, grasslands can be considered a source of biodiversity, not only directly through the diversity of plant species within grassland communities, but also indirectly through the diversity of habitats and trophic networks these ecosystems host. Nevertheless, the level at which these different services can be provided depends on local management practices. In general, moderate intensification of grassland production through both an increase in herbage production and an increase in stocking density should be beneficial in many regions (Soussana et al., 2010). Optimizing crop and grassland areas within a territory depends on local conditions, from rangeland areas where the introduction of small spot of cropping area can help for a more sustainable whole production system, to intensive cropping areas where the re-introduction of cultivated grassland areas within integrated crop–livestock system should help for mitigation of environmental impacts resulting from intensification.

Globally, the focus on animal production for feeding human population is questioned for two reasons: (i) inherent low efficiency of converting plant proteins into animal proteins and (ii) contribution of ruminants to CH_4 emission to the atmosphere. Concerning the first point, it is clear that domestic herbivores would not compete directly with humans for plant resources as long as they are fed by grassland resources. But when herbage is produced on land areas suitable for crop production, there is an indirect competition with human food production. However, incorporating some grasslands into cropping areas offers possibilities for mitigating some of the environmental impacts resulting from intensive agriculture. Distinct opportunities exist, in any landscape or regional level, for an equilibrium between crops and grasslands to optimize tradeoffs between food production and environment preservation. The unavoidable CH_4 emission by herbivores should be compensated by soil C sequestration in grassland areas.

5. Conclusion

As stated by Steiner and Franzluebbers (2009), "Achieving sustainable mixed agricultural landscapes in grassland environments is a broad, perhaps audacious goal; yet, the need for change in current agricultural systems is undeniable. Today's agriculture and food systems are deeply rooted from the era of cheap energy and fertilizers, an assumption of static climate, and the ability of entities to 'externalize' environmental and social costs. With society currently facing the end of cheap energy and a growing awareness of climate change linked to rising concentrations of greenhouse gases, additional pressures are likely to emerge expanding human population and increasing competition for scarce water supplies." We must improve upon agricultural systems of the past to meet the impending challenge of food security for a growing human population, while at the same time preserving/improving environmental quality associated with agricultural production and adapting farming systems to the hazards and uncertainties of climate change and commodity price fluctuations. These seemingly diametrically opposed objectives could be simultaneously achieved by better integrating crop and livestock systems to achieve economic,

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sociological, ecological, energy, environmental, and biogeochemical synergies and efficiencies. We postulate that a diversity of integrated systems must be developed for different agro-ecological regions of the world, and that combining innovative technologies with proven management practices can lead to an exciting, sustainable future for agricultural producers and its customers.

References

Allen, V.G., Brown, C.P., Segarra, E., Green, C.J., Wheeler, T.A., Acosta-Martinez, V., Zobeck, T.M., 2007. In search of sustainable agricultural systems for the Llano Estacado of the U.S Southern high plains. Agric. Ecosyst. Environ. 124, 3–12.

Andrieu, N., Poix, C., Josien, E., Duru, M., 2007. Simulation of forage management strategies considering farm-level land diversity: example of dairy farms in the Auvergne. Comput. Electron. Agric. 55, 36–48.

Bossuyt, H., Six, J., Hendrix, P.F., 2005. Protection of soil carbon by microaggregates within earthworm casts. Soil Biol. Biochem. 37, 251–258.

Bouwman, A.F., Van der Hoek, K.W., Eickhout, B., Soenario, I., 2005. Exploring changes in world ruminant production systems. Agric. Syst. 84, 121–153.

Bretagnolle, V., Gauffre, B., Meiss, H., Badenhausser, I., 2011a. The role of grassland areas within arable cropping systems for conservation of biodiversity at the regional level. In: Lemaire, G., Hodgson, J., Chabbi, A. (Eds.), Grassland Productivity and Ecosystem Services. CAB Int., Wallingford, UK, pp. 251–260.

Bretagnolle, V., Villers, A., Denonfoux, L., Cornulier, T., Inchausti, P., Badenhauser, I., 2011b. Rapid recovery of a depleted population of Little Bustard (*Tetrax tetrax*) following provision of alfalfa through an agri-environment scheme. Ibis 153, 4–13.

Carvalho, C.F.P., Batello, C., 2009. Access to land, livestock production and ecosystem conservation in the Brazilian Campos biome: the natural grassland dilemma. Livestock Sci. 120, 158–162.

Carvalho, P.C.F., Anghinoni, I., Moraes, A., 2010. Managing grazing animals to achieve nutrient cycling and soil improvement in no-till integrated systems. Nutr. Cycling Agroecosyst. 88, 259–273.

Charroin, T., Veysset, P., Fromont, J.L., Devienne, S., Palazon, R., Ferrand, M., 2012. Productivité du travail et économie des élevages d'herbivores: définition des concepts, analyses et enjeux. INRA Prod. Anim. 25, 193–210.

Darnhofer, I., Gibbon, D., Dedieu, B. (Eds.), 2012. Farming Systems Research into the 21st Century: The New Dynamic. Springer, p. 490.

Dedieu, B., Serviere, G., 2012. Vingt ans de recherche—développement sur le travail en élevage: acquis et perspectives. INRA Prod. Anim.s 25 (2), 85–100.

Duteurtre, G., Faye, B., 2009. L'élevage, richesse des pauvres: stratégies d'élevages et organisations sociales face aux risques dans les pays du Sud. Editions Quae, Versailles, France, pp. 289.

Evans, N., 2009. Adjustment strategies revisited: agricultural change in the Welsh Marches. J. Rural Studies 25, 217–230.

Flechard, C.R., Neftel, A., Jocher, M., Ammann, C., Fuhrer, J., 2005. Bi-directional soil/atmosphere N_2O exchange over two mown grassland systems with contrasting management practices. Global Change Biol. 11, 2114–2127.

Franzluebbers, A.J., 2007. Integrated crop–livestock systems in the southeastern USA. Agron. J. 99, 361–372.

Franzluebbers, A.J., Stuedemann, J.A., 2007. Crop and cattle responses to tillage systems for integrated crop–livestock production in the Southern Piedmont, USA. Renewable Agric. Food Syst. 22, 168–180.

Franzluebbers, A.J., Stuedemann, J.A., 2010. Surface soil changes during twelve years of pasture management in the Southern Piedmont USA. Soil Sci. Soc. Am. J. 74, 2131–2141.

Franzluebbers, A.J., Sulc, R.M., Russelle, M.P., 2011. Opportunities and challenge for integrating North-American crop and livestock systems. In: Lemaire, G., Hodgson, J., Chabbi, A. (Eds.), Grassland Productivity and Ecosystem Services. CAB Int., Wallingford, UK, pp. 208–218.

Gardner, J.C., Faulkner, D.B., 1991. Use of cover crops with integrated crop–livestock production systems. In: Hargrove, W.L. (Ed.), Cover Crops for Clean Water. Soil and water Conservation Society. Ankeny, IA, pp. 185–191.

Gavier-Pizzaro, G.I., Calamari, N.C., Thompson, J.J., Canavelli, S.B., Solari, L.M., Decarre, J., Goijman, A.P., Suarez, R.P., Bernardos, J.N., Zaccagnini, M.E., 2012. Intensification of row crop agriculture in the Pampas and Espinal of Argentina can reduce ecosystem service provision by changing avian density. Agric. Ecosyst. Environ. 154, 44–55.

Gibon, A., Sheeren, D., Monteil, C., Ladet, S., Balent, G., 2010. Modelling and simulating change in reforesting mountain landscapes using a social-ecological framework. Landscape Ecol. 25, 267–285.

Goudriaan, J., 1992. Biosphere structure, carbon sequestering potential and the 14C carbon atmospheric record. J. Exp. Bot. 43, 1110–1120.

Hanson, J., Hendrickson, J., 2009. Toward a sustainable agriculture. In: Franzluebbers, A.J. (Ed.), Farming with Grass: Achieving Sustainable Mixed Agricultural Landscapes. Soil and Water Association Society, Ankeny, IA, pp. 26–36.

Hoagland, L., Hodges, L., Helmers, G.A., Brandle, J.R., Francis, C.A., 2010. Labor availability in an integrated agricultural system. J. Sustainable Agric. 34, 532–548.

Hargrove, W.L. (Ed.), 1991. Cover Crops for Clean Water. Soil and Water Conservation Society, Ankeny, IA.

Hendrickson, J., Sassenrath, G.F., Archer, D., Hanson, J., Halloran, J., 2008. Interactions in integrated US agricultural systems: the past, present and future. Renewable Agric. Food Syst. 23, 314–324.

Holling, C.S., 1973. Resilience and stability of ecological systems. Ann. Rev. Ecol. Syst. 41, 1–23.

Hostiou, N., Dedieu, B., 2009. Diversity of forage system work and adoption of intensive techniques in dairy cattle farms of Amazonia. Agron. Sustainable Dev. 29 (4), 535–544.

Hostiou, N., Pham Duy, K., Duteurtre, G., Tron Binh, V., Dedieu, B., 2012. Relationships between work organisation and size of dairy farms: a case study based in Vietnam. Trop. Anim. Health Prod., http://dx.doi.org/10.1007/s11250-012-0128-y.

Ickowicz, A., Bah, A., Bommel, P., Choisis, J.P., Etienne, M., Gibon, A., Lasseur, J., Morales, H., Toure, I., Tourrand, J.F., 2010. Facteurs de transformation des systèmes d'élevage extensifs des territoires: étude comparée des dynamiques locales sur trois continents. Cah. Agric. 19, 127–134.

Katsvairo, T.W., Wright, T.W., Marois, D.L., Hartzog, J.J., Rich, D.L., Wiatrak, J.R.P.J., 2006. Sod-livestock integration into peatnut-cotton rotation: a system farming approach. Agron. J. 98, 1156–1171.

Lambin, E.F., Rounsevell, M.D.A., Geist, H.J., 2000. Are agricultural land-use models able to predict changes in land-use intensity? Agric. Ecosyst. Environ. 82, 321–331.

Lazrak, E.-G., Mari, J.-F., Benoit, M., 2010. Landscape regularity modelling for environmental challenges in agriculture. Landscape Ecol. 25, 169–183.

Ledgard, S.F., Schils, R., Eriksen, J., Luo, J., 2009. Environmental impacts of grazed clover/grass pastures. Irish J. Agric. Res. 48, 209–226.

Lemaire, G., Wilkins, R., Hodgson, J., 2005. Challenge for grassland science: Managing research priorities. Agric. Ecosyst. Environ. 108, 99–108.

Lemaire, G., Hodgson, J., Chabbi, A., 2011. Food security and environmental impacts—challenge for grassland sciences. In: Lemaire, G., Hodgson, J., Chabbi, A. (Eds.), Grassland Productivity and Ecosystem Services. CAB Int., Wallingford, UK, pxii- xvii.

Madelrieux, S., Dedieu, B., 2008. Qualification and assessment of work organisation in livestock farms. Animal 2, 435–447.

Milestadt, R., Dedieu, B., Darnhofer, I., Bellon, S., 2012. Farms and famers facing change: the adaptive approach. In: Darnhofer, I., Gibbon, D., Dedieu, B. (Eds.), Farming Systems Research into the 21st century: The New Dynamic. Springer, pp. 365–385.

Paillard, S., Treyer, S., Dorin, B. (Eds.), 2011. Agrimonde. Scenarios and Challenges for Feeding the World in 2050. Editions Quae, Versailles, p. 295.

Parsons, A.J., Rowarth, J., Thornley, J., Newton, J., 2011. Primary production of grasslands, herbage accumulation and use and impacts of climate change. In: Lemaire, G., Hodgson, J., Chabbi (Eds.), Grassland Productivity and Ecosystem Services. CAB Int., Wallingford, UK, pp. 3–18.

Rasse, D.P., Rumpel, C., Dignac, M.-F., 2005. Is soil carbon mostly root carbon? Mechanisms for a specific stabilisation. Plant Soil 269, 341–356.

Russelle, M.P., Entz, M.H., Franzluebbers, A.J., 2007. Reconsidering integrated crop–livestock systems in North-America. Agron. J. 99, 325–334.

Schiere, J.B., Ibrahim, M.N.M., van Keulen, H., 2002. The role of livestock for sustainability in mixed farming: criteria and scenario studies under varying resource allocation. Agric. Ecosyst. Environ. 90, 139–153.

Schmidt, M.W., Torn, M.S., Abiven, S., Dittmar, T., Guggenberger, G., 2011. Persistence of soil organic matter as an ecosystem property. Nature 478, 49–56.

Soussana, J.F., Tallec, T., Blanfort, V., 2010. Mitigating the greenhouse gas balance of ruminant production systems through carbon sequestration in grasslands. Animal 4 (3), 334–350.

Steiner, J.L., Franzluebbers, A.J., 2009. Farming with grass—for people, for profit, for production, for protection. J. Soil Water Conserv. 64, 75A–80A.

Sulc, R.M., Tracy, B.F., 2007. Integrated crop–livestock systems in the US Corn Belt. Agron. J. 99, 335–345.

Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R., Polasky, S., 2002. Agricultural sustainability and intensive production practices. Nature 418, 671–677.

Zimmer, A.H., Almeida, R.G., Vilela, L., Macedo, M.C.M., Kichel, A., 2011. Uso da mehoria da produção animal. In: Cecato, U., Barbosa, M.A., de Galbeiro, S., Paris, W., Grecco, F.C., de A., R., Viegas, C.S., Teixeira, S. (Eds.), Proceedings Simpósio de Produção Animal a Pasto. Maringá-PR, Brazil, pp. 39–78.

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