Diversification within and among agro-ecosystems for sustainable agriculture production.

Role of crop-livestock integration

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Abstract

Most of the environmental impacts of modern agriculture are due more to a too high level of simplification/homogeneity of agriculture systems at fields, farm, landscape and region scale than to a too high level of intensification of production. Environmental impacts due to emissions to atmosphere and hydrosphere are mainly due to an imbalance between C-N-P decoupling and coupling processes within agro-ecosystem...that has been highly aggravated by the historical link between intensification and simplification/homogeneity of agriculture production systems. Loss of biodiversity is also highly linked to the decrease in diversity within agro-ecosystems and among them at landscape level leading to reductions in trophic networks and habitats.

According to these common features we postulate that, by restoring and increasing "diversity" in agro-ecosystems, it should be possible to maintain a high level of productivity of agriculture production while a satisfactory level of environment quality and biodiversity could be maintained or restored.

Grassland-arable cropping integration and agroforestry are two important ways for diversifying agriculture systems owing to their high degree for coupling C-N-P for allowing possible agriculture intensification while minimizing risks for environment. Crop-livestock integration is a way for developing more diversified agriculture production systems. Some results obtained from long term experiments allow the illustration of agronomical and environmental benefits resulting from associations between grasslands and arable cropping systems.

Diversification of agriculture systems has to be analyzed not only at farm but also at landscape, regional and continental levels for matching environmental and biodiversity issues with socio-economic drivers. Socio-economic analyses are necessary for studying the possible ways for disconnecting specialization/homogeneity from intensification (economy of scale) and for promoting the links between intensification and diversity (economy of scope). Global analysis on equilibrium between food/non-food production of agriculture (agroforestry) and animal/plant in human diet (integrated crop-livestock systems) are necessary for optimizing the trade-off between agriculture production and environment quality at the level of the planet....

Keywords: Biodiversity, bio-geochemical cycles, sod-based rotations, crop-livestock integration, greenhouse gas emission, nitrate leaching, sustainable agriculture.

Introduction

Worldwide, agriculture have to face two apparent contradictions: (i) the necessity to continue to increase food production for matching needs of increasing human population with limited land and water resources; and in the same time (ii) the urgency to reduce impacts on soil, water and air quality and on biodiversity caused by modern agriculture (Tilman et al. 2002). In consequence several questions emerge:

- *Is this trade-off between agriculture production and environment quality solvable?*
- *Is the limitation of intensification the only way for a sustainable agriculture production?*
- *Are agriculture productivity and preservation of environment reconcilable?*

During the last 70 years, in industrialized countries, intensification of agriculture production has been achieved through the narrow association of two factors: (i) an increasing use of energy, water and chemical inputs coupled with a huge reduction in human labor; and (ii) an increasing simplification of agriculture systems at all level of organization, the field, the farm, the landscape and the region, leading to uniformity both within and among agro-ecosystems (Hendrickson et al. 2008; Lemaire et al. 2014). As modern agro-ecosystems are resulting from the historical link between intensification and simplification, we can ask the following question:

- *Are the negative impacts on environment of modern agriculture due to an excess of intensification or to a lack of diversity?*

Competitiveness in the world market and reduction in human workload are the two main drivers of simplification and uniformity in agro-ecosystems as a consequence of the paradigm of *economy of scale*. Nevertheless farming systems need also to adapt to overcome hazards (Milestadt et al. 2012), and therefore, diversity should be an important factor of flexibility that put into question the “specialization—higher productivity” path of development (Evans 2009).

Ecological intensification of agriculture, i.e. the use of ecosystem processes and more particularly biological regulations, is argued as being the way for reconciling agriculture productivity with environment quality (Doré et al. 2011). The challenge 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 productivity per unit of natural resources (Lemaire et al. 2014). Successful ecological intensification of agriculture requires diversity at field scale where biogeochemical processes are operating; at farm scale where management decisions are made; at landscape scale where ecosystem processes and interactions between land use components are occurring; and region scale where socio-economic and political constraints are operating as driving forces (Lemaire et al. 2014). The historical link between intensification of production per unit of land or per unit of human labor and simplification and uniformity of management systems must be broken. Then, a positive relationship between socio-economic outcomes and values associated with the diversity of agricultural products and ecosystem services should emerge.

Grasslands, a source of diversity in agro-systems for regulating environment

In terrestrial ecosystems, N and P are coupled closely with the C cycle through two important types of processes: (i) in vegetation, through light interception, plant photosynthesis, N and P assimilation, plant tissue synthesis and plant biomass accumulation, and (ii) in soils, through organic matter dynamics with constant releases and reuses of mineral N and P by micro-organisms. In grassland ecosystems, the active vegetation period throughout the year leads to more intense soil-vegetation interactions. Then N-P cycles are coupled strongly with C (Soussana et al. 2007) that increases the mineralization-immobilization turnover of N, leading to low residence time of reactive N in soil and low risks for N losses to hydrosphere and atmosphere. As a consequence, grasslands are considered as a favorable land-use system for preservation of environment (Lemaire 2012). Moreover, the high rate of accumulation of fresh organic matter through leaf and root litters having a high C/N ratio leads to a high capacity of CO_2 sequestration in soil organic matter as shown by Franzluebbers et al. (2012). Nevertheless, long term stabilization capacity of C through clay and mineral bounds in soils progressively saturates as grassland ages, and after 30 years the CO_2 sink of grassland become asymptotically equal to zero (Figure 1).

Exploitation of herbage resources from grasslands by grazing animals provokes perturbations in ecosystem: (i) a reduction of leaf litter flow in soil in proportion to the herbage intake; (ii) a N-P decoupling from C by digestion processes, leading to CO_2 and CH_4 emissions by animal, a high N concentration in urine and P in feces, and a high patchiness of N-P restitutions leading to an increased spatial and temporal heterogeneity of pasture. All these grazing effects are quantitatively linked to stocking density and lead to erase a more or less part of the C-N-P coupling capacity of soil-vegetation system.

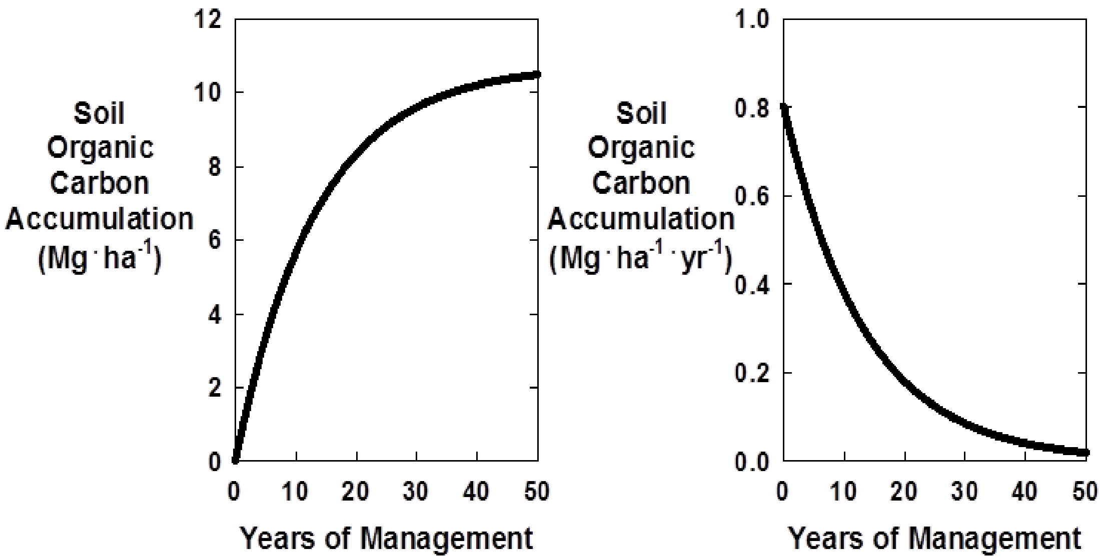

Figure 1. Soil organic carbon accumulation (a) and rate of accumulation under pasture management (b). Reprinted from Franzluebbers et al (2012).

Intensification of grassland management can be achieved through two complementary ways: (i) N and P supply and/or increase in contribution of legume species for N_2 fixation, leading to an increased herbage production; and (ii) an increase in stocking density for valorizing the supplement of herbage produced. Increased herbage production should lead to increased C flows into ecosystem favoring then CO_2 sequestration of grassland. But in the same time, increased N nutrition of vegetation (lower C/N ratio) and increased stocking density should reduce the residence time of C within ecosystem. Then, as shown by Soussana and Lemaire (2014) and as illustrated in Figure 2, moderate intensification of grassland remains a sustainable option, while too high levels of intensification lead to only a marginal increase in animal outputs associated with high risks for environment. To overcome this trade-off it is necessary to develop the concept of '*grassland environmental carrying capacity'*, which is the stocking density achieving a balance between C–N coupling capacity of vegetation and C-N de-coupling activity of domestic herbivores (Lemaire, 2012). Therefore, for each location and condition (e.g. soil, climate, vegetation), a threshold level of intensification needs to be determined, beyond which negative environmental impacts (CO_2 balance, CH_4 and N_2O emissions, nitrate leaching, etc.) due to grazing animals will exceed the positive impacts provided by soil–vegetation C–N coupling (Soussana et al. 2004; Parsons et al. 2011).

Moderately intensified grasslands should remain an important land use system, but an important research question remains: *what level of spatial and temporal interactions of grassland areas with arable cropping systems will be most beneficial to mitigate some of the negative impacts resulting from agricultural intensification?*

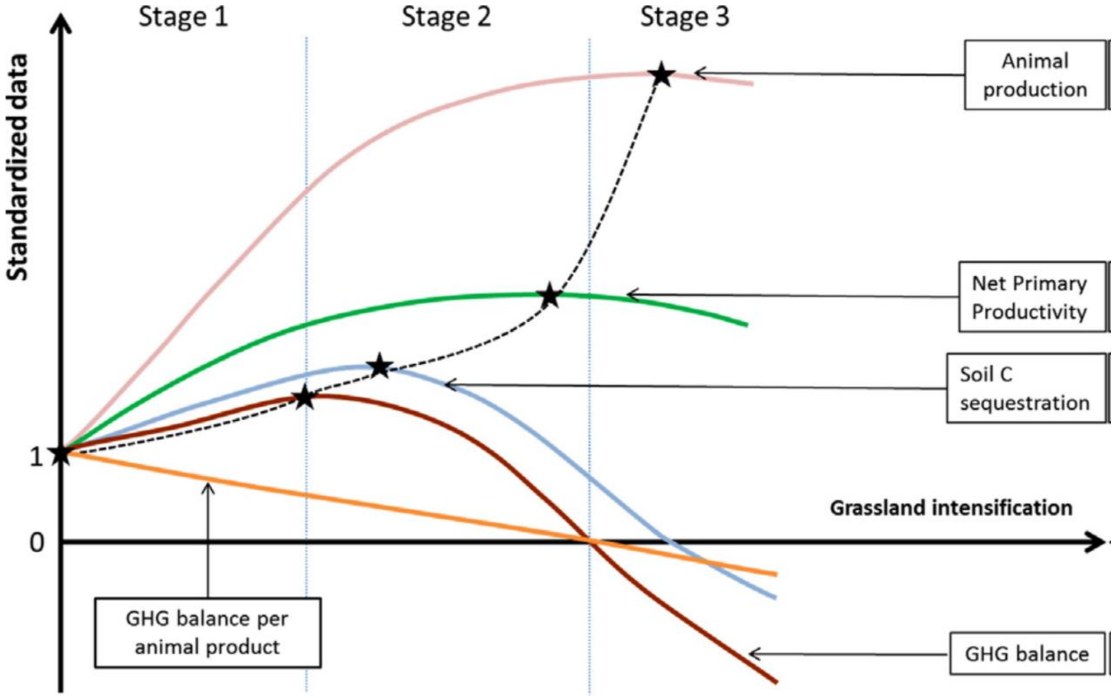

Figure 2. Effects of grassland intensification on net primary production, animal production, soil N sequestration and GHG balance expressed in standardized values (1 representing an unintensified situation). After Soussana and Lemaire, 2014.

Decoupling C-N-P cycles in simplified arable cropping systems and environmental impacts

The main effect of arable cropping is the temporal disruption of the soil-vegetation interactions. During the inter-crop period, the cessation of C flows from plants into rhizosphere provokes C starvation of soil microbe community and a large decrease in N immobilization capacity in soil. Then as N absorption flow by plants is also stopped, mineral N produced by soil organic matter mineralization accumulates in soil leading to increased risks for N_2O emission in atmosphere and NO_3^- leaching. In addition, mineral N fertilization applications increase mineral N concentration in soils and associated environmental risks rise. Simplification of crop rotations with tendency to mono-culture is associated with increasing inter-crop periods with bare soils that is a factor for additional risks for soil erosion and P run-off. Moreover, increase in field size associated with simplification of cropping systems leads to landscape uniformity. Then control of weed, disease and insect populations without massive use of pesticides becomes more and more difficult in absence of ecological regulations, accentuating then deterioration of water and air quality and accelerating biodiversity decline. Attempts for mitigating these negative environmental impacts of simplified arable cropping systems have been made by the use of no-tillage and conservation management systems, the introduction of catch crop sequences, and a wider use of legume crop within rotations for reducing rates of mineral N fertilizer applications. But adoption by farmers of these new management systems is limited because of additional management costs and absence of financial incentives. Re-introduction of inter-crop vegetation sequences without any productive function represents a financial handicap. So, introduction of grassland periods within arable crop rotations should be a more sustainable solution by providing direct economic values through integrated crop-livestock systems.

Grassland-arable crop association as a pathway to sustainable agro-ecosystems

As shown above, grasslands can provide several ecosystem services in addition to their productive function and economical valorisation. Services, such as atmospheric CO_2 sequestration or control of GHG emissions, must be estimated at the global scale, and are determined by *how much* land area is covered by grasslands. Other regulation services, such as control of soil erosion, maintaining of surface and ground water quality and limiting biodiversity loss, are resulting of spatial and temporal interactions between grassland areas and other local ecosystems at farm and landscape levels and depends *where* grassland areas are located that requires explicit analysis of land use pattern at local scale.

In sub-tropical Brazil, winter annual pastures preceding summer cash crops such as soya bean (*Glycine max*) or maize improve soil C stocks (Martins et al., 2014), crop yield (Moraes et al., 2014) and economic stability of cropping systems (Oliveira et al., 2014). Several other studies showed that grain yields increased when grasslands were introduced into arable rotations (Nafziger and Dunker, 2011; Posner et al., 2008; Grover et al., 2009). Use of legume-based grasslands may lead to large economy in N fertilizers for following crops. For example, alfalfa (*Medicago sativa*) may release between 100 and 200 kg mineral N per hectare to subsequent maize or cereal crops (Hesterman et al. 1987; Bruulsema and Christie 1987).

Introduction of grasslands into arable crop rotations allows a better control of pests and diseases (Rodriguez-Kabana et al. 1989) and weed development (Entz et al. 2002; Nazarko et al. 2005; Katsvairo et al. 2006). Reducing use of pesticides resulting from this better control should reduce pollution of water, air and soil. The grassland effect operates not only directly, in proportion to the land area covered by grassland, but also indirectly, through its spatial and temporal interactions with adjacent arable land areas. This synergetic effect highlights the need for local integration among agro-ecosystems.

Grassland-crop rotations have an intermediary C sequestration capacity between those of pure cropping or pure grassland systems, with C accumulation during grassland sequences and C loss during cropping sequences (Soussana et al. 2004). As shown by (Studert et al. 1997) and illustrated in Figure 3, the long-term net C balance depends on the relative durations of grass vs. crop phases in the rotation.

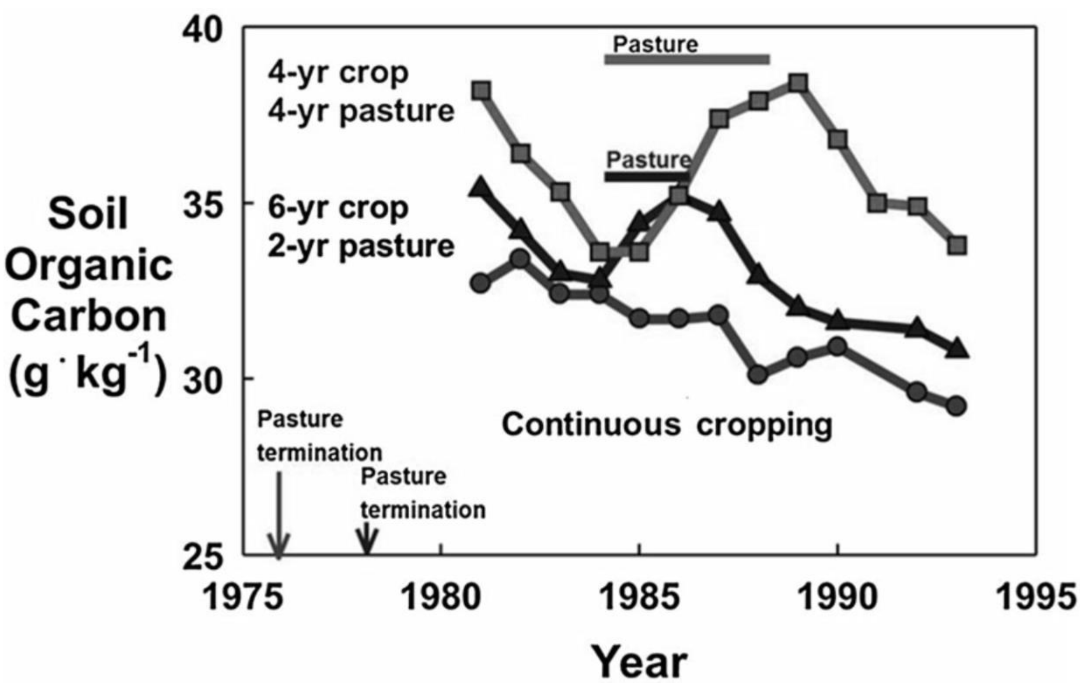

Figure 3. Effect of long-term cropping and grass-crop rotation sequences on soil organic C in Argentina. Data from Studdert et al. (1997).

As mentioned above, the risk of nitrate leaching is generally low in grasslands if the stocking density remains moderate and under mowing management. Converting grassland into arable crops can induce a large flux of mineralised N, with a high risk of N being leached as nitrate (Eriksen and Jensen, 2001; Vertes et al., 2007). Kunrath et al. (2015) observed that this risk is low when grassland is ploughed in early spring, just before a maize crop was sown. Average nitrate concentrations in drainage water in grassland-arable crop rotations decreased exponentially as the proportion of grassland in the total rotation duration increased as shown in Figure 4.

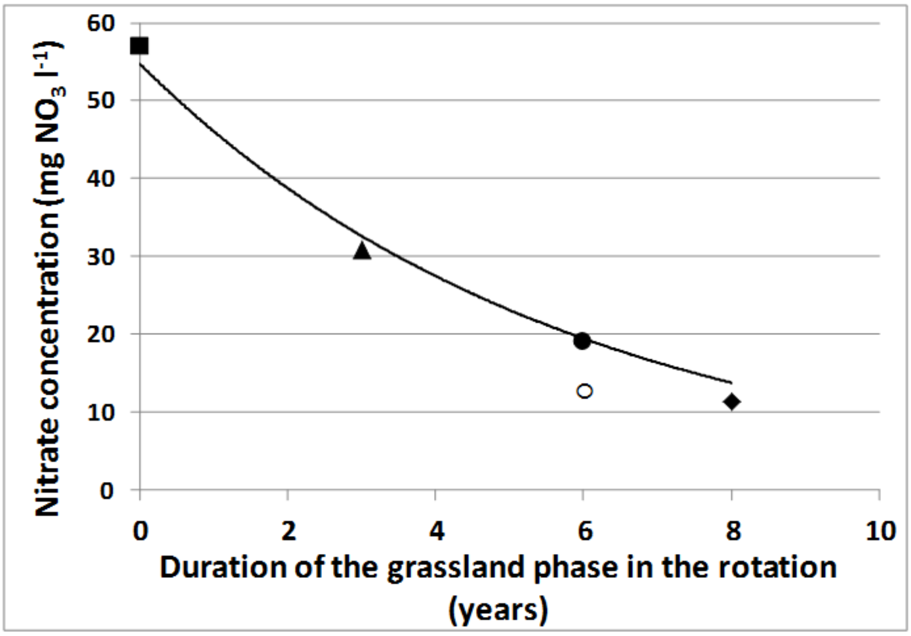

Figure 4. Effect of introduction of grassland phases within an arable crop rotation (maize, wheat, barley) on average nitrate concentration of drainage water. After Kunrath et al. 2015.

Synergies between grasslands and arable crops are also the base for biodiversity dynamics at the landscape level (Ryschawy et al., 2012). Agriculture intensification when associated with landscape uniformity, has resulted in drastic declines in plant, insect, bird and mammal communities in many countries (Benton et al. 2003; Inchausti and Bretagnolle, 2005). Experiments have shown that re-introduction of grasslands into an arable landscape can increase plant species richness (Meiss et al. 2010) and insect diversity (Badenhauser et al. 2009). As demonstrated by Robinson and Sutherland (2002), the ratio of grassland:arable land is an important factor determining bird species richness. The perennial habitats provided by grasslands allow the dynamics of meta-populations and meta-communities of many organisms based on dispersal and colonisation phenomena. Therefore, grassland-crop rotations generate patterns of landscape heterogeneity favourable to biodiversity dynamics of many taxa (Bretagnolle et al. 2011).

There is wide agreement about the multiple benefits of close integration of grasslands in arable cropping systems, not only to increase and stabilise arable crop yields but also to protect the physical and biological environment. These benefits result from spatial and temporal interactions among crops, animals and grasslands operating at different levels (Moraine et al., 2014). Some of these interactions are mediated by herbivores, either directly by grazing or indirectly by recycling nutrients from manure produced in barns, allowing temporal coordination between crop and livestock components of the system. Maximising coordination among crops, animals and grasslands should enable higher total agricultural production than the total production of the sub-systems managed independently, in line with the concept of emergent properties of natural ecosystems as applied to agricultural systems (Schiere et al., 2002).

Crop-Livestock Integration Systems, from farm to landscape and region…

After agriculture revolution in the 16th century, cereal production was associated with forage production and was the dominant farming system in Western Europe and North America until 1960s. Thereafter, specialisation of agriculture systems in these countries increased rapidly for different reasons: (i) increasing market demand for food-industry standards, (ii) capturing economies of scale under conditions of low-cost inputs on large farms, (iii) responding to policy incentives for international markets, and (iv) the necessity to reduce workload and to optimize work management (Steiner and Franzluebbers, 2009).

In different regions around the world two types of farming systems coexist in the same territory: (i) large farms increasingly specialised in pure arable cropping or feedlot livestock production; and (ii) small or medium family farms with greater diversity in agricultural production that use human labour more intensively and promote flexibility. Reintroduction of livestock within specialized cereal farms seems difficult, given the high workload and work-management constraints of livestock production (Peyraud et al., 2014). Integration of crops and livestock among specialised farms at the regional level could be a promising option to bypass this major locking. Promoting exchanges of feed resources, organic matter and N-P nutrients beyond the farm scale by connecting specialised farms should have many economic and social benefits that can be obtained only at the territory level (Asai et al., 2014; Martin et al., 2014; Russelle et al., 2007).

Collective land-use organisation could increase crop and grassland diversification and would result in a more heterogeneous landscape mosaic, an increased continuity among semi-natural components and thus among ecological networks (de Groot et al., 2010). So connections with agro-forestry and sylvo-pastoralism systems should be encouraged. Economic benefits could be achieved through collective organisation of farmers for decreasing costs by collectively purchasing inputs (e.g. feed, fertilisers or seeds) and sharing equipment. Considering these economic aspects of farm activity is essential, as few incentives support this kind of coordination (Sulc and Tracy, 2007).

Targeted political incentives are needed to promote crop-livestock integration at farm or regional levels. Subsidies based on diversifying production or autonomy through interactions between crops and livestock should be tested (Ryschawy et al., 2014). The environmental sustainability of such systems could justify political intervention at the regional level (Ryschawy, 2012). Integration of crops and livestock beyond the farm level would require a specific governance structure involving landscape planning at the regional level (de Groot et al., 2010). Specific research and advice are needed to develop tools and portfolios of locally-adapted innovations that farmers would likely adopt to better coordinate crops and livestock (Martin et al., 2014). As Herrero et al. (2010) highlight for developing countries, governments should work with scientists and other stakeholders to precisely target technological investment and policy options, as well to adapt them to different farming systems and regions.

Conclusions

The high capacity for coupling C and N cycles allows grasslands to be considered an agro-ecosystem favorable for minimizing environmental impacts while achieving relatively high level of animal outputs. For global objectives in regulating greenhouse gas emissions, the question is *how much* grassland areas are necessary? For more regional and local objectives such as soil quality conservation, ground and surface water quality preservation, and biodiversity regulation, the question is *where* these grassland areas should be situated for providing these services in term of spatial and temporal interactions with other land use systems. Agronomic and environmental benefits of grasslands rotated with arable cropping systems are well documented in qualitative and general quantitative terms, but specific quantification relative to numerous management options will be necessary for the evaluation of the best compromise between socio-economic and environmental values of integrated systems.

The application of paradigm of *economy of scale* to agriculture systems leads to intensification of livestock and arable crop systems separately in different farms and territories, and then generates the unacceptable deterioration of environment we observe today. Inclusion of grasslands within arable crop rotations allows mixed crop-livestock systems to reach high productivity levels with reduced environment damages by increasing diversity at farm and landscape level. But it is necessary to analyze socio-economic and politic levers and lockings for a higher adoption of integrated crop-livestock systems by farmers and stakeholders.

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