RAPA Revista Argentina de Producción Animal

Conferencia[1]

ROLE OF DOMESTIC HERBIVORES IN IMPROVING SOIL FERTILITY FOR SUSTAINABLE CROPPING SYSTEMS

El rol de los herbívoros domésticos en la mejora de la fertilidad del suelo para sistemas de cultivo sustentables

Lemaire G
Institut national de recherche pour l'agriculture, l'alimentation et l'environnement (INRAE)
E-mail: gilles.lemaire.inra@gmail.com

Abstract
Since the origin of agriculture, domestic herbivore livestock has been associated with the evolution and development of agriculture systems worldwide. Beyond their contribution in producing meat, milk, wool and leather, their major role was to enhance and maintain the soil fertility of cultivated areas through the recycling of nutrients such as nitrogen (N), phosphorus (P) and all other elements, allowing an increase in cereal production to feed a growing human population. More recently, this close coupling between livestock and cereal systems has been disrupted. Since 1950s the increasing meccanization power and industrial fertilizer use have questioned this crop-livestock integration. Farms, territories and regions, became more and more specialized: cropping *vs* livestock production, crop rotation simplification, leading then to homogeneity of landscapes. The intensification of production within these disconnected systems has resulted in huge flows of N to the environment leading to a dramatic deterioration in the quality of soil, air, and ground- and surface water. Consequently, to reduce the too high dependency of agriculture on the massive use of fertilizers, we argue that a close reconnection at the local scale, of herbivore livestock with cereal-based cropping systems, becomes necessary for agriculture sustainability. An equilibrium between cropping and livestock system must be achieve at local scale. The diversification of cropping rotations through incorporation of temporary grasslands and forage crop, should allow a decrease in pressure of weeds and plant diseases and insects, leading to a reduction in pesticide use, in complement with a corresponding reduction of external fertilizer use. Despite domestic herbivores emit methane (CH_4), an important greenhouse gas, they participate to nutrient recycling, which can be viewed as a solution to maintaining long-term soil fertility in agro-ecosystems; at a moderate stocking density, ecosystem services provided by ruminants would be greater than the adverse effect of greenhouse gas (GHG).
Key words. Crop-livestock integration, greenhouse gas, nutrient recycling

Resumen
Desde el origen de la agricultura, el ganado herbívoro doméstico se ha asociado con la evolución y desarrollo de los sistemas agrícolas a nivel mundial. Más allá de su contribución en la producción de carne, leche, lana y cuero, su rol principal fue mejorar y mantener la fertilidad del suelo de las áreas cultivadas mediante el reciclaje de nutrientes como el nitrógeno (N), el fósforo (P) y todos los demás elementos, permitiendo un aumento de la producción de cereales para alimentar a una población humana en aumento. Más recientemente, este estrecho vínculo entre los sistemas ganaderos y agrícolas se ha visto alterado. Desde la década de 1950, el creciente poder de mecanización y el uso de fertilizantes industriales han cuestionado esta integración agricultura-ganadería. Los establecimientos, los territorios y las regiones se especializaron cada vez más: producción agrícola *vs* producción ganadera, simplificación de la rotación de cultivos, lo que condujo a la homogeneidad de los paisajes. La intensificación de la producción dentro de estos sistemas desconectados ha resultado en enormes flujos de N al medio ambiente, lo que ha provocado un deterioro dramático en la calidad del suelo, el aire y el agua subterránea y superficial. En consecuencia, para reducir la excesiva dependencia de la agricultura del uso masivo de fertilizantes, sostenemos que para la sostenibilidad de la agricultura se hace necesaria una estrecha reconexión a escala local de la ganadería con herbívoros con los sistemas de cultivo basados en cereales. Se debe lograr un equilibrio entre el sistema agrícola y ganadero a escala local. La diversificación de las rotaciones de cultivos mediante la incorporación de pasturas temporales y cultivos forrajeros debería permitir una disminución de la presión de las malezas y las enfermedades e insectos de las plantas, lo que conduciría a una reducción del uso de pesticidas, además de la correspondiente reducción del uso de fertilizantes externos. A pesar de que los herbívoros domésticos emiten metano (CH_4), un importante gas de efecto invernadero, participan en el reciclaje de nutrientes, lo que puede verse como una solución para mantener la fertilidad del suelo a largo plazo en los agro-ecosistemas; con una densidad de población moderada, los servicios ecosistémicos proporcionados por los rumiantes serían mayores que el efecto adverso de los gases de efecto invernadero (GEI).
Palabras clave. Integración agrícola-ganadera, gas de efecto invernadero, reciclado de nutrientes

Received: october 2023
Accepted: december 2023

[1] Conferencia plenaria presentada en el 46° Congreso Argentino de Producción Animal realizado en la ciudad de Pergamino (Buenos Aires) entre los días 13 y 15 de Setiembre de 2023. El trabajo fue compaginado por Juan Mattera.

Introduction

In this presentation it is analyzed the important role domestic herbivores have played during long time in the past, and should play again in the future, for improving and maintaining the fertility of soils in arable cropping systems. In a first part, it is analyzed the processes at the origin of the acquisition and conservation of fertility in soil. In a second part, it is developed an historical analysis of the role of domestic herbivores in renewing soil fertility in agricultural systems from the Neolithic era until modern agriculture era. In a third part, it is analyzed the current crisis in industrialized agriculture and the necessity for recoupling livestock with arable crop production. Finally, the conclusions with the lessons learned and future efforts.

On a worldwide scale, agriculture must reconcile two apparent opposite issues: i) to produce enough food for a burgeoning human population, ii) to reduce drastically its negative impacts on environment. Such a trade-off between two apparent contradictory objectives requires not only the redesign of agricultural production systems, but also of the whole food supply and demand chain. To face this challenge two important questions emerged about the importance domestic herbivores should have within agro-systems according to the 2 main questions: i) a reduction of the animal-based product in human diet?, and ii) a reduction of CH_4 emissions by ruminants?. To answer these questions, it is necessary to take into account the highly positive effect domestic herbivore livestock should play in recycling nutrient and maintaining soil fertility with a high reduction in the greenhouse gas (GHG) emissions associated with industrial fertilizer use.

The objectives of this presentation are: i) to analyze the ecological roles of herbivore livestock from a historical perspective and for future agro-systems; ii) to assess their contribution not only for feeding human population, but also for fostering agro-system resilience; iii) to achieve a better coupling of C, N, P, micro- and oligo-elements cycles for renewing and enhancing soil fertility while minimizing the use of external fertilizers. For that, it is necessary to study the continuum between plants, soils, herbivores, agriculture systems, and human diet to account for the multiple trade-offs among these different aspects. It is also necessary to counter the relatively hasty analysis that herbivores have to be excluded from agriculture because ruminants emit methane. Biogenic methane has to be considered as the counter-part of all the other ecosystem services provided by integrating domestic herbivore livestock and the associated grasslands and forage production within sustainable agro-ecosystems.

I. Origin of the acquisition and conservation of fertility in soil

How soil fertility has been elaborated and cumulated over long geological periods?

In a natural ecosystem, either with lignified or/and herbaceous vegetation, mineral nutrients available for plants (P, K, micro-elements, and oligo-elements) are provided by the very slow weathering bedrock process and they are stored in soils through more or less important linkage with soil colloids as a reservoir (Figure 1). N gradually accumulated in system through N_2 symbiotic and non-symbiotic fixation and to a small extent through atmospheric deposition; there is an internal recycling of nutrients in plant during leaf senescence: about 80% is recycled within plant as reserve for a new regrowth period, while only about 20% of nutrients return to soil via leaf and root litter deposition (Sanaullah *et al*. 2010; Lodge *et al*. 2006). These 20% of nutrients are then involved in the fresh organic matter input in soil, are recycled through microbial mineralization-immobilization turnover, and are transformed in available forms for being reused concurrently by plants and microbial communities of the soil for their own development. This recycling system is very efficient because available forms of N as nitrate and ammonium cannot accumulate too high in soil solution because of the high competition between plants and microbes for their reabsorption. Then losses of the more mobile forms such as nitrate and ammonium to atmosphere and hydrosphere were very low leading to a relatively high conservative soil fertility in a long-term run.

Soil microbes play a fundamental role for this conservative nutrient cycle through the mineralization-immobilization turnover. As plants are coupling N and P with carbon through autotrophy, microbes are decoupling N-P from C for producing available ammonium, nitrate, sulfate and phosphate for plant nutrition, but they are also using these available forms for their own population and community development (Briat *et al*. 2020). So, soil microbes are both providing available nutrients for plants and competing with plants for their use. Therefore, plants and microbes are competing each other for these nutrient resources, and it is the reason why these available forms cannot accumulate in large quantity in soil.

What happen with herbivores?

Herbage consumption by herbivore reduced the internal recycling of nutrients in plants and the rumen fermentation decouples and recouples C-N-P (Soussana and Lemaire 2014). Then feces and urine depositions recycle C-N-P with stoichiometric proportion very favorable for stimulating microbial mineralization-immobilization turnover in soil. It has been well demonstrated that exclusion of great herbivores from areas in African Savana ecosystems had a negative effect on capacity of soil to provide nutrients for vegetation (Naidu *et al*. 2022). Microbial communities in rumen and microbial communities in soils are constituted by similar populations with a very common genetic pattern (Schmitz *et al*. 2018) and are considered as being in close interdependency for accelerating nutrient cycling within ecosystem. In this view, the CH_4 emission due to the digestion of cellulose must be considered as the “price to pay” to benefit of this high efficient nutrient cycling and then cannot be considered as only a negative output.

What happen with soil cultivation?

When cover vegetation is suppressed by soil cultivation, the disruption of C flow from plants reduces N immobilization by microbes in arable cropping (Lemaire *et al*. 2004). Mineral N forms accumulate in soil when plant N absorption is low and particularly in bare soil periods, leading then to high risk of losses in atmosphere and hydrosphere.

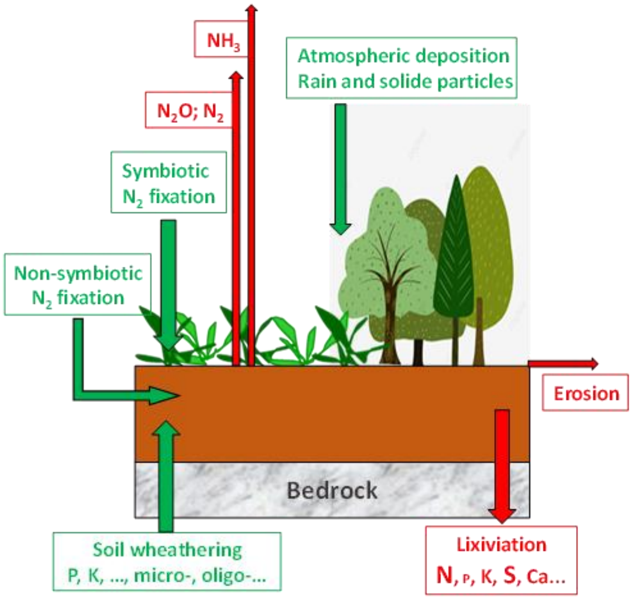

Figure 1. Soil fertility construction in the long term in a natural ecosystem with the inputs into the soil (green arrows) and with the outputs from the soil (red arrows). Adapted from Lemaire *et al*. (2023).

Figura 1. *Construcción de la fertilidad del suelo en el largo plazo en un ecosistema natural con las entradas en el suelo (flechas verdes) y las salidas desde el suelo (flechas rojas). Adaptado de Lemaire et al. (2023).*

II. Historical analysis of the role of domestic herbivores in renewing soil fertility

In this section, it is shown how soil fertility has been improved and maintained from the beginning of Agriculture in Neolithic until the modern era. Except for the Nile and Euphrates Valleys where soil fertility was renewed each year by loam deposition during flooding periods. Agriculture expanded in most of the other regions in the world by the "slash and burn" method, destroying the natural vegetation for cultivation during a short period of time (Mazoyer and Roudart 1997; Lintemani 2020). Soil fertility rapidly decreased after 1 to 3 years, that implied the clearing of a new area of natural vegetation and a long fallow period (several decades) that enabled a slow regeneration of natural vegetation and soil fertility restoration. Such a semi-nomadic system did not allow the food production for a large human population, and it was progressively replaced by a more efficient one, even if it continue to be used until now in some part of the globe.

In Mediterranean and European regions, and more particularly within the Roman Empire, a more structured system based on three embedded ecosystems has been developed (Mazoyer and Roudart 1997):

- *Ager*, the cultivated area with fallow-cereal crop rotation;
- *Saltus*, the domestic herbivore grazing area;
- *Silva*, the forest area.

Livestock were grazing *Saltus* and a part of *Silva* during the day and were parked night on fallow area that allowed transfer of nutrients from *Saltus* and *Silva* into the ager area. This system allowed feeding about 15 and 39 habitant per square kilometer according to climate and soil conditions (Figure 2).

Later in Middle Age (+ 1000 years), the system evolved under the demographic pressure. Forage harvest and hay storage technology allowed an increase in stocking density by feeding animal in barns in winter that increased the volume of manure and the flow of nutrient transfer to ager area. This higher soil fertility allowed the use of a triennial rotation that contributed to increase food production (Mazoyer and Roudart 1997). Such a system allowed food production for population density between 55-80 habitants per square kilometer.

The First Agricultural Revolution in Europe (XVIth-XVIIth centuries) with the generalization of the Norfolk rotation (Riches 1967), was based on the suppression of fallow periods and the introduction of artificial meadows with legume species within a quadrennial rotation (Figure 4). *Saltus* areas were progressively incorporated to *Ager* moving from a common to a private status and then become part of individual farms. The higher contribution of N_2 fixation by legumes allowed an increase in cereal yield from 1 ton per Ha to about 2 tons that allowed the feeding of an increasing urban population. The productivity of this system was then limited by P and K deficiencies in soil and by other limiting factors as low pH, excess of water, among others.

III. Current crisis in industrialized agriculture and the necessity to recouple nutrient cycles

The Second Agriculture Revolution after the Second World War with the development of mechanization and the suppression of animal traction in farms, the industrial production of N fertilizers, and the mining of P and K resulted in the progressive abandon of herbivores for maintaining soil fertility. This rapid evolution had important consequences: decoupling livestock from crops, nutrients not fluxing in circularity; and soil fertility controlled by fertilizer industry. This decoupling of livestock from crops has been achieved through an excessive simplification of arable cropping systems, leading in some regions to monoculture systems. The consequence of this simplification are: long periods of bare soil with risks for erosion

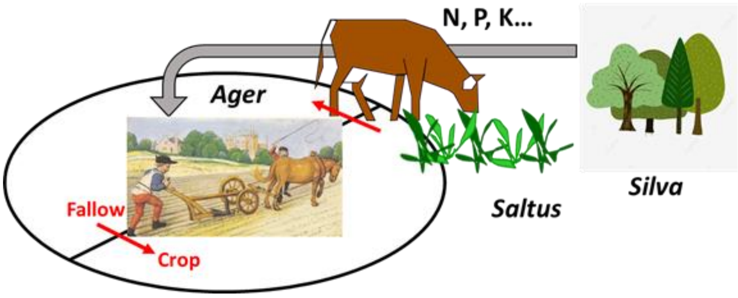

Figure 2. Agriculture and livestock system during the Roman Empire considering the three ecosystems developed (*Ager*: cultivated area, *Saltus*: domestic grazing area and *Silva*: forest area). This system produce food for a population density between 15-39 habitants/km^2. Adapted from Mazoyer and Roudart 1997.

Figura 2. *Sistema de agricultura y ganadería durante el Imperio Romano considerando los tres ecosistemas desarrollados (Ager: área cultivada, Saltus: área de pastoreo doméstico y Silva: área forestada). Este sistema produce alimento para una población entre 15-39 habitantes por km^2. Adaptado de Mazoyer y Roudart 1997.*

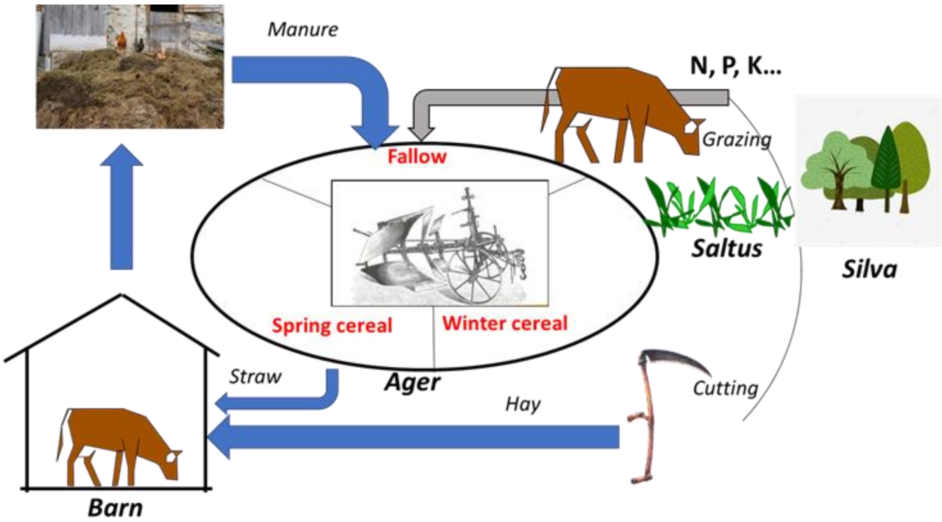

Figure 3. Agriculture and livestock system developed during the Middle Age that include the three ecosystems previously developed during the Roman Empire (*Ager*: cultivated area, *Saltus*: domestic grazing area and *Silva*: forest area) with the addition of animals feeding in barns and the utilization of manure to fertilize crops. This system produce food for a population density between 55-80 habitants/km^2. Adapted from Mazoyer and Roudart 1977.

Figura 3. *Sistema de agricultura y ganadería desarrollado durante la Edad Media que incluye los tres ecosistemas previamente desarrollados durante el Imperio Romano (Ager: área cultivada, Saltus: área de pastoreo doméstico and Silva: área forestada) con el agregado de animales alimentados en corrales y la utilización del estiércol para fertilizar los cultivos. Este sistema produce alimento para una población entre 55-80 habitantes/km^2. Adaptado de Mazoyer y Roudart 1997.*

and $N0_3^-$ leaching, soil organic matter decline and soil quality degradation, and increased weeds, fungi and insect invasion and pesticide use.

Agriculture at world level must face the contradiction between increasing food production and highly reducing environmental impacts. These environmental impacts are more the consequence of the simplification and homogeneity of the land use systems than of a too high productivity level (Lemaire *et al*. 2014). Spatial separation of livestock production systems from arable cropping systems is at the origin of this simplification and homogenization of food production systems. Then, re-coupling livestock with cropping system should allow the increase of local diversification necessary to resorb negative environmental impacts. In this view, there is a balance between CH_4 emission by livestock and their high contribution to reduce drastically GHG emissions associated with the use of industrial fertilizers. The re-coupling between livestock and cropping system must be realized, not only at individual farm level but also and more importantly beyond the farm gate at landscape level through exchanges and interactions among different specialized farms (Figure 5). The stocking density at local scale must remain under a threshold level if we want that the GHG balance would remain positive at landscape scale (Soussana and Lemaire 2014). Therefore, it is important to avoid high spot of intensive livestock production in some region and high spot of cereal cropping without livestock in other region.

The importance of legume species due to the contribution of N_2 fixation within this integrated crop-livestock system is an important factor for the system sustainability (Peoples *et al*. 2019). So, legume species must be incorporated either within arable cropping systems for grain protein production, and within grasslands and forage system. In addition, forage crops

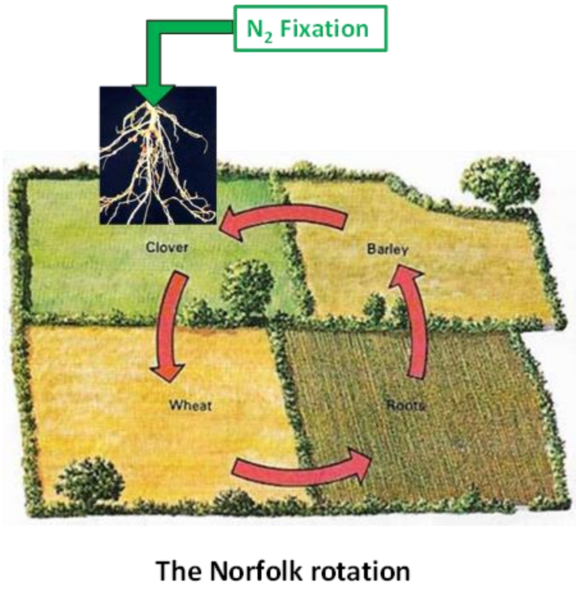

Figure 4. The Norfolk rotation with a quadrennial rotation system developed during XVI^th^-XVII^th^ centuries that include the introduction of artificial meadows with legume species within a quadrennial rotation that increases crop yield due to biological nitrogen fixation.
Figura 4. *La rotación Norfolk con un sistema de rotación de cuatro años desarrollado durante los siglos XVI y XVII que incluyo la introducción de pasturas artificiales con especies leguminosas en una rotación de cuatro años que incrementó los rendimientos de los cultivos debido a la fijación biológica de nitrógeno.*

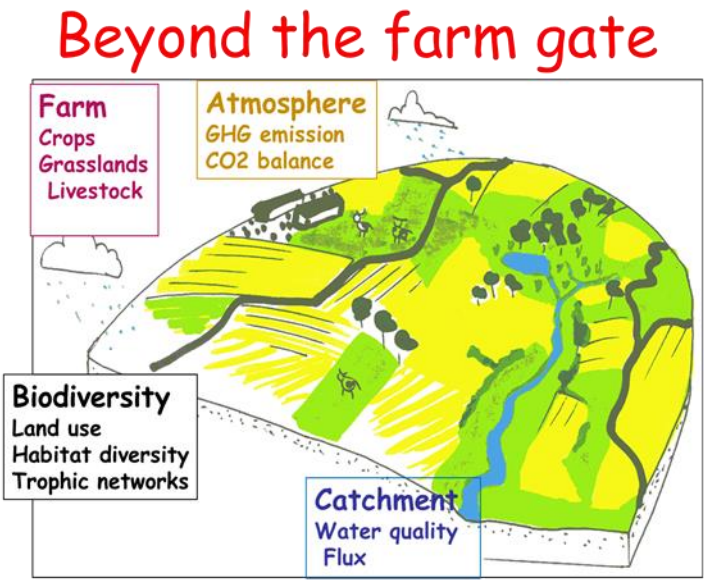

Figure 5. Livestock and arable lands integration at landscape scale. This approach consider that the re-coupling of livestock with agriculture must be done beyond the farm gate considering a stocking density under a local threshold that maintain positive greenhouse gas (GHG) balance.
Figura 5. *Integración de la agricultura y la ganadería a escala de paisaje. Esta aproximación considera que la integración de la agricultura con la ganadería debe hacerse por fuera de la tranquera del establecimiento, considerando una carga animal a nivel local por debajo de un umbral que mantenga positivo el balance de gases de efecto invernadero (GEI).*

contribute to the diversification of rotations that allows a better control of weeds and diseases and then a reduction of pesticides use, and an enhancement in biodiversity at landscape level. Gilles Billen and colleagues have simulated the food production and food consumption of the Paris region in France at the scale of the watershed of the river Seine with two objectives: reducing GHG emissions and N flows in hydro-system for an attenuation of the river and costal eutrophication (Billen *et al*. 2013; Garnier *et al*. 2016). Simulations have been made on 3 scenarios: i) the current (2006) situation; ii) the integrated Crop-Livestock-System (CLS); and iii) the CLS + a reduction of 30% of animal sourced products in the diet (CLS +30%). From "Current" to "CLS" with the increases in livestock from 18 live unit/km^2 until 48 live unit/km^2 there is an important reduction in N emissions into hydrosphere from 33 mg N/l to 23 mg N/l. When a more vegetarian diet is applied, CLS+30%, a more important reduction of N emission can be achieved. This result is obtained mainly by the reduction in monogastric livestock production and not by reduction in herbivore livestock whose role for N transfer is very crucial. This purely biogeochemical approach does not take into account several limitations: reluctance of farmers to change their practices according to their economic and social constraints, and resistance of consumers to change their eating habits according to cultural and commercial advertising influences. A more global socio-political approach is necessary for promoting this integrated crop-livestock at large scale enough for a more sustainable agriculture and food production. Domestic herbivores have to be considered as a source of solutions and not excluded as a source of problems.

Conclusions

Sustainable food production requires a high renewal fluxes of nutrients, N, P, K, S in soils to compensate for their exportation. To maintain soil fertility, intensive agriculture production systems have relied on the massive use of external fertilizers that inevitably lead to unwarrantable environmental emissions (GHG emissions and N flow in hydrosphere). Therefore, herbivore livestock production must be re-integrated locally with arable cropping to provide a more sustainable agro-ecosystem. The threshold livestock stocking capacity must be determined according to local conditions—soil/climate and types of arable cropping systems—which requires ad hoc experimental and modeling studies. Moreover, at a global level it is necessary to promote a decrease of proportion of animal-based food consumption in diet in some rich regions of the world (e.g. Europe and North America) associated with an increase in regions where populations are affected by malnutrition. Nevertheless, the integrated livestock with arable crop systems, although very necessary from an ecological and environmental point of view, can be not fully compatible with socio-economic and political constraints that favor a high specialization of food production and distribution systems, in addition to activism against animal production. Thus, without a clear identification of these locking and of the alternative socioeconomic systems that will have to be promoted, this necessity for integrated herbivore–cropping systems would remain only a sincere hope.

References

Billen G, Garnier J, Lassaletta L (2013) The nitrogen cascade from agricultural soils to the sea: modelling N transfers at regional watershed and global scales. *Philosophical Transactions of the Royal Society B: Biological Sciences* **368**, 20130123.

Briat JF, Gojon A, Rouached H, Plassard C, Lemaire G (2020) Reappraisal of the Concept of Nutrient Availability for Plants in Soils at the Light of the Recent Molecular Physiology Advances. *European Journal of Agronomy* **116**, 126069

Garnier J, Anglade J, Benoit M, Billen G, Puech T, Ramarson A, Passy P, Silvestre M, Lassaletta L, Trommenschlager JM, *et al*. (2016) Reconnecting crop and cattle farming to reduce nitrogen losses in river water of an intensive agricultural catchment (Seine Basin, France). *Environmental Science & Policy* **63**, 76-90.

Lemaire G, Recous S, Mary B (2004) Managing residues and nutrients of intensive cropping systems. New understanding for efficient recovery by crops. In 'Proceedings of the 4th International Crop Science Congress´ Brisbane, Australia. 26 September- 2-October 2004. (Invited paper)

Lemaire G, Franzluebbers A, Carvalho PCdF, Dedieu B (2014) Integrated Crop-Livestock Systems: Strategies to achieve synergy between agricultural production and environmental quality. *Agriculture, Ecosystems & Environment* **190**, 4-8.

Lemaire G, Gastal F, Franzluebbers AJ, Chabbi A (2015) Grassland-Cropping Rotations: An Avenue for Agricultural Diversification to Reconcile High Production with Environmental Quality. *Environmental Management* **56**, 1065-1077

Lemaire G, Garnier J, da Silveira Pontes L, de Facio Carvalho PC, Billen G, Simeoni-Assman T (2023) Domestic herbivores, the crucial trophic level for sustainable agriculture: Avenues for reconnecting livestock to cropping systems. *MDPI Agronomy* **13**, 982.

Lintemani MG (2020) Long Fallows Allow Soil Regeneration in Slash-And-Burn Agriculture. *Journal of the Science of Food and Agriculture* **100**, 1142-1154.

Lodge GM, King KL, Harden S (2006) Effects of pasture treatments on detached pasture litter mass, quality, litter loss, decomposition rates, and residence time in northern New South Wales. *Australian Journal of Agricultural Research* **57**, 1073-1085.

Mazoyer M, Roudart L (1997) Histoire des agricultures du monde. Du Néolithique à La Crise Contemporaine. Seuil, d., Ed.; Média Diffusion: Paris, France.

Naidua DGT, Roy S, Bagchi S (2022) Loss of grazing by large mammalian herbivores can destabilize the soil carbon pool. *Proceedings of the National Academy of Sciences **119**, e2211317119.*

Peoples MB, Hauggaard-Nielsen H, Huguenin-Elie O, Steen-Jensen E, Justes E, Williams M (2019) The contribution of legumes to reducing the environmental risk of agriculture production. In 'Agroecosystem Diversity: Reconciling Contemporary Agriculture and Environmental Quality' (Eds. Lemaire G, de Facio Carvalho PC, Kronberg S, Recous S) pp. 122-144. Academic Press: London, UK.

Riches N (1967) 'The Agricultural Revolution in Norfolk' 2nd ed.; Frank Cass & Company Ltd.: London, UK.

Sanaullah A, Chabbi A, Lemaire G, Charrier X, Rumpel C (2010) How Does Plant Leaf Senescence of Grassland Species Influence decomposition Kinetics and Litter Compounds Dynamics? *Nutrient Cycling in Agroecosystems* **88**, 159-171.

Schmitz ODJ, Wilmers CC, Leroux SJ, Doughty CE, Atwood TB, Galetti M, Davies AB, Goetz SJ (2018) Animals and the zoogeochemistry of the carbon cycle. *Science* **362**, 1127-1138.

Soussana JF, Lemaire G (2014) Coupling carbon and nitrogen cycles for environmentally sustainable intensification of grasslands and crop-livestock systems. *Agriculture, Ecosystem & Environment* **190**, 9-17.

Appendix

Questions of the audience

Question 1: Regarding the coupling and uncoupling of nutrients (pastures-herbivores-soil-agriculture). In Argentina, the direct sowing system represents more than 90% of the surface sown with crops and is based on non-removal of the soil, permanent soil coverage and balanced grass-legume rotations that optimize the use of water, nutrients and promote a less use of phytosanitary products. This system is currently very efficient, simple, extensively outsourced and practically does not rotate with pastures. Furthermore, agriculture is practiced on the most productive soils while livestock is pushed to inferior quality soils or in industrial-scale establishments, so that both systems are separate even within the same field. In this scenario, what could be the additional contributions of mixed grass-legume pastures, grazed by ruminants that justify the replacement of a simple system to a more complex one (agriculture-livestock rotation), with greater capital investment and requirements (for now) of qualified work?

Lemaire G. response: Yes, I agree that the direct sowing system with the "soil conservation" concept is already a relatively sustainable system as it allows a relatively high degree of re-coupling C-N-P…. and the use of legumes. Nevertheless, the problem is that if such a system is mainly composed of two main crops such as soybean and maize that are used for feeding animals elsewhere (in other regions or even in Europe…!!!) in how to maintain long term soil fertility? How to compensate N, P, K…. exports? Moreover, how to organize the N, P, K… recycling from "feed-lot" livestock systems if these systems are not spatially very close from and well associated with the arable grain production system? This question demonstrates very clearly that, as indicated in the oral presentation, the sustainability of agriculture system must be analyzed at whole scale from production system until feeding system. If the sustainability analysis is only restricted to a part of the whole system, there is a high risk to transfer environmental risks from one component of the whole system to another one. So, the main question is whether the "direct sowing" arable cropping system is able to maintain long-term soil fertility without any external N, P, K… fertilizer application? In other words are N, P, K… exports by grain are compensated by N, P, K…internal recycling or not?

Question 2: Animal stoking threshold: Many studies indicate that animal stocking largely regulates the productivity of the system. Therefore, it would seem that the animal stocking threshold would be a consequence of the market demand for products and that this will be the driving force to which the role of herbivores in the production system will have to adapt. Therefore, at the farm level, in closed agricultural-livestock systems, the limit would be given by the amount of food that can be produced. In Argentina, this in turn will depend on the amount of P that we should import. The question then is, whether you think there is room at the production system level to increase the amount of N of symbiotic origin? the N that is used in harvest crops and the ability to acquire N via symbiotic fixation by legumes. The latter is the only one that can be handled.

Lemaire G. response: The animal stocking threshold is first determined at local (territory) level as the equilibrium between decoupling C-N-P…. by animals and the C-N-P…. recoupling by vegetation. It is relatively simple to determine this threshold in grazing system at farm level, but a little bit more complex for more integrated crop-livestock systems at local level by taking into account beyond farm gate. Yes, this threshold is only based on environmental target, and it must be confronted with socio-economic target and constraints for farmer decisions. It is clear that increasing N_2 symbiotic fixation is the only way for compensate ultimate N export by human food consumption, as the only other issue would be a full recycling of human excreta, that is difficult to realize owing the fact that these excreta are concentrated in town very far from cropping areas, and that human excreta are now mixed with other domestic wastes containing a wide range of pollutants. The great chance of Argentina is that soybean production is obtained by N_2-symbiotic fixation. However, as the grain N is largely exported for feeding livestock elsewhere, the main problem is then how these livestock systems are reconnected with cropping systems. The problem is more accurate for cereal production systems (maize and wheat). Are the rotations of these crops with soybean sufficient for providing N? Not sure because most of N_2 fixed by soybean is exported by grains and low N remains in soils…? So, the introduction of forage crop such as alfalfa would allow, not only recycle N (and P) through forage and livestock feeding… but also to provide large N residues in soil for wheat and/or maize production. However, this integrated system requires herbivore livestock production system, associated with cereal production system, either within the same farm unit of at least in close interaction between neighborhood farms.

Question 3: On an industrial scale where the different actors in the production chain are separated (farmers that breed, rebreed, complete the cycle, dairy farms, food suppliers) a business based on the recovery and distribution of manure, slurry and bedding should emerge strongly (at least in Argentina), for intensive fattening systems like cattle, pigs and poultry. The question is: what is the experience from other countries? Is this activity regulated or is it a business that is driven by supply and demand?

Lemaire G. response: Yes you are right. The problem today is not to go back with the traditional farm integrating cereal crops with some cattle, poultry and pork within an autarkic system, but to conceive integrated system by association of different specialized production unit within a more coherent whole production system. So, it is clear that local or regional organization for exchanging forages and straw resources, and for recycling manure, slurry and bedding… among different production unit is a key questions. This whole system organization could also benefit from more technical progress associated with energy production through methanization, etc… At our knowledge, scientific literature is very poor in reporting and analyzing concrete experience of such integrated systems at territory level, except in reporting modelling exercises. The problems are not mainly the technical or agronomical aspects of these systems, but the socio-economic constraints for their financial investments, their governance and their management.