THE ROLE OF LIVESTOCK IN MAINTAINING SOIL ORGANIC MATTER

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1. Introduction

The realization that soils are a sink for atmospheric carbon has generated considerable interest in the scientific community and prompted research aimed at finding ways to store more C in the soils. Soil C sequestration is a delicate balance between the amount of plant residues (roots and surface litter) containing organic C that are added to the soil and the amount of CO_2 lost during the decomposition process [1]. The relative significance of livestock for soil organic C is not well recognized, despite the fact that much of our temperate cropland is devoted to raising food for animals.

Protein-rich grain is an important component of livestock diets. In 2006-07, about 55% of the soybeans produced in the United States were transformed to soybean meal and fed to livestock [2]. During the same period, 46% of the maize produced in the United States was used to feed domestic livestock and 63% of the maize produced world-wide was consumed by animals [3]. The discrepancy between these values is attributed to demand for maize grain as a feedstock for bioethanol production in the United States [4]. In the past fifty years, producers have relied upon intensive cultivation and agrochemical inputs (inorganic fertilizers, pesticides) to achieve maximum grain yields. The adoption of conservation tillage practices like chisel ploughing and direct seeding, especially in semi-arid regions, recaptures some of the soil organic C that was lost when these soils were plowed [5]. Animal manure application in these systems reduces the requirement for inorganic fertilizers and contains carbon as undigested feed material considered to be a form of C recycling rather than a C input in the soil organic C budget.

Perennial forages are just as important in the livestock diet, especially for ruminants capable of digesting fibrous ligno-cellulosic plant materials. About 41% of the agricultural land in the United States and 23% of cropland in Canada [6, 7] is planted with forages that are harvested as hay or left as pasture for livestock grazing. Manure application to hayfields and feces deposited by grazing animals provide essential plant nutrients and recycle some of the C captured by plants. The vegetative cover provided by forages maximizes photosynthesis and CO_2 fixation, permits biological N_2 fixation when legumes are present, conserves soil water and reduces soil loss due to erosion. Animal-forage systems are also characterised by lower capital investments and greater enterprise flexibility than annual crop production systems.

The goal of sustainable livestock farming is to select crops that meet the dietary requirements of animals and maximize output [8]. This implies that on-farm crop production will provide the right amount of nutrient-rich feedstuffs for efficient animal growth with few off-farm inputs (energy, agrochemicals). A major challenge to developing such efficient livestock farming systems is the variation in animal production practices. These range from extensive grazing systems such as for sheep and beef cattle, to intensive management systems such as for meat, milk and eggs. The innate behaviour and dietary preferences of each animal species and changes in nutritional requirements during the animal's lifespan cannot be overlooked. Crop biomass and quality is not constant due to year-to-year variation in temperature and rainfall.

Since it is not possible to make broad generalizations about the role of livestock in maintaining soil organic C, this paper will focus on two case studies from temperate agro-ecosystems in Quebec, Canada. The first case study evaluates the soil organic C balance in crop rotations that are used on farms with 1) ruminants, specifically dairy cattle and 2) non-ruminants, namely pigs. The second case study examines the soil organic C balance in integrated forestry-livestock systems.

2. Case 1: soil organic matter balance as influenced by crop rotation and livestock

Livestock have an important role to play in maintaining the organic matter level of agricultural land, because not only do they return organic matter to the soil in terms of manure, but they consume crops which can increase the soil organic matter content. Among all types of domestic livestock, cattle allow for an even more flexible crop rotation because of the forage crops consumed.

The objective of this case study was to conduct a simple carbon balance for two farms, one with ruminants, namely dairy cows and another with non ruminant or monogastric animals, namely grower hogs. The investigation will nevertheless assume that soil erosion is minimized, crop yields are optimized with good management practices and crop residues are incorporated into the soil before growing the next crop.

2.1. Description of hypothetical farms

For the dairy farm, it was assumed that the feed required by one (1) 700 kg cow could be produced on 1.18 ha (0.36ha of corn silage, 0.20 ha of alfalfa hay, 0.12 ha of grass hay, 0.24 ha of grain corn and 0.26 ha of soybean). For the grower hog farm, it was assumed that 25 grower hogs could be finished from 20 to 110 kg from the crops of 1.0 ha (0.5 ha of grain corn and 0.5 ha of soybean). It was also assumed that the cow excreted 30% of all dry matter ingested while the hog excreted only 10%, based on normal daily manure production [9]. The analysis was repeated with the same farms where cereals replaced 33% of the grain corn in the ration. This implied the growing of 0.18 ha of cereals and 0.16 ha of grain corn on the dairy farm for a total of 1.28 ha of grains compared to 1.18 ha of grain corn, for one 700 kg dairy cow. For the hog farm, 0.4 ha of cereals were grown with 0.33 ha of grain corn and 0.5ha of soybeans for a total of 1.23 ha compared to 1.0 ha for grain corn and soybeans only, for 25 grower hogs.

2.2. Crop impact on soil C change

The impact of the crop on the change in soil carbon and nitrogen was studied over long periods by a number of researchers (Table 1). Over all, these studies suggest that grain corn and corn silage add and remove respectively, 2.0 and 0.5 tons of soil C /ha/yr. Cereals and soybeans generally reduce soil carbon at a rate of 2.0 and 1.0 t/ha/year, respectively. Alfalfa was found to increase the soil carbon at a rate of 2 t /ha/yr. While limited data was found on grass hay, it was assumed that this crop can fix 1 t of soil carbon /ha/yr.

During a study conducted in Nebraska and for crop residues incorporated into the ground, only 33% of corn stalks degrade after 6 months, whereas the degradation of straw reaches 66% over the same period. For alfalfa, 75% of its residues degraded whether at the soil surface or ploughed under while for wheat straw, 45-50% degraded when left at the soil surface and 80% degraded when ploughed under, after 78 days at 28°C [9]. This explains why a cereal crop leaves a soil organic matter deficit while a grain corn crop increases the organic matter of a soil, even when incorporating the residues to the soil.

2.3. Results

Accordingly, Table 2 summarizes the average change in soil organic matter for the dairy and hog farm, both for the corn/soybean/alfalfa/grass rotation with and without cereal, and for the hog farm with the corn/soybean rotation again with and without cereals. The soil organic C changes were compared to a control farm with a corn/soybean rotation with and without cereals, but with no livestock.

Table 1.- Rate of crop residue application and effect on soil organic matter and C.

Authors	Study period (yrs) and crop	Location	Climate	Organic residue application (ton/ha/yr)
[10] McCalla and Dubley (1943)	6 months	Nebraska, USA	Continental	33% corn stalk degradation 66% wheat straw degradation
[11] Hobbs and Brown (1965)	40 years Small grains	Kansas, USA	Continental	Constant soil organic matter with 20 tons/ha/yr of manure.
[12] Larson *et al.* (1972)	12 years corn	Iowa, USA	Continental	Constant soil organic matter with 6 tons/ha/yr of plant residue.
[13] Anderson and Peterson (1973)	60 years corn	Nebraska, USA	Continental	Increased soil N with 27 tons/ha/yr of manure.
[14] Black (1973)	7 years Wheat fallow	Montana USA	Continental	Constant soil C and N with 3.6t/ha/yr straw.
[15] Jenkinson and Johnson (1977)	123 years barley	Rothamsted, England	Humid temperate	Increased soil N with 35 tons/yr of manure.
[16] Rasmussen *et al.* (1980)	45 years wheat-fallow	Northwest Pacific (US)	Semi arid	Stable soil C and N when leaving the straw and adding 22.4 tons/ha/yr of manure.
[17] Angers (1992)	5 years Corn silage alfalfa	Quebec City Canada	Humid Temperate	Corn silage lost 0.5 t C/year/ha Alfalfa added 2.5 t C/year/ha & reached a maximum after 3 years.
[18] Anthoni *et al.* (2004)	1 year Winter wheat	Thuringia, Germany	Temperate	Loss of 2.4 t/ha/yr of C despite addition of 3 t/ha of solid manure.
[19] Baker and Griffis (2005)	2 year Corn/soybean	Minnesota, USA	Continental	Gain of 900kg C/ha/yr.
[20] Hollinger *et al.* (2005)	5 years Corn/soybean	Illinois USA	Continental	Gain of 1.84 t/ha/yr of C with corn and loss of 0.94 t/ha/yr of C with soybeans.
[21] Masri and Ryan (2006)	12 years Cereals/medic/ vetch	Syria	Semi arid Mediterranean	Irrigated medic and vetch increased soil organic matter by 3.0 tons/ha/yr.
[22] Su (2007)	1 year Alfalfa	China	arid	Alfalfa added 0.57 t/ha/year of C under irrigation.

The results illustrated in Table 2 suggest that the dairy farm offers the best combination to increase soil organic matter, which after a number of years [17], reaches a maximum stabilized level. The inclusion of cereals in the rotations reduces the rate of C accumulation in the soil and increases the cropping area required per dairy cow. As for the hog farm, a net amount of soil C can be accumulated on a yearly basis, but at a lower rate compared to the dairy farm, because of a lower manure C return, the ration being more extensively digested. The control farm with no livestock and selling all their crop, can still maintain its soil organic C even with cereals but needs to grow good yields to maximize the mass of crop residues to incorporate into the soil and to protect its soils against erosion.

Table 2.- Soil accumulation of C for various crops

Farm	Manure (t C/ha/yr)	Crop residues (t C /ha/yr)	Net change in soil C (t C/ha/yr)
Dairy without cereals	1.20	0.5	1.7
Dairy with cereals	1.20	0.03	1.23
Hog without cereals	0.44	0.13	0.57
Hog with cereals	0.44	0.5	0.94
Farm with corn & soybean without cereals	0.00	0.5	0.50
Farm with corn, soybeans and cereals	0.00	0.13	0.13

2.4. Conclusion

The present analysis suggests that modern farms can maintain their soil organic matter and even increase it, with good management practices. These results coincide with the trend observed in Canada where soil organic matter has been increasing at a rate of 4.4 tons/ha/yr since 1991, as reported by Agriculture and Agri-Food Canada [23]. Livestock contribute to increasing the soil organic matter by returning some of the carbon to the soil. Therefore, cash crop farms benefit when they receiving manures from farms with a shortage of land for disposal.

3. Case 2: Soil organic C balance in integrated forestry-livestock systems

Growing trees and livestock together can be a complementary and sustainable production enterprise. Silvopasture is a type of agroforestry system where an understory forage crop is planted between widely spaced trees and livestock are permitted to graze upon the forage. The trees are regularly trimmed to yield straight, high-value logs and to allow sufficient light infiltration for forage production. At the same time, trees provide shade and shelter for the livestock, thus improving animal welfare. Some forages have a lower fiber content when grown in a partially shaded environment and are thus more digestible [24]. Plantations of conifers grown as Christmas trees can be adapted into silvopasture systems, and some nut and fruit orchards may also be grazed.

The difference between silvopasture and rangeland or woodlot grazing is that the agroforestry system is more intensively managed. Generally, silvopasture systems are established on an existing pasture that has been limed, manured and seeded with the desired forage. Another way to establish a silvopasture system is to thin trees from a timber stand and plant an improved forage species between the remaining trees. Cattle, sheep, goats, horses, poultry and game animals can be selected as the grazing animal, depending on the type and age of trees and the forage grown. Sheep, goats and deer tend to browse on trees while larger cattle and elk are likely to step on young trees. Animal training, careful selection of grazing periods, multi-pasture rotational grazing and barriers can minimize tree damage, overgrazing and soil compaction [25]. Compared to intensive livestock production in feedlots, silvopastural systems are less likely to raise concerns related to animal welfare, noise, dust, odors and water quality.

The goal of silvopasture is to provide short-term cash flow by supporting livestock production and high-value tree products that will be harvested in the medium- to long-term. Potential tree products include: sawlogs, veneer logs, pulpwood, firewood, pine straw, nuts, fruit, ornamental greenery, maple syrup, mushrooms and organic mulch. Silvopasture systems generally have greater wildlife diversity due to the presence of trees and less soil erosion because the soil surface is protected by the forage.

3.1. Soil organic C in silvopasture systems

The net C storage is expected to be greater in a silvopasture system than other types of grazing systems, mainly due to the C stored in trees. The soil organic C pool may be maintained or increase as a consequence of the C inputs from trees (leaf litterfall, dead branches and roots) and forages (ungrazed leaves and stems, dead roots) that are transformed into soil organic C by decomposer organisms. Some of the plant C consumed by grazing animals is retained in the system (e.g., in dung patches) and the rest is converted into animal biomass or lost via animal respiration and metabolic processes. Key differences between the C cycle in silvopasture and traditional pasture systems are illustrated in Fig. 1.

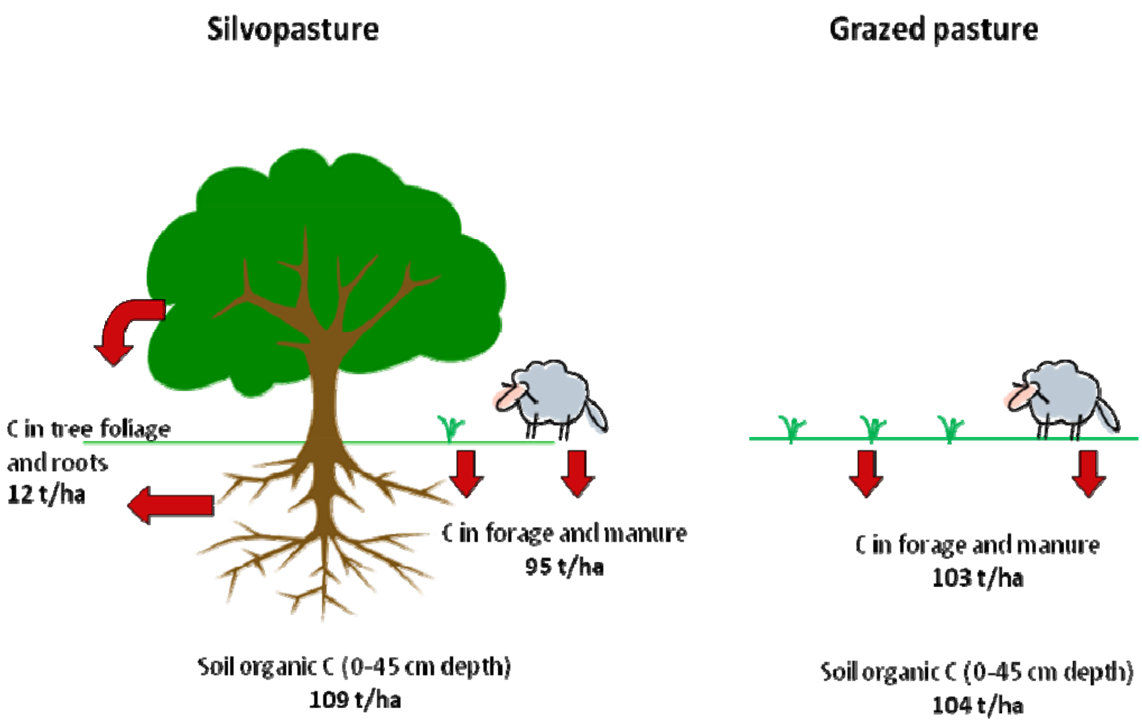

Figure 1.- Carbon storage in a silvopasture system with 11 year old Douglas-fir and perennial ryegrass/clover understory, compared to a grazed pasture with perennial ryegrass/clover vegetation. The silvopasture system accumulated 520 kg C ha^{-1} y^{-1} more than the grazed pasture, due to the C stored in tree foliage, bark, branches, stem and roots (adapted from [26])

Silvopasture systems are common in temperate regions that seldom have frost or snow during winter months. For instance, cattle can graze in pine monocultures throughout the year in the southeastern U.S. (Florida, Louisiana, Mississipi), and sheep grazing in hybrid poplar plantations has been successful in Oregon, in the U.S. northwest [25]. Silvopasture has not been demonstrated successfully in Canada because grazing activities are limited to the spring and summer months. As an example, the province of Quebec has a frost-free period of 160 days and receives about 225 cm of snowfall per year. Despite the absence of silvopasture in the province, there may be other ways to integrate forestry and livestock production.

3.2. Soil organic C in short-rotation hybrid poplar plantations receiving manure

Quebec possesses a temperate mixed-deciduous forest in the southern part of the province and an extensive boreal forest dominated by conifers (fir, spruce, pine) and aspens (*Populus* spp.). In the past decade, more than 3000 hectares of short rotation forests were planted with hybrid poplar, a relative of the native aspens that grows more quickly [27]. Within 10-12 years of planting, hybrid poplars can be harvested and transformed into paper, wood pellets and veneer/lumber. Since plantations are generally established in forest clearcuts or on marginal agricultural land with low inherent soil fertility, it is necessary to add a balanced fertilizer source to achieve optimal hybrid poplar growth [28].

In regions where there is a surplus of animal manure and other wastes, there is an opportunity to recycle N, P, K and other nutrients by applying manure to hybrid poplars. When liquid pig slurry was applied at a rate of 140 kg N ha^{-1} y^{-1}, the tree diameter doubled and trees grew 1.5 times taller than unfertilized hybrid poplar [29]. We applied liquid pig slurry to the soil surface, around the base of the tree, and did not incorporate the slurry to avoid damaging tree roots. This probably contributed to some loss of N fertilizer efficiency, since pig slurry is susceptible to lose nitrogen via NH_3 volatilization when it is left at the soil surface. In fact, the best experimental fertilizer treatment was a mixture of pig slurry and composted papermill biosolids (C/N ratio = 16). The mixed fertilizer treatment produced trees with 3-fold larger diameter that were twice as tall as the unfertilized trees [29]. It seems likely that the papermill biosolids absorbed some of the NH_4^+ in the pig slurry and thus reduced the N loss from volatilization, based on soil mineral N results [29].

Results from this study [29] revealed that the rapid growth of hybrid poplars led to 0.3 to 2.3 Mg C ha^{-1} y^{-1} sequestered in above-ground biomass, an estimated 0.1 to 0.9 Mg C ha^{-1} y^{-1} in roots, and about 0.9 Mg C ha^{-1} y^{-1} in unmowed vegetation that grew between the tree rows. There was as much as 4 times more C sequestration in the short-rotation forest than in a nearby unimproved hayfield. To achieve a 1 tonne CO_2-C emission reduction on this farm would require several years and more land, if trees were unfertilized, but could be accomplished on less than 1 ha within one year, if trees were fertilized. Tree and crop growth on this farm are constrained by several factors: 1) low soil fertility levels, 2) rocky soil conditions, and 3) poor natural drainage.

3.3. Results

For the farm described above, the carbon sequestration potential for 1 ha of farmland was considered for three possible land uses: maize production, hay production and a tree-hay intercrop with hybrid poplar. We assumed that the producer would apply liquid pig slurry to all crops growing on this low fertility site. Table 3 gives the expected annual biomass production (above-ground and below-ground biomass) for each crop. We assumed that corn grain would be removed at harvest, but stems and roots would be left on the land and contribute to carbon sequestration. The hayfield (mixed grass-legume forage) would be harvested twice per season, which is appropriate for this region. Carbon sequestration in the hayfield is due to the C input from roots, which are left in the field. The hybrid poplars would be planted in widely-spaced rows, permitting the producer to harvest a hay crop from between the tree rows; leaving sufficient space between the rows (about 9 meters) also allows the producer to apply liquid pig slurry to the trees and hay growing between the tree rows with a conventional tanker truck. Carbon sequestration in the hybrid poplar-hay intercrop would be a result of CO_2 fixation and storage in the tree trunk, branches, leaves and roots, as well as the C input from roots in the hayfield.

More carbon sequestration is expected in the tree-hay intercrop than the other land uses. A simple economic analysis was undertaken to compare the production costs and revenues expected from each land use based on the marketable yield of each crop (Table 3).

Table 3.- Carbon sequestration based on crop production system

Parameter	Corn	Hay	Tree-hay intercrop (400 trees/ha)
Above ground biomass (t/ha/y)	16 - 20	5 – 8	5 - 8 (hay) plus 2 - 9 (poplar)
Below ground biomass (t/ha/y)	3 - 4	10 – 16	10 – 18
Harvest index (above ground biomass)	55%	80%	Annual hay harvest Trees harvested after 15 years
C sequestration (t/ha/y)	10 - 11	11 – 18	12 – 30
CO_2 sequestration (t/ha/y)	37 - 40	40 – 66	44 – 110
Production costs ($/ha/y)	$850[a]	$500[a]	$710[b]
Annual revenue ($/t harvested)	$1056 - $1320[c]	$572 - $915[d]	$572 - $915[d]
Tree revenue ($/harvest) (after 15 years)	$0	$0	$3125 - $14,062[e]
Net gain ($/ha/y)[f]	$206 to $470	$72 to $415	$70 to $1142

[a]Production costs for corn and hay were estimated from another study and include fertilizer, seed and machinery costs.
[b]Production costs include $500 per year for the hayfield plus installation and maintenance of the hybrid poplars ($210 per year).
[c]Corn grain sells for $150/t and costs $30/t to dry (net revenue = $120/t).
[d]Hay sells for $143/t.
[e]After 15 years, trees are harvested and sold. Hybrid poplar has a value of $\$40/m^3$ and the density of poplar wood is $384\ kg/m^3$.
[f]Net annual gain based on anticipated one-time revenue from tree harvest (value was not discounted for future benefits and costs).

3.4. Conclusion

In Quebec, Canada, the cold climate limits our ability to establish silvopasture systems for grazing animals. However, an integrated forestry-livestock system can be envisioned that recycles nutrients from animal manure and supports the production of mixed grass-legume forage. Since fast-growing hybrid poplars are responsive to organic fertilizers such as liquid pig slurry, they could be planted in widely spaced rows, leaving room for the producer to spread liquid pig slurry and harvest a hay crop each year until the trees are large enough to be harvested (about 15 years). A simple economic assessment suggests that a tree-hay intercrop could be a sustainable and profitable option, and it would also promote carbon sequestration. Integrated forestry-livestock systems could be a good option for farms with marginal lands that are not suited for annual field crop production (e.g., low fertility, rocky, poor drainage), especially if these farms are located in regions with a surplus of animal manure.

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