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48 Abstract

By reconstructing the nutrient balance of a Catalan village circa 1861–65 we examine the sustainability of organic agricultural systems in the northwest Mediterranean bioregion prior to the green revolution and the question of whether the nutrients extracted from the soil were replenished. With a population density of 59 inhabitants per square km, similar to other northern European rural areas at that time, and a lower livestock density per cropland unit, this village experienced a manure shortage. The gap was filled by other labour-intensive ways of transferring nutrients from uncultivated areas into the cropland. Key elements in this agricultural system were vineyards because they have few nutrient requirements, and woodland and scrublands as sources of relevant amounts of nutrients collected in several ways.

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Fertilizing Methods and Nutrient Balance at the End of Traditional Organic Agriculture in the Mediterranean Bioregion: Catalonia (Spain) in the 1860s

Enric Tello · Ramon Garrabou · Xavier Cussó · José Ramón Olarieta · Elena Galán

Abstract By reconstructing the nutrient balance of a Catalan village circa 1861–65 we examine the sustainability of organic agricultural systems in the northwest Mediterranean bioregion prior to the green revolution and the question of whether the nutrients extracted from the soil were replenished. With a population density of 59 inhabitants per square km, similar to other northern European rural areas at that time, and a lower livestock density per cropland unit, this village experienced a manure shortage. The gap was filled by other labour-intensive ways of transferring nutrients from uncultivated areas into the cropland. Key elements in this agricultural system were vineyards because they have few nutrient requirements, and woodland and scrublands as sources of relevant amounts of nutrients collected in several ways.

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Keywords Fertilizing methods · Nutrient balance · Past organic agricultural systems · Agricultural sustainability · Catalonia

Introduction

This work is part of a larger project that seeks to clarify the reasons for the abandonment of traditional organic management in Mediterranean agriculture. We wished to determine how sustainable these systems were with respect to nutrient replenishment into the soil and whether our results could contribute to improve contemporary organic farming practices in a region such as Catalonia (Spain). In an earlier study in which we reconstructed the energy balance in the same area for 1860 we found a positive return on energy investment of around 1.41 or 1.67 depending on the boundaries of the area under study (Cussó *et al*. 2006a, b; Tello *et al*. 2006, 2008). In this study we complete this socio-metabolic investigation by estimating the nutrient balance and assessing the maintenance of soil fertility.

Agrological and Socioeconomic Features of the Area Under Study

The municipality of Sentmenat is located in the Catalan Vallès county, some 35 km northeast of Barcelona, with a total area of 2,750 ha, of which 59 % were cultivated in 1861 (Fig. 1). The village was settled during the tenth century AD in a small plain located in a tectonic basin between Catalonia's littoral and pre-littoral mountain ranges. It has an average slope of 9.7 % and an annual rainfall of 643 mm. The heliothermic Huglin index of 2,168 is good enough for winegrowing—it has a minimum

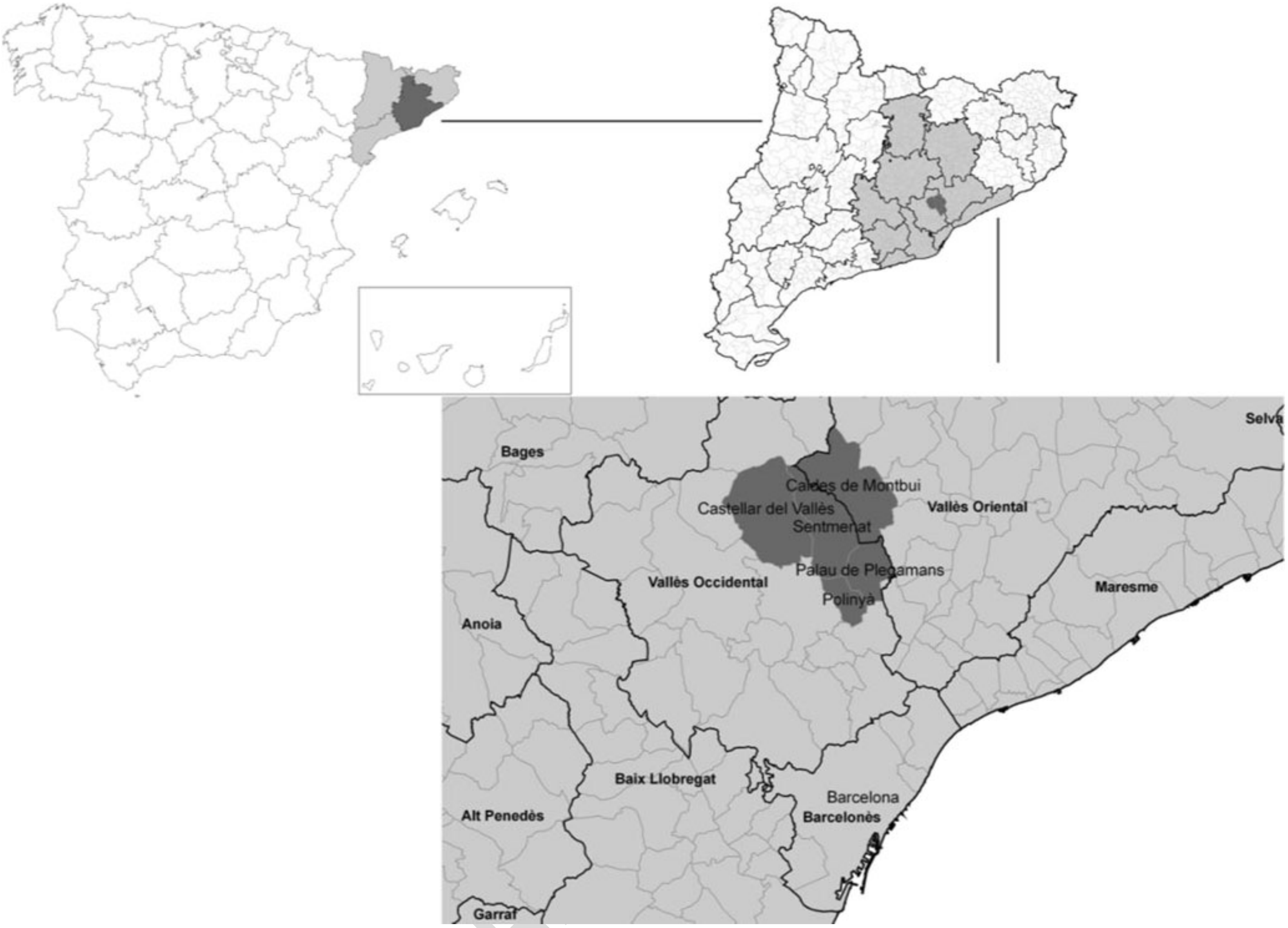

Fig. 1 Location of the study area: the municipality of Sentmenat and neighbouring townships in the province of Barcelona and Catalonia (Spain)

requirement of 1,500 and reaches a maximum municipal score of 2,778 in Catalonia (Badia-Miró *et al.* 2010). Rainfall and temperature allow for reasonable yields in cereal crops, at least in flatlands with a higher water retention capacity.

In 1860, 354 families and 1,713 people were registered in Sentmenat, a population density of 59 inhabitants per square km., allowing 1.7 ha (including the municipal area) or 1.4 of cropland per inhabitant. Seventy per cent of labour capacity was devoted to agriculture and 21 % to industrial activities. As many as 208 out of the 241 agricultural families were "peasants" or "landowners", while 21 worked as ploughmen tenants and 12 as daily labourers. Moreover, 187 out of the 208 landowners were so-called autonomous peasants who primarily worked their land with family labour, only hiring labour in peak seasons. Many landless labourers had kinship ties with peasant owners (Garrabou *et al*. 2010). Despite being far from egalitarian, this rural society enjoyed a broad degree of access to the land and can be basically seen as a peasant community (Netting 1993; Ploeg 2008).

The Gini coefficient of inequality in owned land distribution was 0.58 in 1859, or 0.51 if only cropland is taken into account. In 1735 this had been 0.77 and 0.67 respectively, and rose again to 0.76 or 0.70 in 1918 following the Phylloxera plague that killed all the old vines in the 1880s (Badia-Miró *et al*. 2010). The reduction in landownership inequality between 1735 and 1859 was driven by vineyard specialization (Garrabou *et al*. 2009). Many landowners and some peasant owners leased poor sloping soils previously covered by scrub and pastureland to an increasing number of non-heir relatives or landless immigrants who built terraces and planted vineyards (Olarieta *et al*. 2008). The use of the Catalan sharecropping contract called *rabassa morta,* which stayed in force until the death of the vines planted, was widespread, and led to lower levels of inequality recorded, reflecting a reduction in land-access and income inequality rather than in landownership distribution as such (Tello and Badia-Miró 2011).

Land-uses, Livestock Densities and Manure

Vineyard specialization developed during the nineteenth century whereby some land, usually the best, was devoted to grain, legume and vegetable polyculture. In 1861, the extreme scarcity of natural pastures (12.4 of the total) seriously constrained livestock production. The majority of cropland consisted of vineyards or olive groves that extracted less nitrogen while pruning supplied a useful by-product contributing nutrients to the soil. At the same time, thanks to the increase of arboriculture, the ratio of uncultivated area to land sown with herbaceous crops could be maintained as high as 2.4, and the ratio of permanent land-covers to annually sown land was as high as 5.1 (Table 1). All these features were typical of the Mediterranean-type of "intensive organic agriculture" (Sieferle 2001; Wrigley 2004) that went into a steep decline during the economic globalization at the end of the nineteenth century leading to World War One (Tello *et al*. 2006, 2008; Marull *et al*. 2008).

A crucial component of this form of pre-industrial organic agriculture was the number of cattle grazed on uncultivated pastures and foraged crop waste in order to provide enough manure to sustain the land sown with cereals (Krausmann 2004): in 1865, only five head per square km in Sentmenat (seven including donkeys)—a live weight density of only 12 livestock units (LU) of a standardised weight of 500 kg (LU500) per cropland square km. (Table 2). In comparison, Cunfer and Krausmann (2009) found 24 LU500 per square km of agricultural area in the intensively cropped Austrian village of Theyern in 1829, and 4–13 LU500 in Finley Township (Kansas) in the very extensive land-use American Great Plains between 1895 to 1915. This density of livestock would provide only 1.5 tonnes of fresh manure per cropland hectare, a figure corresponding to the 1.37 tonnes recorded in 1919 in the first statistical survey of fertilizers in the province of Barcelona. The input to sustain a highly intensive regime of organic agriculture recommended by agronomists of the time—was 10 tonnes per cropland hectare or almost ten times these amounts (Aguilera 1906; Cascón 1918; Slicher van Bath 1963).

Nevertheless, these average figures do not account for marked differences between crops. No manure was used for growing vines, and only very small quantities in olive groves. This explains the role played by vineyard specialization in reducing the ratio between land sown with cereals and uncultivated land (Table 1). If we assume that all manure was applied to growing grains, livestock densities would rise to 46 LU500 per square km of cropland and average inputs to 5.6 tonnes of fresh manure per sown-land hectare, which corresponds to the 6–7 tonnes per hectare attributed by other sources to the rain-fed cultivation of cereals in the province of Barcelona during the second half of the nineteenth century—including applications ranging from 22–32 tonnes per hectare on irrigated lands. These would be double the inputs of between 2.5–5 tonnes per hectare applied in the United States at that time (Cunfer 2004, 2005; Burke *et al*. 2002), and matched the average of 4 to 5 tonnes per hectare in England and Wales from the mid-nineteenth century to World War Two (Brassley 2000).

How the Nutrients Gap Was Closed

Even assuming woody crops received no manure, there remains a significant gap between available livestock densities and fertilization required. Hence we conclude that either other organic inputs were used or unsustainable soil

Table 1 Cropland and other land-uses in Sentmenat in 1861

	ha	% of cropland	% of total area
Vegetal gardens and irrigated herbaceous crops	67.8	4.2	2.5
Rain-fed herbaceous crops	365.5	22.6	13.3
Vineyards	1,066.1	65.9	38.8
Olive groves	113.1	7.0	4.1
Other rain-fed woody crops	5.2	0.3	0.2
Total cropland	1,617.7	100.0	58.8
Woodland and scrub	698.4	–	25.4
Pasture	341.4	–	12.4
Unproductive or developed	92.5	–	3.4
TOTAL AREA	2,750	–	100.0
ratio between woodland, scrub and pasture/cropland			0.64
ratio between woodland or scrub/cropland			0.43
ratio between woodland, scrub and pasture/herbaceous crops & vegetable gardens			2.40
ratio between woodland or scrub/herbaceous crops & vegetable gardens			1.61
ratio between woodland, scrub, pasture, vineyards,olive groves, and other woody crops/herbaceous crops & vegetable gardens			5.13
ratio between woodland, scrub, pasture, vineyards, olive groves and other woody crops/cropland			1.37

Source: our own from cadastral records in the Archive of the Crown of Aragon (Barcelona)

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t2.1 **Table 2** Livestock and manure in Sentmenat in 1865

	Manure produced	Heads	Per head kg a day	Total kg a year	Total available[a]
t2.2					
t2.3	Horses	5	22	40,150	40,150
t2.4	Mules	103	22	827,090	827,090
t2.5	Donkeys	76	8	221,920	221,920
t2.6	Cows and oxen	26	34.15	324,060	324,084
t2.7	Sheep	225	2.3	188,888	94,444
t2.8	Goats	70	2.3	58,765	29,383
t2.9	Pigs	310	6.5	735,475	735,475
t2.10	Chickens and rabbits[b]	1,735	0.137	86,759	86,759
t2.11	Transhumant sheep	350	1.15	146,913	73,456
t2.12	TOTAL (weight of fresh manure)			2,630,042	2,432,760
t2.13	%N-P-K losses from fresh to composted manure[c]		50 % N	3 % P	20 % K
t2.14	N-P-K contained in composted manure[d]		8,515 kg N	3,776 kg P	8,563 kg K
t2.15	Livestock Units of 500 kg (LU500)[e]	199.3		t cropland ha^{-1}	1.50
t2.16	LU500 square km^{-1}	7.25		t sown-land[e] ha^{-1}	5.61
t2.17	LU500 cropland ha^{-1}	0.12			
t2.18	LU500 sown-land[e] ha^{-1}	0.46			

[a] For sheep and goats maintained in grasslands 50 % of manure has been discounted considering that it could not be recovered by locking the herd at night in a pen or taking it to stall. [b] Estimated by us from the available feed and assuming the existence of five chickens or rabbits per household. [c d] See Table 7. [e] Rain-fed and irrigated herbaceous crops and vegetable gardens

Source: our own estimate made from the livestock census of 1865 in the district, the data provided by contemporary literature and the assumptions made in the energy balance published by Cussó *et al*. (2006b). The following references have also been taken into account: Bouldin *et al*. (1984), Loomis and Connor (1992), Sørensen *et al*. (1994), Tisdale and Nelson (1956), Tivy (1995) Q3

mining was occurring until chemical fertilizers came to be used. Cunfer and Krausmann (2009) conclude that thanks to high livestock densities Austrian farmers were able to return over 90 % of nitrogen (N) extracted to cropland, although they produced little marketable crop surplus. In contrast, farmers on the American Great Plains produced plenty of exports but used few animals to exploit rich grassland soils, thus returning less than half of N extracted. After depleting soil fertility for over six decades, they faced a steep decline in crop yields from 1880 to 1940, when chemical fertilizers were introduced (ibid).

To compare these cases with Western Mediterranean agriculture we reconstruct a complete nutrient balance for our case study. Nutrient outputs and inputs in crops and seeds have been estimated, taking into account both the harvest index and the reuse of by-products (Table 3). Some 40 kg N per hectare were removed annually from irrigated lands and vegetable gardens, three times more than the average and 5.6 times the N taken up by vineyards. Rain-fed intensive rotations of grains sown without fallow extracted 39 % of all N in 22.6 % of cropland, about 22 kg N per hectare. Vineyards drew 7 kg N per hectare, including grapes and pruning-shoots. Although occupying two-thirds of cropland, vineyards removed only 38 % of N, 28 % of P and 18 % of K.

Overall, this distribution reveals the rationale behind the priority given to the scarce manure: it was first applied to irrigated land, and then to rain-fed cereals rotated with N-fixing leguminous crops or green manures. Vineyards were not fertilized with manure except at planting, and only received small amounts of other organic fertilizers such as leaf litter and branches buried in ditches dug between rows of vines, or burning and ploughing into the soil the *hormigueros* (*formiguers* in Catalan). These resembled small charcoal-kilns made with piles of dried vegetation that were burnt under a soil cover to generate slow and incomplete combustion. The material obtained was used as fertilizer or soil conditioner (Olarieta *et al*. 2011; Figs. 2 and 3). Q13

Some 20,195 kg of N were annually removed from the 1,618 ha of ploughed land in Sentmenat circa 1860–65, equivalent to 12.5 kg N per hectare. All locally produced manure contained only about 12,164 kg N. Considering that at least 50 % was lost in the dung pile, the N available would be reduced to 6,082 kg, or a maximum of 3.8 kg N per hectare a year (Cascón 1918; Tisdale and Nelson 1956; Johnston 1991), thus requiring alternative sources of nutrients and agricultural fertilization practices to fill this gap. Five different possibilities are considered: 1) human sewage and garbage; 2) symbiotic bacterial fixation through leguminous crops; 3) green manures; 4) burying fresh biomass into the soil; and 5) material generated by *hormigueros*.

One of the most difficult components of any organic nutrient balance to measure is the value adopted for

Table 3 Estimates of nutrients removed by crops in Sentmenat around 1861–1865

3.1. Main product for human consumption or animal feed						
	net fresh weight kg		kg N a year	kg P a year	kg K a year	
Irrigated wheat	19,166		353	63	67	
Irrigated corn	17,856		276	49	67	
Hemp	15,561		230	36	72	
Beans	18,323		651	86	315	
Rain-fed wheat	1,879		1,879	337	357	
Rain-fed corn	29,884		541	97	103	
Mixture of rye and other cereals	15,052		241	43	59	
Barley	26,513		459	188	125	
Forages	174,903		1,235	268	752	
Peas	41,155		1,070	96	254	
Olive oil from olive groves	16,104		0	0	0	
Grape juice from vineyards	2,070,079		0	414	2,070	
Vegetables in orchards and gardens	171,618		422	211	492	
Fresh fruits in orchards	27,878		8	5	23	
Nuts in orchards	6,638		11	5	16	
NET TOTAL HARVEST	2,652,609		7,376	1,898	4,772	
3.2. Crop by-products and residues						
	fresh weight kg		kg N a year	kg P a year	Kg K a year	
Straw & stubble of irrigated wheat	45,699		243	155	226	
Straw & stubble irrigated corn	9,723		50	37	152	
Residues & stubble of hemp	11,413		55	43	183	
Straw & stubble of beans	13,111		178	51	151	
Straw & stubble of rain-fed wheat	194,029		1,063	658	955	
Straw & stubble of rain-fed corn	57,536		47	30	122	
Id. mixture of rye and other cereals	48,505		158	100	147	
Straw & stubble of barley	91,696		440	174	275	
Straw & stubble of forages	69,621		518	115	323	
Straw & stubble of peas	21,422		257	91	442	
Pruning from olive Groves	309,950		1,937	542	2,015	
Pruning from vineyards	2,733,716		7,574	1,981	4,303	
By-products & residues of gardens	66,289		287	93	264	
TOTAL BY-PRODUCTS	3,672,710		12,807	4,070	9,558	
3.3. Distribution of nutrients removal between the main agro-ecological flows						
	kg N a year	%	kg P a year	%	kg K a year	%
Vegetable garden products	654	3.2	286	4.8	686	4.8
Cereals and legumes for food[ab]	5,414	26.8	1,621	27.1	2,612	18.2
Feed and fodder for livestock[b]	4,529	22.4	1,098	18.4	2,534	17.7
Vineyards	7,574	37.5	2,395	40.1	6,373	44.5
Olive groves	2,011	10.0	570	9.5	2,123	14.8
TOTAL REMOVED BY CROPS	20,182	100.0	5,970	100.0	14,328	100.0
Losses by natural processes	9,049	–	0	–	2,051	–
NUTRIENTS REMOVED	29,231		5,970		16,379	

[a] Hemp included; [b] Either rain-fed or irrigated. Source: our own from Cussó *et al.* (2006b), and taking into account, among others, Tisdale and Nelson (1956), Loomis and Connor (1992), and Angás *et al.* (2006)

atmospheric N fixation made by symbiotic bacteria. Even today, the scientific literature presents bewildering variation in the figures of N fixed by leguminous plants. This can be largely explained by the circumstantial nature of the symbiosis between legumes and Rhizobium bacteria whereby the presence of high doses of mineral N in the soil suppresses

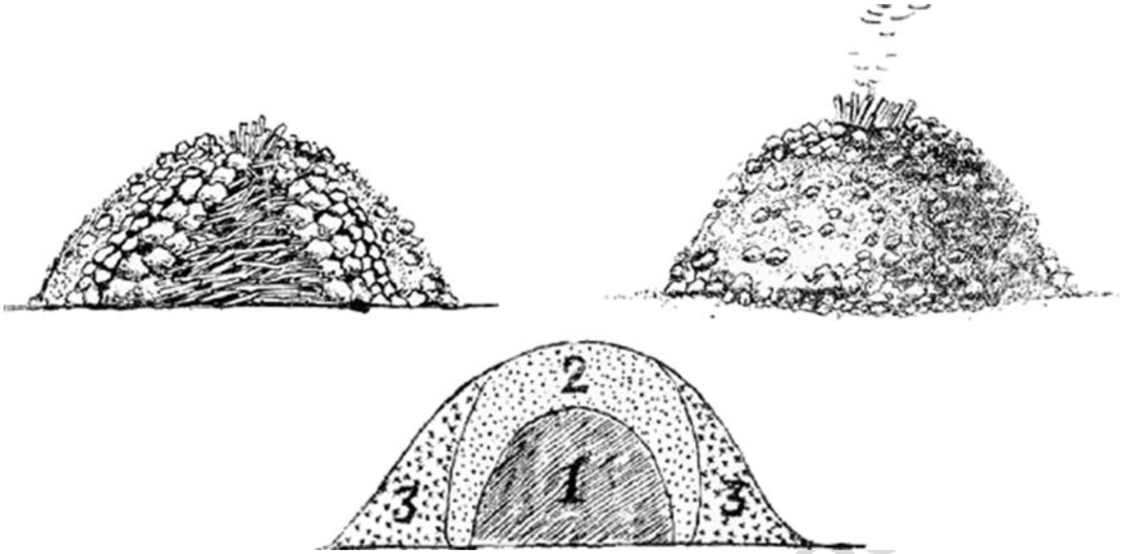

Fig. 2 Preparation and composition of a fertilizing *hormiguero*

bacterial fixation. Moreover, only a part of the N content of a leguminous plant comes from the atmosphere. Before the Rhizobium nodulation develops in the roots, the plant needs to uptake mineral N from the soil and therefore not all the N absorbed before the flowering and maturation of the grain can be attributed to the Rhizobium nodules. The lower energy cost of drifting carbon for their own growth, rather than Rhizobium colonies that may remain inactive, explains why legumes break symbiotic N fixation when there is enough mineral N in the soil.

This flexibility has a lot to do with the crucial role legumes played in the millennial development of organic agriculture, in which the mineral N was practically always lacking in the soil (McNeill and Winiwarter 2006). Unfortunately, this creates considerable uncertainty about the actual symbiotic fixation in each particular circumstance. Values ranging from 10 kg to over 300 kg N per hectare a year have been estimated. There are examples and opinions that reduce N symbiotic fixation to very low values, or even assume a net negative outcome if the grain is removed and plant residues are not incorporated into the soil. The only safe rule is to assume that they are inversely related in that symbiotic and free fixation is greater the poorer the mineral N content of the soil. Therefore, the N mobilized by leguminous crops from the atmosphere would have been higher in past organic agricultural systems, a hypothesis that contemporary organic farming may well help to corroborate

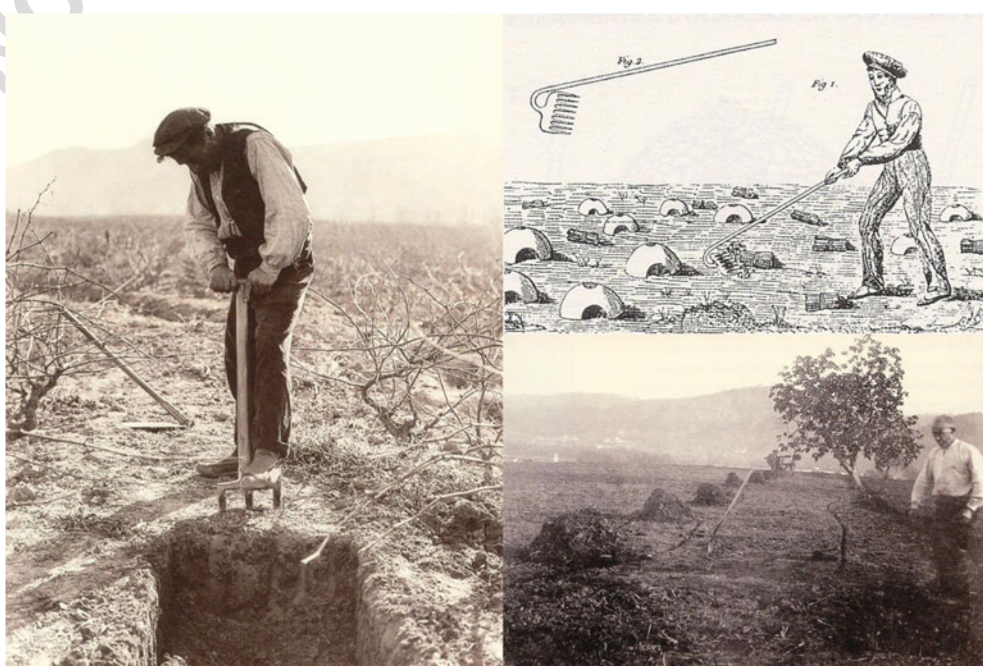

Fig. 3 Biomass buried in a ditch dug between vines (*left*) and fertilizing *hormigueros* (*right*)

(Obersom *et al*. 2007). Despite these uncertainties, we arrived at the preliminary estimates shown in Table 4.

Green manure provided another important source of leguminous N-fixing properties. We have found sufficient historical sources to conclude that green manures were used in the province of Barcelona during the second half of the nineteenth century, and were widely endorsed by agronomists of that period. However, we do not have precise data for the average area sown, the species used or the amount of atmospheric N fixed. As a very preliminary rough estimate, and assuming that 3.6 % of herbaceous cropland was sown annually with green manure, about 165,900 kg of aerial biomass may have been buried into the soil. We assume that the atmospheric N fixed was the only net input flow from green manure that must be included in the calculation, since the rest of the nutrients are simply recycled into the soil.

According to many local contemporary sources, crop by-products and forest biomass were directly applied to the soils as fertilizers, besides being used as compost matter in the manure pile. Two procedures were employed: 1) a direct burial of fresh vegetal matter in ditches dug between rows of vines; 2) ploughing into the soil ashes, charcoal and topsoil burnt in the *hormigueros* (Miret 2004).

In order to estimate the local biomass potential, the ratio between land sown with grains, land devoted to arboriculture and the available biomass that could be removed from woodland or scrubland was analysed. The amount of nutrients added to the soil by the burial of fresh biomass is easy to infer from its N-P-K content (although only the organic N is taken into account, disregarding any possible loss by mineralization). The amount of nutrients supplied by each *hormiguero* has been taken from Olarieta *et al*. (2011). It seems that any net N contribution would have been negligible but the *hormigueros* would have added some amounts of P and K, which could also result in a significant yield increase of legumes intended to supply N (Johnston 1991).

However, there remain some unknown aspects of the impact this method may have had to the biotic component of soil fertility. According to the agronomist Cristobal Mestre and the chemist Antonio Mestres (1949), the rise in temperature experienced by the topsoil covering the *hormiguero* caused a variation in the populations of soil micro-organisms that may help to explain the harvest increases obtained in experimental fields fertilized in this way compared with control plots—for example, by increasing free atmospheric N fixation (see Table 5 for our own preliminary estimate).

We assume that the burial of biomass and the *hormigueros* played a role in filling the remaining gaps in the nutrient balance. They appear in our balance sheet as a minor component because the estimated number of *hormigueros* is small due to the considerable uncertainties that still prevail about the size of each *hormiguero* and the amount of biomass burnt in them. Acknowledging that this issue deserves to be further studied, we have taken as a cautionary option an average figure of 13 *hormigueros* per cropland hectare per year (or 20 if only applied to vineyards), a figure adjusted to the locally available forest biomass—while figures up to 200 (Roca 2008) or even 700 per hectare per year (Barón de Avalat 1780) can be found. Taking into account the high labour inputs demanded by these techniques, it seems reasonable to assume that their use would depend on the relative scarcity of other fertilizers and the abundance of cheap labour. We came to a similar conclusion considering the task of removing fallen branches and dried biomass from the Mediterranean forests and scrub land, which usually become prone to wildfires (Pyne 1997; Grove and Rackham 2001).

An Organic Nutrient Balance Close to Equilibrium?

We matched the nutrients utilized by crops, or lost through other processes, with two different estimates of their replacement by various fertilizing methods: a) a maximum potential amount of N-P-K which the mass balance tells us should be somewhere in the local agro-ecosystem; and b) the fraction we believe was actually put into the soil discounting material losses by these fertilizing methods: manure piles, cesspools,

Table 4 Estimates of N added to the soil by leguminous crops in Sentmenat towards 1861-1865

	estimated N average fixation kg ha^{-1} $year^{-1}$	cropland sown ha $year^{-1}$	%	N incorporated kg $year^{-1}$
Beans	34.5	23.5	15.2	810.8
Alfalfa and other forages	26.2	65.7	42.4	1,720.3
Peas	20.0	65.7	42.4	1,304.4
TOTAL	Weighted average: 24.8	154.9	100.0	3,835.5

Source: our own, based on the N-P-K composition per unit weight of the legumes used in our balance (Bassanino *et al*. (2007), Berry *et al*. (2003), Castellanos *et al*. (1996), Drinkwater *et al*. (1998), Domburg *et al*. (2000), Holland *et al*. (1999), LaRue and Patterson (1982), Loomis and Connor (1992), Obersom *et al*. (2007), Peoples and Craswell (1992), Phillips and DeJong (1984), Schmidtke *et al*. (2004), Tisdale and Nelson (1956), Wilson ed. (1988) and the other references given in Table 7

Table 5 Estimates of nutrient added to the soil by burying fresh biomass and burning piles of *hormigueros* in Sentmenat towards 1861–1865

Nutrients	Available matter in kg	N kg year^{-1}	P kg year^{-1}	K kg year^{-1}
Biomass from pruning buried	497,590	2,141.6	1,181.2	1,754.2
Biomass from woodland or scrub buried[a]	111,522	557.6	167.3	669.1
«*hormigueros*» burnt and ploughed[b]	1,472,509	0.0	30.3	606.3
TOTAL FROM BIOMASS	2,081,621	2,699.2	1,378.8	3,029.6

[a] Mulch, grasses, acorns, branches or bushes that could also be partly used to burn in «*hormigueros*», along with pruning and other by-products of crops. We have assumed that only a quarter of the available biomass in woodland and scrubland was used in this way. [b] We have considered the maximum potential number of «*hormigueros*» according to the available biomass. Source: our own from Cussó *et al*. (2006b), and results of fieldwork and analysis performed by José Ramon Olarieta

latrines, *hormigueros*, burial of fresh biomass, crop legumes or green manure (Table 6). This balance is not designed to assess accurately all nutrient flow transported by livestock, agricultural labour and natural processes. Some minor flows have been omitted, such as erosion losses which could be largely offset by the accumulation of sediments in other near-by lands—depending on the scale of analysis. Nor have we assigned values to the mineralization processes in the soil, or the possible increase obtained in atmospheric N fixation by stimulating free bacterial activity through piles of *hormigueros*. But even admitting a margin of error, which can only be reduced through future calibration and comparison with other balances, we believe that the usefulness of this assessment lies in its heuristic function Table 7.

We think that this balance sheet helps us to reveal some basic features of the societal attempts made to close the flow of nutrients in highly intensive organic agriculture of a Mediterranean-type. Despite inaccuracies and uncertainties it allows us to formulate some results. First, the amount of nutrients available to sustain cropland fertility could have been almost large enough to replace the main macro-elements taken from the soil by crops and natural processes, provided that the processing efficiency of animal manure and human sewage was not lower than 50 % in N, 90 % in P and 80 % in K. We suppose as well a high labour input allocated to make *hormigueros* or bury fresh biomass in order to import nutrients –mainly K— from uncultivated areas to cropland. Should these assumptions be changed—for example by considering a loss higher than 50 % of N content in manure management and reuse of sewages— the totality of nutrients extracted would not have been replenished (Fig. 4). On the other hand, we know that N losses in manure piles could only be reduced up to 30 % if the floor of livestock stall was paved and the compost process was accurately managed (Cascón 1918).

In any event, we are not assuming that actual fertilization always balanced crop extractions in each farm or plot. A very important issue that is masked in average figures is to how social inequality affected the availability of livestock manure, woodland or scrubland cuts, and latrines. In spite of the fact that the maximum potential of fertilizers available was probably enough to maintain soil fertility, we believe that poorer winegrowing tenants may have worked at a deficit level.

Commoner (1971) considered a basic principle of an ecosystem's functioning to be "everything goes somewhere." Our balance shows, for example, that a portion of K was obtained from burying or burning biomass in *hormigueros*. Thus, any remaining K gap could probably have been closed by increasing labour and biomass allocated to make them. Another important issue that requires comment is that the proportion of cropland devoted to feed and fodder to support livestock could be kept relatively low due to the role played by agricultural recycling and natural pastures (Figs 4 and 5). This material eco-efficiency required careful management of cropland, uncultivated land and livestock breeding—which was also a key to the corresponding high degree of energy efficiency (Cussó *et al.* 2006a, b).

Discussion

These results help to explain the high incidence of winegrowing in Sentmenat circa 1860–65. Two-thirds of the cropland acreage devoted to vineyards brought about a significant saving of N and P. The importation of 1,556 Hl a year of wheat, together with some amounts of salted fish and rice, meant an annual gain of 2,561 kg N, 433 kg P and 459 kg K which accumulated in sewage. While the N content in the wine exported was negligible, the P taken yearly from wine was around 414 kg and the K around 2,070 kg. As a consequence, the nutrient trade balance led to a net annual gain of some 2,561 kg N and 433 kg P, together with a net annual loss of 1,611 kg of K (Tello *et al.* 2006, 2008; Garrabou *et al.* 2009, 2010; Badia-Miró *et al.* 2010).

However, the ability to access the full potential of nutrients available in the local agro-ecosystem is not the same as the ability to collect and reintroduce them into

Table 6 Annual output and input flows of nutrients in cropland of Sentmenat towards 1861–1865

6.1. Nutrient content of material flows (N, P, K in kg per year)						
	content of N		content of P		content of K	
1. Natural atmospheric deposition	1,132		0		1,455	
2. N fixation by free bacteria in the soil	7,584		0		0	
3. Seeds	769		140		205	
4. Total manure available	12,164		3,892		10,704	
5. Manure finally applied to the soil	6,082		3,776		8,563	
6. N fixation by leguminous plant grown	3,835		0		0	
7. Nutrients buried by green manure	1,371		116		912	
8. N atmospheric fixation by green manure	973		0		0	
9. Other biomass buried	2,699		1,349		2,423	
10. Available human sewage	7,030		1,268		1,914	
11. Human sewage finally applied	3,515		1,230		1,531	
12. Household and village garbage	664		918		566	
13. «*Hormigueros*» burnt and ploughed	0		30		606	
I=1+2+3+5+6+8+11+12+13						
I.INPUTS ACTUALLY DRAWN	27,253		7,443		15,349	
A. Losses by natural processes	9,049		0		2,051	
B. Nutrients extracted by crops	20,195		5,971		14,332	
II. NUTRIENTS REMOVED (A+B)	29,244		5,971		16,383	
Balance with the inputs actually applied (I-II)	−1,991		1,472		−1,034	
6.2. Nutrient flows per unit area (kg ha-1 year-1 of N, P, K or in % of total removed)						
	N ha-1	%N	Pha-1	%P	K ha-1	%K
1. Natural atmospheric deposition	0.7	3.9	0.0	0.0	0.9	8.9
2. N fixation by free bacteria in the soil	4.7	25.9	0.0	0.0	0.0	0.0
3. Seeds	0.5	2.6	0.1	2.3	0.1	1.3
4. Total manure available	7.5	41.6	2.4	65.2	6.6	65.3
5. Manure finally applied to the soil	3.8	20.8	2.3	63.2	5.3	52.3
6. N fixation by leguminous plant grown	2.4	13.1	0.0	0.0	0.0	0.0
7. Nutrients buried by green manure	0.8	4.7	0.1	1.9	0.6	5.6
8. N atmospheric fixation by green manure	0.6	3.3	0.0	0.0	0.0	0.0
9. Other biomass buried	1.7	9.2	0.8	22.6	1.5	14.8
10. Available human sewage	4.3	24.0	0.8	21.2	1.2	11.7
11. Human sewage finally applied	2.2	12.0	0.8	20.6	0.9	9.3
12. Household and village garbage	0.4	2.3	0.6	15.4	0.4	3.5
13. «*Hormigueros*» burnt and ploughed	0.0	0.0	0.0	0.5	0.4	3.7
I=1+2+3+5+6+8+11+12+13						
I.INPUTS ACTUALLY DRAWN	16.9	100.0	4.6	100.0	9.5	100.0
A. Losses by natural processes	5.6	30.9	0.0	0.0	1.3	12.5
B. Nutrients extracted by crops	12.5	69.1	3.7	100.0	8.9	87.5
II. NUTRIENTS REMOVED (A+B)	18.1	100.0	3.7	100.0	10.1	100.0
Balance with the inputs actually applied (I-II)	−1.2	−6.8	0.9	24.7	−0.6	−6.3

Source: our own based on the previous tables

croplands. Most of our uncertainties arise over the difference between potential and actual nutrient availability. Bearing in mind the processing losses of animal manure and human sewage, the actual availability of animal manure and human wastes would cover only 33 % of N, 84 % of P and 62 % of K required to replace extraction by crops. Therefore, sustaining cropland fertility depends on whether other forms of organic fertilization could cover this gap. Two stand out: the symbiotic N fixation by legume crops and their use as green manure, which could have covered about 16 % of extractions; and the K obtained by burying fresh biomass or burning it in *hormigueros*, which should

Q4 t7.1 **Table 7** Summary of the estimations and sources

	Item	Source	Estimation
t7.2	Item	Source	Estimation
t7.3	1. Natural annual atmospheric deposition	MOGUNTIA model at Holland *et al.* (1999)	0.7 kg N/ha
t7.4	2. N free annual fixation by bacteria in the soil	Loomis and Connor (1992). Berry *et al.* (2003)	1–5 kg N/ha
t7.5 Q5	Livestock average live weights	Livestock census of 1865 and the assumptions used in Cussó *et al.* (2006a, b)	Cattle: 371 kg
t7.6			Horse and Mule: 326 kg
t7.7			Donkey: 172 kg
t7.8			Sheep: 30 kg
t7.9			Goat:34 kg
t7.10			Pig: 77 kg
t7.11			Poultry: 2 kg
Q6 t7.12	Daily average manure production per head of livestock	Aguilera (1906), López Sánchez (1910), Cascón (1918), Camps (w.d.), Matons (1923)	Horse and Mule: 22 kg
t7.13			Donkey: 8 kg
t7.14			Cow: 34.2 kg
t7.15			Sheep and goat: 2.3 kg
t7.16			Pig: 6.5 kg
t7.17			Poultry: 0.137 kg
t7.18	4. Manure composition (fresh weight).	López Sánchez (1910), Cascón (1918), Tisdale and Nelson (1956)	0.50 %N
t7.19			0.16 %P
t7.20			0.44 %K
t7.21	4 and 11. Losses during biomass composting, manure and human sewage storage manure piles.	Cascón (1918), Aguilera (1906), Urbano Terrón (1989)	50 % N or 30 % N
t7.22			0.3 % P
t7.23			20 % K
t7.24	Manufactured fertilizers.	Garrabou and Planas (1998)	Small capacity of manufacturers. Tiny imports of guano and industrial fertilizers. So we consider none.
t7.25	6 and 8. N symbiotic fixation.	Gonzalez de Molina *et al.* (2010)	N content coming from atmosphere: 60 %
t7.26			N content in grain: 3.5 %
t7.27			N content in aerial biomass: 62 %
t7.28			N content in roots: 33 %
t7.29			N deposited into the soil by roots: 18 % of the total N fixed
t7.30	10 and 12. Garbage and human sewage.	Mataix (2002), Tarr (1975), Schmid-Neset (2005), García Faria (1893:72–73)	Garbage: 57 Kg/inhabitant
t7.31	13. «*Hormigueros*»	Olarieta *et al.* (2011)	- The soil cover of the«*hormiguero*» comes from the same cultivated area.
t7.32			- Each«*hormiguero*»is made with an average of 68 kg of woody biomass.
t7.33			- As a result of the combustion we have 2.5 kg of char and 2.5 of ashes.
t7.34			- The composition of the ashes from the«*hormiguero*»is the same as if the same type of woody biomass were burnt elsewhere.
t7.35			- They are made in equal parts of pruning and woodland or scrub cuts.
t7.36	A. Average natural losses	Drinkwater *et al.* (1998), Galloway *et al.* (2004)), Jambert *et al.* (1997), Kosmas *et al.* (1997), Parton *et al.* (1996), Rana and Mastrorilli (1998), Rosswall and Paustian (1984), Tisdale and Nelson (1956), Torrent *et al.* (2007)	Leaching: 5.5 kg N/ha
t7.37			Denitrification: 1.5 kg N/ha irrigated
t7.38			Ammonia volatilization: 5 % green manure N inputs
t7.39	B. NPK composition of nutrients extracted by crops	Soroa (1934), CESNID (2003), Mataix (2002). Moreiras-Varela *et al.* (1997)	

Source: our own based on the previous tables. (Item number corresponds with the numbers in Table 6)

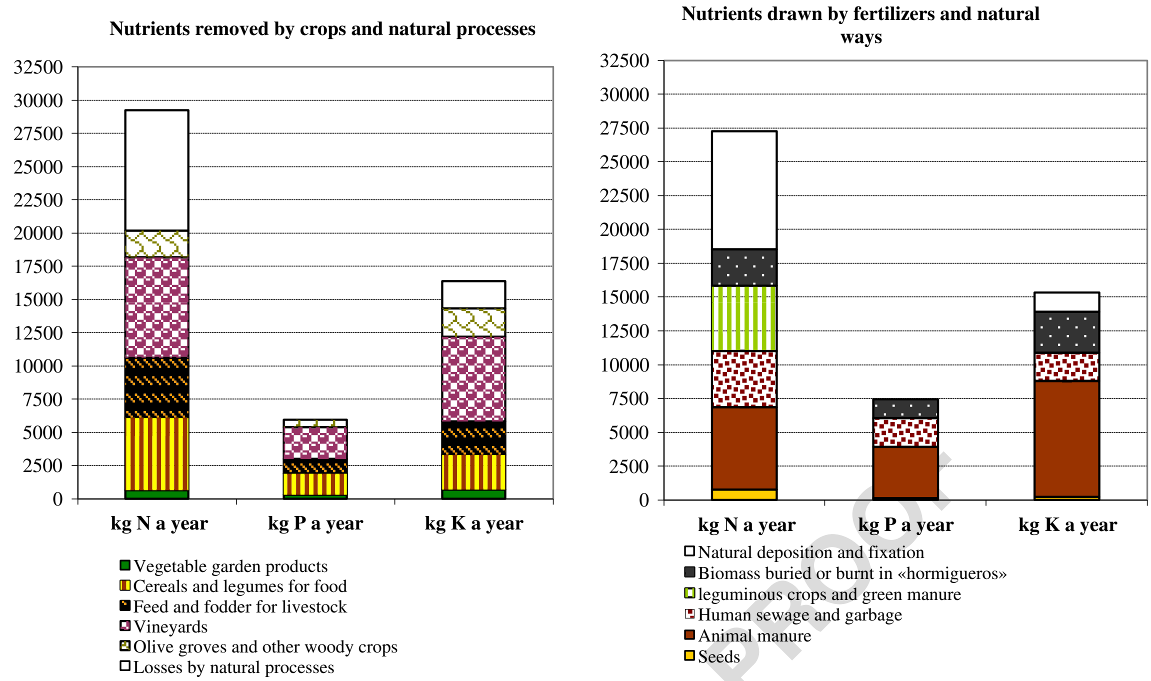

Fig. 4 Summary of the nutrient balance in the municipality of Sentmenat in 1861–1865

have covered about 14 % of the K required in order to balance the local agro-ecosystem in 1860–65.

In other words, while the agronomists of the day were correct in noting the inadequacy of local livestock densities, other options were available for Mediterranean-type intensive organic agriculture. Nevertheless, these alternatives were highly labour-intensive. Hence we come to a third conclusion: the main limiting factor regarding organic nutrients was not biophysical, but technical and economic. Rather than the maximum potential of N-P-K available in the agro-ecosystem, what mattered most was the actual capacity to combine and recycle them as fertilizer taking into account the chain of losses experienced in dung piles, latrines, cesspools, sewers or *hormigueros*. A key limiting factor was the amount of human and animal labour needed for that purpose.

There are, of course, some ultimate agro-ecological limits inherent in any organic-based agrarian economy aiming to increase yields without overshooting the renewable resources available. Before reaching these limits it was possible to increase leguminous crops, which in 1860–65 covered just one quarter of cropland, and to use them as green manure. Here again the limiting factors appear to be more economic than agro-ecological. The water stress typical of the Mediterranean region was dealt with to some extent through increasing the water retention capacity of soils by increasing their organic matter content, or with temporary and permanent irrigation. Another option was specialization in arboriculture, which requires less water and extracts fewer nutrients from the soil. However, all these alternatives needed land improvements and labour investments, and these in turn had opportunity costs according to the relative market profitability of their alternative uses.

Fourth, the scope for increasing agricultural yields through more intensive organic fertilization was very limited unless land-uses were changed, as recommended by agronomists, by increasing the land sown with leguminous crops and using them as green manure or by increasing forage, livestock and manure. To a degree, either of these land-use changes were constrained either by the rainfall levels of the Mediterranean environment, or by actual market opportunities to reallocate land towards commercial woody crops (González de Molina 2002; Guzmán Casado and GonzálezDeMolina 2008; González de Molina *et al*. 2010; Vanwalleghem *et al*. 2011).

Finally, it should be emphasised that in Sentmenat circa 1860–65 the maintenance of cropland fertility was only possible through a permanent transfer of nutrients from uncultivated areas of woodland, scrub and pasture. This was of course an overriding feature of any past organic-based agricultural system. What draws most attention in this case study is the key role played by human labour in cropping legumes and green manure and transferring nutrients from woodland or scrub by means of *hormigueros* burnt and biomass buried into cropland as compared to the less significant role of livestock in that transfer. This was a key feature of Mediterranean organic agriculture that contrasted with other European bioregions (Fig. 5).

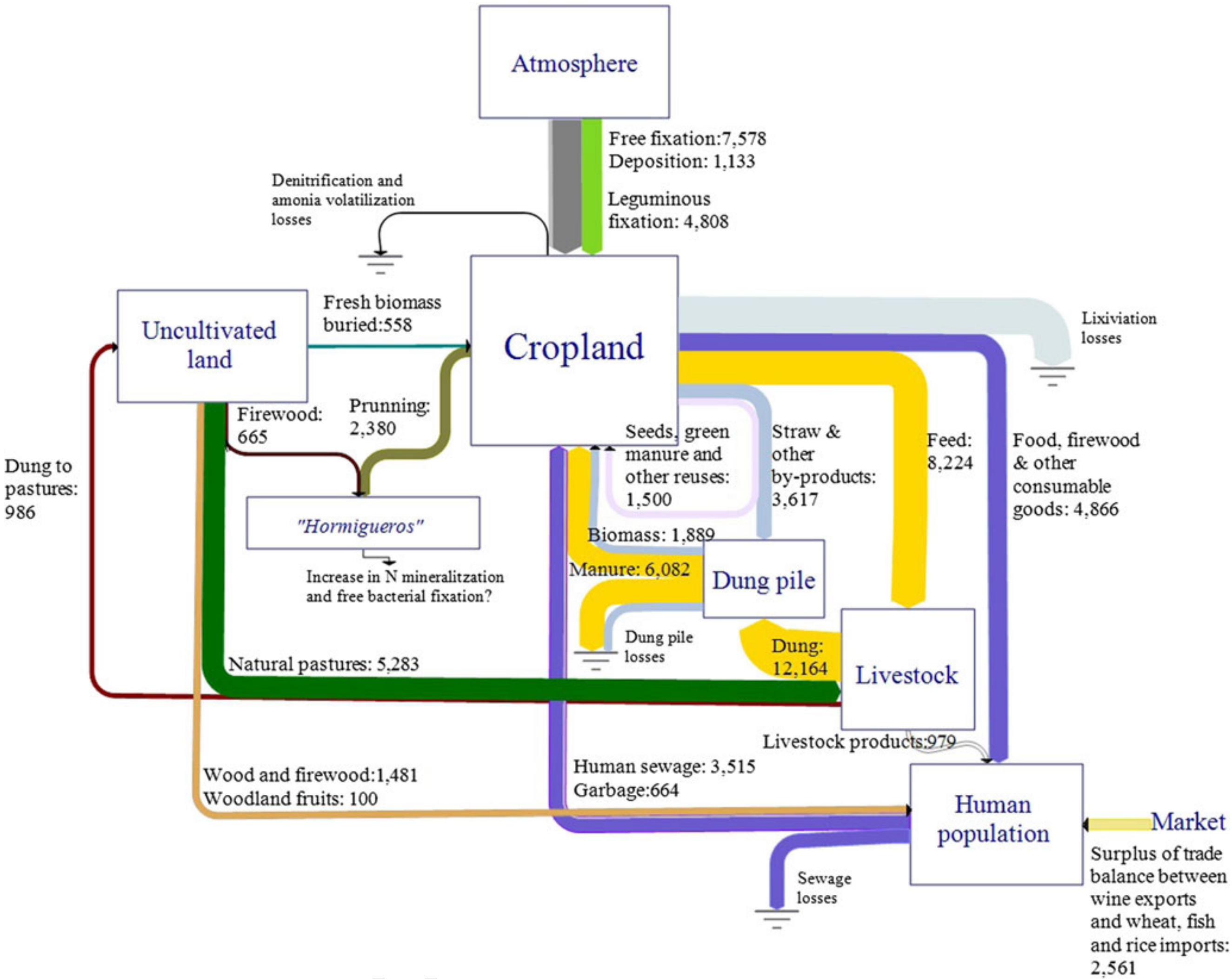

Fig. 5 Annual flows of N in the municipality of Sentmenat towards 1861–1865

Thus we come to our fifth and last conclusion: organic fertilizers rather than animal manure played a key role – albeit small in absolute terms— in transferring nutrients from uncultivated areas into cropland. Besides being highly labour-intensive, these transfers imposed a relevant nutrient tribute on woodland or scrubland, mainly in terms of K, which added to the simultaneous extraction of timber, firewood or charcoal. The maintenance of cropland fertility was closely related to the sustainability of this multiple-use of forests, which up to a point might have been overexploited. Photographs taken during the first third of the twentieth century show diminished forest cover. At that time woodlands were reduced to a minimum in Catalonia, and even more in Spain: forest land occupied only 15 % of the country area in 1915 (Tello and Sudrià 2010), and about 20 % in 1955 (Schwarzlmüller 2009).

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