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GUIDELINE FOR CONSTRUCTING NUTRIENT BALANCE IN HISTORICAL AGRICULTURAL SYSTEMS

(And Its Application To Three Case-Studies In Southern Spain)

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Abstract: The purpose of this paper is to provide interested researchers with a simple tool to evaluate the efficacy of different methods of fertility replenishment that have accompanied and made possible the contemporary agriculture. We propose a nutrient balance model created especially to be applied to the past. In the first part of this working paper each term in the balance is defined and specified the information the user must input into the model. The second part of this paper reports on the application of this methodology based on the balances of nutrients to the evolution of Andalusian agriculture since the mid 18th Century. The nutrient balances show the effects of agrarian growth in an environmentally limited context, offering reasonable doubt regarding the medium and long-term stability of certain forms of cultivation. The balances show that in the last decades of the 19th Century, productive intensification had reached its ceiling, with livestock numbers levelling off or clearly declining. The deficits of nutrients even began to exceed the fertilisation capacity of the available livestock. The intensification applied in unfertilised rotations and crops had to be sustained through the extraction of soil reserves.

Key words: Soil Fertility Management, Nutrient Balances, Past Organic Agricultures, Agrarian Growth, Socio-Ecological Transition, Agricultural Change.

JEL: Q10, Q11, Q19, N53

Resumen: El propósito de este documento de trabajo es proporcionar al investigador interesado una herramienta sencilla para evaluar la eficacia de las distintas formas de reposición de la fertilidad que han acompañado y hecho posible el desarrollo de la agricultura contemporánea. Para ello hemos utilizado la técnica del balance de nutrientes, que permite detectar problemas agronómicos y en general ambientales asociados a la implementación de dichos manejos. En este documento de trabajo proponemos un modelo de balance de nutrientes especialmente ideado para su aplicación al pasado. En él se define cada término del balance y se precisa la información que el usuario debe introducir en el modelo. La segunda parte de este documento recoge la aplicación de este modelo a la evolución de la agricultura andaluza desde mediados del siglo XVIII. Los balances de nutrientes muestran los efectos del crecimiento agrario en un contexto ambientalmente limitado, ofreciendo dudas razonables sobre la estabilidad a medio y largo plazo de algunas formas de cultivo. Ponen de manifiesto también que en las últimas décadas del siglo XIX se había llegado al tope de la intensificación productiva, superando incluso la capacidad de fertilización de la propia cabaña ganadera. La intensificación sufrida en las rotaciones y cultivos no fertilizados, se tuvo que sostener sobre la extracción de las reservas del suelo.

Summary

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Introduction[1]

The development of the agrarian sector over the last three centuries cannot be understood without in-depth knowledge of how soil fertility has been managed. Fertilisers, either organic or chemical, have been chiefly responsible for improvements in land productivity. This is particularly applicable to farming systems such as Europe or Asia where the replenishment of nutrients exported with the harvest has been an essential cultural practice to avoid the deterioration of lands cultivated for centuries and ensure the viability of future harvests. The study of fertilisation systems is, therefore, essential to understanding agrarian growth and the process of agricultural intensification in the 18th Century.

However, a simple description of soil fertility management is not sufficient in itself to carry out such a study with the required rigour. The purpose of this paper is to provide interested researchers with a simple tool to evaluate the efficacy of different methods of fertility replenishment that have accompanied and made possible the contemporary agriculture. For this purpose, the nutrient balance technique has been used to detect agronomical and general environmental problems associated with the implementation of these management approaches. Risks of contamination through nitrogen leaching, eutrophication of continental waters, chemical deterioration of the soil and loss of potential production capacity are usually detected using this technique under conditions of modern-day agriculture, characterised by the relative abundance of macronutrients. But it is also useful for the opposite situation, characteristic of organically-based agricultural systems: the structural scarcity of nutrients and associated phenomena such as the sufficiency or insufficiency of fertilisation, nutritional

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[1] This research was made possible by the financial support of the Ministry of Education and Science (National R&D/Innovation Programme; HUM"2006-04177), entitled: "History and sustainability: Recovering traditional management for the design of sustainable agrarian systems, the olive grove in Andalusia (XVIII-XX)".

deficiencies, the mining of soil reserves. It is useful, therefore, given the close link between soil productivity and nutrient replenishment, when highlighting the vicissitudes, limitations and opportunities in the development of agriculture.

This paper proposes a nutrient balance model created especially to be applied to the past. It defines each term in the balance and specifies the information the user must input into the model. To facilitate understanding of how it works, one of the case studies has been used, corresponding to the second part of this paper, for one of the dates considered, 1752. This was deemed to be the best way of explaining the different steps taken when creating the balance. The different sections look at problems such as the lack of information when studying the past and the uncertainty regarding the data provided by sources. However, information that cannot be obtained and compared with documentary or oral sources can be reconstructed by means of a double strategy: on the one hand, by constructing models to recreate values that cannot be measured in the field or when sufficient information is lacking. These models simulate the conditions that should have existed in the past. For example, if the organic matter present in soils cannot be measured, a model can be created that, according to the fertility management approach used, the use made of vegetable waste, grazing, etc. and the characteristics of the land (texture, pH, etc.), provides a reasonable approximation of the organic matter content of terrain subject to a specific crop or rotation.

Experimental history (Guzmán Casado and González de Molina, 2009), on the other hand, can provide extremely interesting information. In this case, experimental history involves carrying out ‘field’ tests in order to reproduce the management conditions of traditional agriculture. Given its high cost, it is not always possible to conduct such tests. One alternative option is to use information from research into organic agriculture, taking into account its similarity with traditional agrarian systems. The case studies included at the end, for example, have benefitted from various tests carried out on organic agriculture which have provided, with greater precision and accuracy, values for some of the variable used in the balances.

The second part of this paper reports on the application of this methodology based on the balances of nutrients to the evolution of Andalusian agriculture since the mid 18th Century. To illustrate this evolution, and given that there are no aggregate data to know production, land uses and other essential data at an Andalusian scale, the methodology has been applied to three case studies, seeking maximum representativeness: two belonging to the western part of the region (Castilleja de la Cuesta, Seville, and Baena in Cordoba), more closely linked with the markets, and another from the eastern area (Montefrío, Granada), which is more isolated. The first two are more representative of the production specialisation experienced by Andalusian agriculture in the 19th Century, and the other was aimed more towards subsistence. The study spans practically a century and a half, from 1752, the date of the Marqués de la Ensenada Cadastral Survey, to the early 20th Century, right in the throes of the end-of-century crisis and, therefore, its main argument is the change experienced by the three agrarian systems from the perspective of fertility replenishment. The results of the study, in our view fairly relevant, show the usefulness of this methodological tool for agrarian historians and academics studying processes of socio-ecological transition in the countryside.

The evolution traced by the application can be summarised in the change from a situation in the mid 18th Century in which there was a large amount of livestock and little manual labour, to the opposite situation in the mid 19th Century, when the population had boomed and there was little fertilisation capacity. In this respect, the application also shows that in the second half of the 19th Century, a situation of relative stagnation had been reached in terms of fertilisation possibilities. The land dedicated to producing food for human consumption grew at the expense of land dedicated to animal feed, leading to the reduction in livestock numbers and the net reduction of their fertilisation capacity. As a consequence, the possibilities of greater crop intensification were severely limited.

The nutrient balances show the effects of agrarian growth in an environmentally limited context, offering reasonable doubt regarding the medium and long-term stability of certain forms of cultivation. The balances were positive for crops that were fertilised with manure and negative when they were not fertilised at all. Certain cereal rotations and woody crops such as olives could be maintained thanks to the fixation of N provided by existing leguminous plants in natural weed cover in the furrows or in the fallow years. The same did not occur with P and K or with other woody crops such as grapevines. In the 18th Century, net extractions caused by the cultivation of grapes and olives were within tolerable limits, thanks to the unintensive management approaches taken. Extractions grew, however, as cultivation became more intense, spurred by the opening up of new markets. The magnitude of the deficits in the balances questions the sustainability of specialising in woody crops, proposed as one of the practicable avenues for agrarian growth in the 19th Century. This was based on the exportation of land. The fact that the growth of the surface area dedicated to grapevines and olive groves was carried out preferably on uncultivated soils, with their nutrient reserves practically intact, might explain why this phenomenon went unheeded by contemporaries.

In any case, the balances show that in the last decades of the 19th Century, productive intensification had reached its ceiling, with livestock numbers levelling off or clearly declining. The deficits of nutrients even began to exceed the fertilisation capacity of the available livestock. The intensification applied in unfertilised rotations and crops had to be sustained through the extraction of soil reserves.

I. First Section: A guideline for constructing nutrient balances

1. General features of the model

Any model which main objective is the reconstruction of historic nutrient balance must, inevitably, be static. Recorded information of some of the inputs and outputs (e.g. harvesting, fertiliser application rate, rainfall...) is fixed, as it is a picture, averaged and results are linked to a specific period of time. Dynamist in the outcome of the nutrient balance, which might reflect changes in the distribution of crops, degree of crops intensification and cropland extension, can be added when the historical information, which is an essential part of the inputs and outputs of the model, have been recorded along various periods of time. If this is the case, the nutrient balance model might incorporate a temporal dimension with socio-cultural and economics implications.

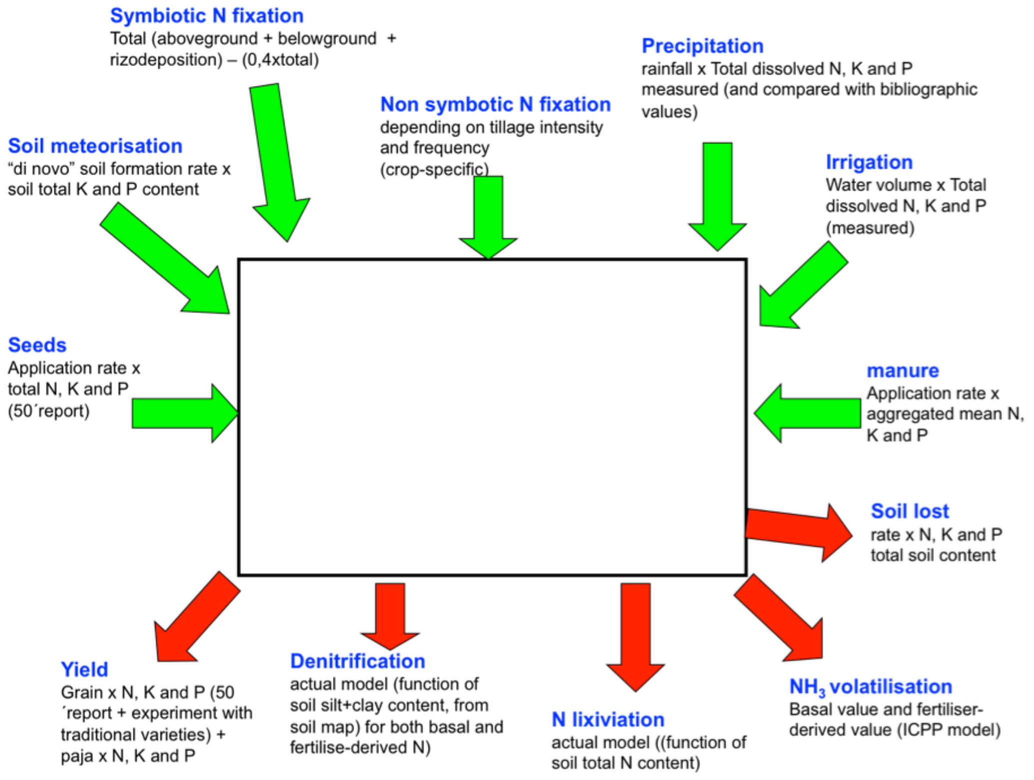
In the reconstruction of any historical nutrient balance great attention in combine weather (specially precipitation regime) and soil (soil type and main physico-chemical properties including texture features and soil content of major elements) information with that historical (cropping pattern and distribution, extension and the regime of the main management practices such as fertilisation and harvesting) and current predictive models for key processes of the soil nitrogen (N), phosphorus (P) and potassium (K) cycling, which are sensitive to these type of information, should be paid. Therefore, to reconstruct the balance for key nutrient not only historical information, as detailed as possible, but also deep knowledge, as comprehensive as possible, site features (soil distribution and main landscape geomorphology features), spatial distribution of crops and climatic conditions, are needed. Therefore, the reconstruction of a historical nutrient balance is a multidisciplinary task. In addition, in any model to make nutrient balance, in historical or current case studies, the geo-referentation of the information, in most historical cases lacking, print accuracy and precision of the results of the nutrient budget.

When constructing a historical balance, a number of inaccuracies might exist. Historical records can be contradictories and in many cases biased, especially when information was recorded for taxation purposes. Historical information on nitrogen (N), phosphorus (P) and potassium (K) content of the crops and manure and on water (rainwater and stream water) and soil N, P and K levels are lacking and, therefore, objective and subjective, although not arbitrary, criteria, based on the deep knowledge, literature reviews and inference from current information, should be applied.

The model for reconstruction of historical balance presented here is a compartment-based model, static for specific period of time and additive in which some of the processes in and out of the compartments come from direct or indirect information, but other from prediction by using current empirical sub model (i.e. N losses from denitrification and lixiviation) or an experimental history approach. The latter approach consist of field experiment which intend to emulate, as accurate as possible, the management practices of traditional agriculture to directly evaluate some of the required variables by the model.

Figure 1 shows the processes and variables should be taking into account when constructing a nutrient budget.

Figure 1. Main processes of input and ouputs of N, K and P, and variables involved, taking into account on constructing the nutrient balance.



Agriculture in Montefrío parish before XX Century is a clear representative of that of Mediterranean inland, with high degree of isolation. Montefrío, northwest of the province of Granada and with an area of 254 km^2, is situated in the central sector of the ridges of the Béticas Mountains. Climate is Mediterranean-continental, with an annual average precipitation (data of 100 years) of about 654 mm and with a potential evapotranspiration of about 800 mm. Landscape is characterised by great abundance of hill and mountains with most of the territory over a slope of 10 %. Agriculture management during the eighteen century was that typical of Mediterranean medium-mountain. Montefrío was a parish dominated by small peasant property. At the eighteen are middle nineteen centuries was a relatively isolated area, with limited possibilities of communication and therefore isolated from the national market, which limited the possibilities for the exchange of energy and materials to and from the outside world and, therefore the agricultural expansion was highly depended on the domestic demand.

Population density was relatively low during the eighteen century and not higher than 20 inhabitants Km^{-2}. Likely, the main limiting factors for a development of agriculture over this period were not the availability of arable land or manure, but the shortage of manpower. A very significant part of the cultivate land of Montefrío (96.4 %), was devoted to subsistence-cereal crop in "one third rotation", with yields very low and without irrigation. The eighteen century Mediterranean "one third rotation" consisted of cultivating the land with wheat during the first year, fallow during the second year and a tillaged-fallow during the third. Another rotation of minor significance (0.31 % of cultivate land); the "ruedo", consisted of a first year of wheat, second of chickpea, third of barley and fourth of beans and was located in dry land near the villages where it was more feasible the application of intensive work and fertilisation. Woody crops consist of olive groves (1.50 %), planted at very low olive trees density usually scattered (Calderón-Espinosa, 2002), and vineyard (0.75 %) not intensively cultivated. Both were not fertilisation nor irrigated. Finally, the most fertilised-intensive production was for irrigated vegetables (0.81 %) which, according to the historical sources, included hemp, barley and beans in one-twentieth of a hectare, and an eventually irrigated rotation of wheat following fallow during the second year and beans or chickpea during the third.

According to the low net primary production which characterised the Andalusia ecosystems, the cattle density was already limited in the mid-eighteenth century, with values below the 20 livestock units. However, a greater proportion of the livestock consisted of revenue producing livestock (sheep, goats and pigs) which made available great amount of manure. However, the manure of this livestock was much more difficult to collect due to their grazing management.

Three orders of soil account for more than 80 % of the area, being Regosol the most abundant, especially in the moderate to high slope areas. Olive groves and vineyards were, likely, located in this soils order. Calcisol is the predominant soil order in the smooth valleys were, with high probability was dedicated to the one third rotation and the four year rotation in which wheat, chickpea, barley and beans alternated. Nowadays there still are cereals grown in these areas. Finally, the Fluvisol is located in the stream basin and likely where constantly irrigated vegetables were grown, as it is currently. Top-10 cm soil total N content is minimal in the Regosol (0.08 %) and maximal in the Calcisol and Fluvisol (0.17 %) (Table 1). Variability of the soil total P content was lower with similar values for the Regosol and Calcisol and maximum for the Fluvisol. Finally, total K in the soil ranged 0.54 % in the Calcisol up to 2.01 % of the Fluvisol (Table 1). Clay plus silt content of the top-10 cm soil ranged 10 % for the Regosol up to 22 % in the Calcisol.

Table 1. Surface distribution (hectarea) of the crops and rotations of Montefrio parish in 1752. Main soil type and total soil content of N, P and K for each crop and rotation is also indicated.

Crop type	Surface	Soil classification	Nitrogen (%)	Phosphorus (%)	Potassium (%)	Clay plus silt (%)
Irrigated vegetables	62.2	Fluvisol	0,17	0,046	2,01	15
Bean-wheat rotation	9.0	Calcisol	0,17	0,036	0,54	22
Ruedo (bean-whear-chickpea-barley rotation)	24.2	Calcisol	0,17	0,036	0,54	17
One third rotation	7348.0	Calcisol	0,17	0,036	0,54	17
Olive grove	117.7	Regosol	0,08	0,036	0,64	10
Vineyard	57.8	Regosol	0,08	0,036	0,64	10
Cultivate area	7618.8					
Utile agrarian area	24476.4					
Total area	25537					

3. Nitrogen, phosphorus and potassium input analysis

One of the major natural routes of entry of nitrogen, phosphorus and potassium, in both natural and managed terrestrial ecosystems, is precipitation. However, the entry of P and K to the arable soil by soil formation should also be considered. Although inputs of P and K from the parent material to the arable soils are not truly an entry at a farming scale, does is at a "crop" scale and therefore should be considered as an input. Parent material is lacking of N, except for some type of rocks, and thus inputs by this mechanism should only be considered for P and K.

However, for N other natural sources should be considered. N can be found in forms of different oxidative state being nitrate the most oxidised and atmospheric N (N bound to N with a triple bound) one of the most reduced. Some of them are in gaseous state, mainly N_2, NH_3 and N_2O. N fixation of the atmospheric N_2 by free microorganisms (non symbiotic N fixation) and by bacteria associated with the root system of mainly legumes might be significant and should be considered.

The anthropogenic routes, and therefore man-managed, of entry of N, P and K are irrigation (for those eventually and constantly irrigated crops) and fertiliser and seed applications.

3.1. Input of N, K and P by rainfall

In several attempts to develop historical balances for N, the input by rainfall has been considered as a fixed value of around 5 Kg N ha^{-1} y^{-1}. For instance, Allen (2008) in a recent study on the retardation of the agrarian revolution in England used this value. However, by using a rigid value, site specifity is lost which is undesirable when comparing nutrient balances for regions with contrasted annual precipitation.

The annual input of N, P and K by rainfall (wet deposition) can be calculated from the concentration of these elements in rainwater (usually expressed as mg element L^{-1} or g element m^{-3}) and the volume of water (L or m^3) per unit area (m^2 or ha). Annual rainfall can vary year to year (up to greater than 100 %) and therefore when reconstructing a historical nutrient balance, annual average, calculated from a comprehensive set of data of minimum 25-50 years, should be considered. For most of the development regions rainfall data are available from middle to the end of the nineteen-century. A large temporal set of data should be analysed for the possible existence of a temporal trend in the annual rainfall by using statistical test such as

Mann-Kendall trend analysis (Mann, 1945; Kendall, 1975). To gain accuracy on the input of these elements, only weather data of the studied area or nearby should be considered.

Nitrogen dry deposition in moderate-high humid regions is negligible and usually is below an order of magnitude lower than that of wet deposition (Holland et al., 2005). Because of the difficulties in estimating dry deposition and its relatively little importance we have not made an intend to incorporate dry deposition in the nutrient balance of our study case.

Whereas it is relatively easy to obtain historical information of the annual average of rainfall, the concentration of the different elements in rainwater in historic periods are lacking because reliable methodologies for total N, P and K analyses were under develop from middle – the end of the nineteen-century. Thus, levels of these elements should be inferred from current data from the studied sites or nearby, not subjected to possible atmospheric pollution to recreate those in the past. However, in the absence of data on rainfall and/or rainwater concentration of the elements in the study area, an approach is the use of existing data in little or no polluted areas. In addition, rainwater concentration of these elements might differ in a seasonal scale and in different rainfall events within the same season even up to one order of magnitude. Therefore, to gain robustness in the subsequent calculations of this entry, it is recommended the use of weighted annual average of N, P and K concentrations in rainfall.

Usually this type of information is relatively abundant in temperate regions (where there is a strong tradition of environmental monitoring stations) but annual average rainfall, and therefore the entries in this way, in these regions tend to be twice those recorded in other regions, such as the Mediterranean.

When reconstructions of a historical nutrient balance, N, P and K inputs via rainfall are insensitive, and therefore fixed, to the type of crop or rotation or the considered periods of time, but sensible to different regions with contrasted annual precipitation.
Weighted annual average for the rainwater concentration of total N, P and K in slightly or not polluted areas range from undetectable to 0.7 g N m^{-3}, 0.2 g P m^{-3} and 3.0 g K m^{-3} (Vázquez et al., 2003), for N, P and K, respectively.

In our study case N and P wet depositions were calculated from the 100-year annual average of rainfall and the weighted annual average of total N and P analysed at in field rainwater collectors. The mean annual precipitation is of 6120 m^3 ha^{-1}, without a significant pattern during the last 100 years, whereas the weighted mean of total N and

P were of 0.57 g N-(NO_3^-+NH_4^+) m^{-3} and 0.1 g P m^{-3}, with a annual coefficient of variation between 17 to 26 %. Total K concentration in the rainwater was assumed to be 0.5 g K m^3, which in the annual grand mean value analysed in rainwater for many sites of Spain by Bellot and Escarre (1989). This value is slightly smaller that the 0.8 g K m^3 recorded by Vázquez et al. (2003) in 14 localities of Spain. Little variations both in the rainfall volume and the rainwater potassium concentration will not affect greatly to the main results of the K balance.

The input of N, P and K by precipitation was estimated as 3.48 Kg N ha^{-1} y^{-1}, 0.61 Kg P ha^{-1} y^{-1} and 3.06 Kg K ha^{-1} y^{-1}, and were a fixed values for each crop and rotation in the selected period.

The values of our study case are similar than that published elsewhere. For instance, and for N, in 16 US river basins, annual net atmospheric N deposition ranged 5.7 to 12.1 Kg N ha^{-1} y^{-1}, however annual precipitation was twice than our site. Moreover, in a recent regional N deposition study, Holland et al. (2005), showed an average of N-nitrate and N-ammonium wet deposition of 1.38 and 1.64 Kg N ha y^{-1} for US, whereas figures were 4.2 Kg N ha^{-1} y^{-1} and 2.6 Kg N ha^{-1} y^{-1} for nitrate and ammonium deposition in western Europe.

3.1.2. Inputs by formation of new soil

The formation of new soil from the bedrock mobilised P and K, which are sequestered in primary minerals, to the reservoir of soil available P and K. Since the bedrock contains not significant amount of N, this entry should only be measured for P and K. The formation of new soil comprises a set of processes which transform the bedrock into soil material. In the initial stages of soil formation there is a marked predominance of physical and chemical changes by the action of weathering and water circulation affecting the bedrocks and its mineral composition. These geochemical reactions are grouped under the concept of weathering. The climatic conditions, especially rainfall and temperature regimes, together with the type of parent material, determine the magnitude and predominance of one type or another of weathering.

Buol et al. (1989) showed a couple of decades ago, the relationship between climate and the extent of weathering, which has been updated by other authors (i.e. Cooke and Doornkamp, 1990). Estimates of soil formation for each crop type need for detailed information on weather conditions and the prevailing bedrock, and if possible the geo-referentation of both. When geo-referentiation of both, type of bedrock and crop, is not possible, the best approach to estimate the soil formation rate is the analysis of the estimates reported in several studies modified depending on climatic conditions and soil type.

Bedrock under climatic conditions characterized by annual precipitation values below 600 L m^{-2} yr^{-1} and mean annual temperature above 10 ^{o}C and a Xeric soil moisture regime, usually have low intensity of chemical and physical weathering (Cooke and Doornkamp, 1990). These conditions are fulfilled, in general, to an important area of the Mediterranean regions. Moreover, the different soil orders show varying degrees of weathering. In our study case, the mineral soils grouped under Entisols are predominant. This soil, with no distinct soil profile, is characterised by low intensity of soil formation. In the Inceptisols, also present in our study case, as its name indicates, the soil is in an incipient state because, in general, the intensity of weathering is low.

Johnson (1987) estimated soil formation rates of between 0.8 mm y^{-1} (about 1 ton ha^{-1} y^{-1}) and 0.25 mm y^{-1} (<0.5 ton ha^{-1} y^{-1}). Moreover, Morgan (1986) considered values of soil formation rates under environmental friendly agricultural practices and in soils with medium to high weathering rate of about 1.2 ton ha^{-1} y^{-1}.

In our study case, we believe that adopting a value of soil formation of 0.5 and 1.0 ton of soil ha^{-1} y^{-1} for sites of low to medium and medium to high annual weathering rates respectively, is reasonable. In case the crops and bedrock types are not geo-referentiated these values are “fixed” and should be applied for the different crops, rotations and woodland crops and for the different periods of time.

The entry of N, P and K in vegetable crops, growing in the floodplain of small-medium temporally or permanent streams, due to sedimentation of soil eroded from the surrounding hillside is difficult to quantify and have not been considered in most of the historical nutrient balance due to lack of information. Therefore, the inputs of these elements for these crops are underestimated. However, usually this is not significant at parish scale because area under this crop type used to be insignificant.

If it is difficult to estimate a value of soil formation rate, similarly is the assignation of a value of P and K content in the newly formed soil. Being aware of some degree of imprecision, we believe the contents of P and K of the newly formed soil would have been close to the those determined at present, in the absence of historical information. Given the lack of geo-referencing, values of P and K content in soil newly formed, should be those resulting from a weighted average for different soil orders found in the study area.

The entries of P and K by the formation of new soil should be the product of soil annual formation rate and soil contents of total P and K. As an example, taking into account a soil formation rate of about 0.5 ton ha^{-1} y^{-1} and a total soil K content of 1.5 % (dry weight), the K inputs to the arable soil profile is of about 7.5 Kg K ha^{-1} y^{-1}.

3.1.3. Inputs of N by natural N fixation

Biological dinitrogen (N_2) fixation is a natural process of significant importance in historic and current agriculture. Recently, Herridge et al. (2008) have reviewed and update long-standing and more recent estimates of biological N_2 fixation for the different agricultural systems, and Vitousek et al. (2002) developed and ecologically based understanding of N fixation in natural and managed ecosystems.

3.1.3.1. Symbiotic N fixation (plant-associated)

The amount of N entering the agro-ecosystem from the atmosphere via symbiotic N_2-fixing bacteria (mainly of the genus *Rhizobium*) in association with the root system of mainly legumes should be assessed in those crops types which include legumes in the rotation and for those which do not, but include a year of fallow which allow for the growth of weeds. In addition, this input should be estimate for those woody or fruit orchards crops which include weeds in a significant part of the surface (> 30 %) for at least 6 – 8 months in a year.

Estimation of the amount of atmospheric nitrogen entering the farming is difficult since an unknown part of the legume N of both above and belowground biomass, come from the soil, and is dependent on the plant species, environmental conditions and the soil available N content, among other variables.

Currently, the most precise and accurate methodologies to determine the amount of N in legumes which come exclusively from the atmosphere are based on ^{15}N analyses of legume and non legume control plants (usually grasses) growing in the same conditions, because the ^{15}N isotope signal in the plant depends on whether the nitrogen comes from the soil (relatively enriched in ^{15}N) or directly from the atmosphere (≈ 0 ‰ ^{15}N enrichment). These analyses require sophisticated equipment (mass spectrometer) and a high degree of technical expertise not available in most laboratories. There are a number of studies, the vast majority from temperate regions, often undertaken at experimental garden or incubation chambers scales using this technique given values of atmospheric N fixation for some species. However, the values cannot be directly extrapolated because: i) the amount of N fixed depends on the plant production and values in the experimental conditions of laboratories and experimental gardens differ of that in field conditions, and ii) generally these studies have been conducted on modern varieties of legume species.

There are many studies which show ranges of N fixation for most of the modern cultivated legume species. For example, Havlin et al. (2005) showed the range and the most characteristic value of atmospheric N fixation for 24 species of legumes with typical values ranging 55 Kg N ha^{-1} y^{-1} for winter peas to 222 Kg N ha^{-1} y^{-1} for alfalfa. However, these values should be taken with caution because they come from the cultivation of these species in monocultures and at optimal conditions with potentially high production levels.

Another approach, also not free of some uncertainty, is to quantify the amount of N fixed in crops or rotation types that include legume from: i) amount of N harvested (based on historical information of the yield and an estimate of the grain and straw N content), ii) amount of that harvested N which come from the atmosphere (based on current information), iii) amount of N in the root system (based on current information), iv) amount of N of the root system which come from the atmosphere (based on current information), and v) N rhizodeposition (based on current information of the amount of N fixed from the atmosphere which have been mobilized directly to the soil).

Thus, using data of yield and grain and straw N content, the aboveground legume N can be estimated, and after applying a coefficient which relate legume aboveground N with that in the belowground, the whole plant N (Kg N per Kg harvested legume) can be quantified. Finally, applying a percentage of N derived exclusively from atmospheric nitrogen (the rest comes from the soil) over the entire plant, and a percentage of plant N that is mobilized directly to the soil (rhizodeposition), it is possible to quantified the amount of N fixed per kilogram of harvested legume. The amount of N in the root system can be estimated from the percentage of N in the belowground biomass of several legume species (beans, alfalfa, soybeans, chickpeas ...) indicated by Wichern et al. (2008) and averaged 38% of total N of the whole plant. The percentage of total N in both the aerial and the root system, derived exclusively from fixed atmospheric nitrogen can be estimated, for instance, from the review of Gathumbi et al. (2002). They found an average value for the percentage of total N derived from atmospheric N ranging between 43 % (36-51 %) of *Macroptilium atropurpureum* and 79% (75-83%) of *Crotalaria grahamiana*. For all the tested species, the grand average was approximately 60%, value that can be set to estimate atmospheric N fixation by legumes. The rhizodeposition can be estimated in 18% of total N fixed, average value recorded by Wichern et al. (2008) after reviewing a set of studies.

The atmospheric N fixation, which remains in the farming after harvesting the legume grain and straw, is that of the roots system (22.8 % of the N yielded) plus that rhizodeposited (10.8 % of the N yielded). The net N input by symbiotic N fixation is thus sensible to the crop or rotation due to the legume species, throughout the species grain and straw N content, and yield.

It is difficult to estimate the amount of nitrogen fixed by the legumes in weeds communities because depends on the production and species composition, both attributes unique and characteristics of a particular site. However, this route of entry of N should be considered because could contribute significantly to the N budget for some crops types, especially in woody crops such as fruit and olive oil groves with a regular arrangement of the trees (between 50 - 70% of the area of one hectare can be occupied by weeds). A quantitative approach that can narrow the fixation of atmospheric N by natural legumes is through ongoing field studies in similar environmental and geomorphological conditions of those of the studied site. In our study case the amount of N that enter from natural legumes growing as weeds of orchard type crops (olive oil groves) and on fallow periods of rotation, has been estimated from a field experiment. Total soil N was determined in a farming which has allowed the growth of weeds (from June to April; during each April-May weeds were clearing) during 5 years and compared to that nearby farming of same soil and environmental conditions but differing in that do not allow weeds to grow (weed suppressors). Top-10 cm-soil total N content averaged 0.202 and 0.180 % for the weed and non-weeds farming, respectively. Taking into account the soil apparent density, the net soil N accumulating rate for the weed-farming was 21.8 Kg N ha^{-1} y^{-1}. Assuming that the N accumulation rate was mainly due to the atmospheric N fixation by natural legumes (both farming were not fertilised), we believe that this value is a reasonable approximation to estimate the input of N in rotations which include a year of fallow and in crops which allow the weeds to grow, despite it is likely that some of this accumulation is also due to reduced net losses of N by leaching or erosion in the weed-farming. This value is similar to that of 15.0 Kg

N ha^{-1} y^{-1} for pasture (Jordan and Weller, 1996) and is within the range of those considered by Smil (1999) to be most reliable.

3.1.3.2. Non symbiotic N fixation (free-living)

This route of entry of atmospheric nitrogen by biological fixation corresponded to that of autotrophic and heterotrophic organisms, which are not in direct symbiotic association with the root system of vascular plants. Details of the biochemistry, physiology and taxonomy of organisms capable of fixing atmospheric nitrogen without symbiosis can be found in Clark and Rosswall (1981), Gordon and Wheeler (1983) and Alexander (1984). The quantification of the amount of non symbiotic N fixation is, usually, indirect and based on incubations of soil samples in the presence of acetylene which is reduced to ethylene by the activity of nitrogenase (family of enzymes that catalyze the breakdown of the triple bond that holds the two N atoms of N_2), and the subsequent determination, by gas chromatography, of the produced ethylene. Other methodologies are based upon the ^{15}N. However, none of these is entirely satisfactory. Estimates of free N fixation in a wide range of ecosystems ranging from 0 to 30 kg N ha^{-1} y^{-1}, and generally higher values correspond to those measured or estimated in semi-arid regions. Unfortunately, the number of estimates of free N fixation in agricultural ecosystems, and the effects of environmental variables and management practices on the process is scarce and incomplete. Nevertheless, intensive and frequent tillage limits the establishment of autotrophic free N-fixing organisms (such as algae) and significantly reduces the soil content of organic carbon content, which is needed for the heterotrophic free N fixation.

Boring et al. (1988) in an extensive literature review showed some estimates of free N fixation for a wide range of ecosystems. These authors presented an average of 4 kg N ha^{-1} yr^{-1}. This value is within the range described recently by Unkovich and Baldock (2008) for different types of agro-ecosystems in different climatic regions (including that Mediterranean) of Australia. However, Boring et al. (1988) and Unkovich and Baldock (2008) pointed out that levels of N that entry by this processes are significantly reduced according to increased the intensity and frequency of tillage.

Therefore, in the absence of information from experiences in the field, it is reasonable to adopt a value of 4 Kg N ha^{-1} y^{-1} for the atmospheric N fixed by free microorganisms. The influence of tillage in this entry can be incorporate by reducing this input according to the tillage regime using a categorical scale.

Input of N by free N fixation, thus, depend of the tillage regime of each type of crop or rotation and is constant for the considered period.

In our study case we have set up a free-living N fixation of 4 Kg N ha^{-1} y^{-1}, for those crop or rotation with not or only once tillage event.

3.2. Anthropogenic N, K and P inputs

Irrigation, fertilisation and seeds application are the major inputs of N, P and K directly managed by the man currently and in historical periods.

3.2.1. N, P and K entries throughout irrigation

Input of N, P and K by irrigated water should only be considered for eventually and constantly irrigated cropland. Quantifying this input require of estimates of the annual irrigate water volume (m^{-3} ha^{-1}) and water content of total N, P and K (g m^{-3}). Eventually and constantly irrigation can be estimated from the description of the water management (type of system and frequency of irrigation) of crops in the historical records. Values of about 5000 and 3000 m^{-3} ha^{-1} y^{-1} for constantly and eventually irrigated crop respectively, would be reasonable and close to those currently used for vegetable crops.

There is no historical data on the concentration of N, P and K in irrigation water because, as mentioned earlier, there were no accurate methodologies for their analyses. However, a reasonable approximation is the use of total N, P and K concentrations in current permanent and temporary small-medium size unpolluted streams nearby the study case. As for the rainwater, intra and inter-annual variability of total N, P and K concentrations might be as high as 100 % and thus weighted average values are desirable. In our study case we have quantified values (annual average) of 2.0, 0.5 and 2.0 mg of N, K and P L^{-1}, in permanent and temporary streams in unpolluted streams.

The entries of N, P and K via irrigation are the product of the irrigation water input (m^{-3} ha^{-1} y^{-1}) and the stream water concentration of N, P and K in water (g m^{-3}). For Montefrío, assuming the above annual mean of total N, P and K in unpolluted stream water and an annual water volume of about 5000 m^{-3} ha^{-1} y^{-1}, inputs in constantly irrigated vegetable cropland are about 7.0 1.8 and 7.0 Kg ha^{-1} y^{-1}, for N, P and K, respectively, whereas figures for the “ruedo” which were eventually irrigated were 6.0, 1.5 and 6.0 Kg ha^{-1} y^{-1}, for N, P and K.

Usually at a parish scale this entry is not significant because of the general reduced area occupied by the irrigated cropland.

3.2.2. N, P and K entries by seeds application

The annual input of N, P and K by seeds application for those seeded crops such as wheat, barley, beans, and chick peas should be estimated from the annual seed application rate (Kg ha^{-1}) and species seeds total N, P and K content. The information on the rate of annual seed application for each type of seeded crop is given in historical information such as “Cartillas Evaluatorias”. In Mediterranean seeded croplands, seeds application rate during XVIII and XIX centuries usually ranged from 89 to 127 Kg ha^{-1} y^{-1} for wheat and 44 to 175 Kg ha^{-1} y^{-1} for beans.

On the other hand, seeds total N, P and K content of different crop species might be estimated from literature reviews of early journals, books or reports and/or from current analyses of traditional seeds varieties. Values of modern cultivars should be avoided because seeds total N, P and K usually are significantly higher than those traditional. In our own experiment, wheat grain and straw total N of four modern varieties were 54 % and 86 % higher than that of four traditional cultivars, on the same farming and at identical management practices. This was not true for phosphorus neither potassium. The analysis of seeds total N, P and K of seeds of traditional cultivars are a reasonable alternative for estimating the nutrient load of this entry.

The inputs of nutrient by seed application are often negligible as usually for each kilogram of seeds more than 9 are produced. In our Mediterranean study case the entry of N by seeds ranged 1.75 to 2.24, 1.78 to 7.10 Kg N ha^{-1} for wheat and beans, respectively, and was 1.66 and 1.98 Kg N ha^{-1} for chickpea and barley, respectively.

3.2.3. N, P and K inputs by fertilisation

Before early XX century, the main entry of N, P and K in the fertilised croplands was throughout organic fertilisation (i.e. animal manure). This input is calculated from the information on annual doses of manure application (Kg fresh weight ha^{-1}) and total N, P and K content of manure.

Unfortunately, most of the records in historic documents related to the manure application rate, do not distinguish the animal origin of the manure. This is particularly important because manure availability and total N, P and K content of the manure might greatly vary not only according to the species but also between varieties within the same species. For instance, Bashkin et al. (2002) reported annual accumulation of nitrogen in animal excreta of about 0.7 Kg N $head^{-1}$ y^{-1} for goat and sheep and 11.35 Kg N $head^{-1}$ y^{-1} for cattle.

However, historic records usually indicate the livestock distribution for different periods (i.e. the abundance of pig, cattle, sheep, horses, donkeys, goats and mules). Therefore, according to the livestock distribution and the annual amount of manure produced by each type of animal, the annual manure availability could be approximately estimated. However, the level of housing differs among the livestock, and therefore not all the produced manure is potentially collected. A reasonable approach is considering that only one third of the manure which is produced by sheep and goat is available taking into account that only during the night this livestock is housed.

Annual manure application rate on a Parish scale should be lower or similar to that of annual manure availability. We believe that the historic information on the annual rate of manure application refers to the manure just before being applied (after semi-composting) and not that "fresh" because the way to record the amount of manure is throughout the number of carts which were likely filled after the manure was accumulated. Information on the amount of manure produced annually for each type of animal is available in the historic records and in case of lacking of such information a reasonable approach is using early reports.

The content of total nitrogen, phosphorus and potassium of the manure (weighted average) should be estimated on the total nitrogen, phosphorus and potassium content of manure of those species of the livestock. However, the nutrient content of the manure is highly variable not only between species but also due to a given proportion of straw and the type of food. In this sense, the use of current information on the nitrogen, phosphorus and potassium content of the manure should be avoided since animal breeds and feed were marked different. We believe the best approach is the use of information (manure nutrient content) which come from early studies (report, journals, studies) and/or from current investigations (if the case) on traditional livestock breed fed with traditional food.

The amount of manure application rate for each crop or rotation at each period of time should be contained in historical documents. However, historical information at this respect, is usually expressed as number of carts applied or similar traditional units, and therefore should be previously converted to current units. In addition, usually the historical information does not detail the type of manure applied and in which crop or rotation. However, a reasonable approach to solve this difficulty is to use the weighted average of N, P and K of manure according to the livestock distribution and total N, P and K for each type of livestock.

The amount of N, P and K that enters via organic fertilisation is, then, calculated taking into account the annual dose of application (kg fresh manure ha^{-1} y^{-1}) in a given crop and the weighted mean of N, P and K (Kg element in fresh manure kg^{-1} of fresh manure) contents in the manure.

Table 2 shows the livestock distribution, manure availability and total N, P and K of the manure for our study case in middle XVIII century.

At Montefrío and for middle XVIII century, between 12.0 to 38.0 Kg N ha^{-1}, 3.8 to 11.5 Kg P ha^{-1} and 12.0 to 36.0 Kg K ha^{-1} were applied annually by manure for the "ruedo" and for the wheat-beans rotation, respectively. Neither the one-third rotation nor woody crops were fertilised.

The amount of N, P and K which entry annually throughout natural and anthropogenic processes (Kg element ha^{-1} y^{-1}) is calculated from each crop and rotation and for each period as: precipitation (for N, P and K) + new soil formation (only P and K) + plant-associated N fixation (only N) + free-living N fixation (only N) + seed (for N, P and K) + irrigation (for N, P and K) + fertilization (for N, P and K).

4. N, P and K outputs

The main routes of outputs of N, P and K to be quantified in historic and current agroecosystems are those due to harvesting and soil loss by erosion. However, for N, net losses of N via gas (N_2 + N_2O by denitrification, and NH_3 through volatilization) and by leaching, should also be taking into account.

The various transformations routes of P and K in natural and agro-ecosystems have a strong geochemical component, in which very dynamic physico-chemical processes, such as adsorption/desorption and precipitation/solubilization, are responsible for the relatively high soil retention capacity. Therefore, the P losses by leaching in historic agro-ecosystems can be considered negligible, especially when climatic conditions are characterized by annual precipitation lower than 650 L m^{-2} y^{-1}. For K, despite in the soil solution is nearly as soluble (mobile) in water as nitrate, the losses by lixiviation is relatively low because of the soil cation exchange capacity (dynamic equilibrium in which adsorption/desorption of K in soil solution with the negative charge on the surface of clay particles and/or soil organic matter) which retain in the soil a considerable amount of K.

4.1. N, P and K outputs by harvesting

The amount of N, P and K annually leaving the farming by harvesting is assessed from the harvest (Kg fresh harvest ha^{-1} y^{-1}) of each crop and rotations and the contents of N, P and K (on wet basis) at harvest. In those crops in which there are marked differences between plant parts (grain and straw) it is highly recommended to differentiate the harvest and nutrient content of both. Crops harvesting information come from the historical records, being, therefore, sensible to various periods of time. However, often the conversion of historical information to current-usable units is not straightforward. Thus, mass or volume units of the historic records are usually expressed in terms of carts and trucks with not use in modern units. Therefore, a conversion between units is essential. In the nutrient balance of our study case, we search for a traditional cart and after filled it we convert cart units into fresh mass units.

Usually, historical information gives only values of harvested grain, and therefore, it is required the application of a coefficient to infer the amount of straw linked to that of grain. This coefficient must be inferred from data of traditional crops, because it is well known that the selection of varieties (for those crops with grain and straw) has been directed toward those with greater biomass ratio grain/straw. Another approach to estimate the harvested straw from that of grain is to extrapolate information from trials in field conditions with traditional varieties, as we did in our case of study (Guzmán et al., in preparation).

Information on the content of N, P and K of the harvest come, as for seeds and manure, from early reports, studies and journals. However, another source of information is that from current experiments using traditional varieties. In our case of study, content of N, P and K for the grain and straw of wheat and barley has been obtained from a current experience under traditional and modern management practices, whereas for beans, chickpeas, olive trees, vineyards and vegetables we used the report of Soroa (1947) for varieties in the early XX century.

4.2. N losses by denitrification

Denitrification is a microbial process in which nitrate is reduced in an anaerobic or micro-anaerobic environment to N_2O and N_2, which are gases which escape to the atmosphere. On a global scale it is a key process to maintain at steady-state the atmospheric levels of N_2 restoring the biologically fixed N. Moreover, the N_2O is the third largest greenhouse gas in absolute importance (and the first in relative terms) and is indirectly involved in the destruction of the ozone layer. The main variables controlling the magnitude and temporal pattern of this process in soils are soil nitrate content and organic carbon, being temperature and soil water content (regulates the existence of anaerobic and/or microanaerobic environments) modulators of the process. For our point of view there are two mechanisms by which N is loss by denitrification in agroeco-systems. N losses by denitrification are those due to soil (baseline soil N losses) and those directly linked to organic fertilisation.

There is no a direct methodology to quantify with some precision the rates of N loss in the form of N_2 because of the relatively huge amount of atmospheric N_2 that avoid any detectable increase after an incubation period. Most techniques which assess soil N losses by denitrification are based on measuring the production of N_2O from soils (with or without fertilizer) in the presence of acetylene (which is an inhibitor of the reduction of N_2O to N_2).

Historic soil basal N losses by denitrification can be estimated by employing current models. There are many models to estimate the soil basal N losses and are grouped into: i) models based on the collection of many values from regions with different climatic conditions, different crops, management practices and different experimental conditions, ii) empirical model based on functional relationships between variables and few measurements of N losses by denitrification, and iii) mixed models that enshrine the former with the latter. In agroecosystems located in temperate regions, the implementation of the first group of models is recommended because they are mainly based on experiments conducted in these regions. The application of models of the second type in the reconstruction of historical balance is difficult because the main input variables in these models are level of nitrate content and/or organic matter (or organic carbon) or the partial pressure of oxygen in the soil. Since there is no historical information on these soil variables for the different crops, these models cannot be applied.

The application of a current model for estimating the soil basal N losses should employ general soil variables relatively easy to obtain from each crop type and rotation. Unfortunately, the use of general soil variables inevitably introduce some imprecision. Nevertheless, the soil N losses are specific for each crop type if those general soil variables can be described for each crop. Vinther and Hansen (2004) developed the SimD general model, which is based on a combination of average values of N_2 losses, resulted from a literature review and manipulative experiments at field conditions. The model takes into account the effect of soil moisture has on the process and the relationship between soil clay content and soil hydraulic conductivity and organic carbon, and establishes a relationship between denitrification rate and clay content in soil. The model establishes a functional relationship (Michaelis-Menten type) between soil clay content and N losses as N_2O. On the other hand, the relationship between N_2 and N_2O is also controlled by the clay content, and thus N_2 can be estimated from those of N_2O. The amount of N annually lost by basal soil denitrification is the sum of that of N_2O and N_2.

In case crops and rotation are georeferentiate and a soil map is available it is relatively straightforward to relate each crop type with each soil type and subsequently for a denitrification value. In our study case, despite crop and rotations are not georeferentiate, the soil map of the whole parish was available (LUCDEME, 1987). In addition, according to the distribution on the landscape of the different crops and the changes in the distribution of the major crops types, it is possible to relate each crop to each soil type, and thus for a clay content and soil basal denitrification value. Soil basal N loss by denitrification in Montefrío range 3.5 and 8.0 kg N ha^{-1} y^{-1} for the olive grove and vineyard, and irrigate vegetables crops, respectively. Hofstra and Bouwman (2005) made a compilation of values of N loss by denitrification in agricultural soils of 336 studies that varied in type and dose of nitrogen fertilizer, crop type, soil pH and drainage conditions, and technique employed. Values varied between 8 and 51 kg N ha^{-1} y^{-1}. The values of N loss calculated for Montefrio is at the lower range of the values given by Hofstra and Bouwman (2005) and also those showed by Roelandt et al. (2005) in another literature review.

In addition to the soil basal N losses there should be other N losses by denitrification linked to the applied N with the organic fertiliser. N losses by denitrification due to fertilization can be measured at laboratory conditions, experimental garden and in the field. However, their analysis requires a degree of manipulation of the experimental units and a high intensity of sampling and analysis, and specialized equipment (gas chromatograph and an electron capture detector). In the reconstruction of historical balances, the inability to perform these studies, makes that estimates of N loss by denitrification associated to fertilization was based on current models. The need to evaluate globally the contribution of different countries in the emission of greenhouse gases has resulted in the compilation of results and conclusions of many experiments to determine the relationship between nitrogen fertilizer use and emission of N_2O (and N_2) by denitrification. The result of these revisions has been the finding of a linear relationship between amount of fertilizer applied and the amount of N lost by denitrification. Following the methodology described in the IPCC (IPCC, 1997), the emission factor of N is 1.25% (1.25% organic fertilizer N lost by denitrification in the form of N_2O), and therefore, this conversion coefficient is an appropriate starting point to quantify the amount of N added with the fertilizer that is lost by denitrification. However, Kasimir-Klemedsson and Klemedsson (2002) suggested after a later comprehensive literature review, an emission value of 2.5% for different types of manures. The amount of N (kg N ha^{-1} y^{-1}) of that added with the organic fertilisation which is lost by denitrification is therefore 1.25 % (IPCC literature review) or 2.5 % (Kasimir-Klemedsson and Klemedsson review) of the N added with the manure.

Finally, the nitrogen lost by denitrification of a specific crop is the sum of basal soil denitrification and that of the organic fertiliser.

For Montefrio, the highest N losses by denitrification including both basal soil and fertilisation derived denitrification was calculated for constantly irrigated vegetables (17.8 kg N ha^{-1} y^{-1}) with an annual rate of organic fertilization of about 33.7 kg N ha^{-1} y^{-1}, whereas was minimal (4.5 kg N ha^{-1} y^{-1}) for olive grove and vineyard without any fertilisation.

4.3 N losses through volatilisation of NH_3

N losses through volatilization of NH_3 are due to the physical-chemical reaction (non-biological process) by which ammonia in the soil solution is transformed into ammonia (gas) with no change in the oxide–reduction state. The main variables governing the process are the soil ammonium content and pH. The greater of both the greater is the N loss. In addition, the degree of exposure to sunlight and soil carbonate content modulates the process; higher levels of both match with major losses. Finally, the temperature of the soil solution, the surface area exposed to the atmosphere and the resistance to NH_3 transport in the atmosphere is also modulators of the process.

The source of NH_3 emission from manure management is the N excreted by livestock. Typically, more than half of the N excreted by mammalian livestock is in the urine, and between 65 and 85 % of urine-N is in the form of urea and other readily-mineralized compounds (Jarvis et al., 1989; Aarnink et al., 1997). Urea is rapidly hydrolyzed by the ureases to ammonium carbonate, and ammonium ions provide the main source of NH_3. Ammonium-N and compounds, including uric acid, which are readily broken down to NH_4^+, are referred to as total ammoniacal-N. In contrast, the majority of N in mammalian livestock faeces is not readily degradable (Van Faassen and Van Dijk, 1987) and only a small percentage of this N is in the form of urea or NH_4^+ (Ettalla and Kreula, 1979), so NH_3 emission is believed to be sufficiently small (Petersen et al., 1998). Poultry produce only faeces, a major constituent of which is uric acid and this, together with other labile compounds, may be degraded to NH_4^+ after hydrolysis to urea (Groot Koerkamp, 1994).

To estimate N losses by volatilisation of NH_3 it should be considered, as in case of denitrification, the soil basal volatilisation of NH_3 and that linked to organic fertilization. Estimations of soil basal N losses by volatilization are poorly known mainly by methodological difficulties and because plants can act as both source and sink for NH_3 (Schjoerring, 1991). Holtan-Hartwig and Bøckman (1994) in a review of a large number of studies that estimated N losses through volatilization of NH_3, found that for croplands of temperate regions, N losses by this process averaged 1 to 2 Kg N ha^{-1} y^{-1}. We believe that in case of lacking of further information, it is reasonable the adoption of an average of 1.5 Kg N ha^{-1} y^{-1} for soil basal N lossess by this via. However, it is likely this value is underestimated for soil with relatively high pH and carbonate, and subjected to periods of high solar radiation, as usually is the case for many soils of the Mediterranean regions. This value is fixed for each crop and rotation and considered period.

Ammonia is emitted wherever manure is exposed to the atmosphere; in livestock housing, manure storage, after manure application to fields and from excreta deposited by grazing animals. Since it is reasonable to assume that the historical data on manure availability and manure application rate refer to that ready to apply, the estimation of N losses by ammonia volatilisation of that applied with the manure, must only be performed considering the applied manure. Indeed, a variable proportion, which may be significant in some cases, of the manure N may be lost through volatilization of ammonia, and depends on the timing and strategy of application, the environmental conditions, soil properties and the type of manure. Nowadays, it is believe livestock excreta accounts for more than 80 % of NH_3 emissions from European agriculture (EEA, 2009). We believe it is reasonable to accept a percentage of N loss through volatilization of ammonia of that applied with the manure. The European guide for emissions inventory (EEA, 1999) suggested that on average, 20% of N content in manure is lost through volatilization of ammonia. This average value comes from the compilation of many published studies during the end of the last century.

For our case of study soil basal soil volatilisation was set at 1.5 Kg N ha^{-1} y^{-1}, whereas fertilised linked ammonia volatilisation ranged 1.5 Kg N ha-1 y-1 (under no fertilisation) to 9.5 Kg N ha^{-1} y^{-1} for the bean and wheat rotation of four years with an annual fertilisation of about 38 Kg N ha^{-1} y^{-1}.

4.4. N losses throughout leaching

Nitrate is highly soluble in water and hardly is retained in the soil by geochemical mechanisms such as precipitation and anion adsorption. Therefore, a great part of the nitrate in the soil solution can be lost with the water that lixiviated by gravity to deeper soil profile (deeper than the maximum root exploration depth) during periods of heavy rainfall or when the soil water content exceeds the water holding capacity. The N leaching losses depend on the concentration of nitrate in the soil solution and water flow downward throughout the soil profile. Di and Cameron (2002) compiled a series of studies evaluating N losses by leaching in grasslands, forest ecosystems, and agroecosystems with contrasted management, given a comprehensive review of the main variables which control and modulate these losses.

In the absence of any historical information on soil nitrate levels of different crops and rotations, the N leaching losses should be estimated from the current general models relating N leaching losses with general soil and meteorological variables historically available. We believe, the general model proposed by Di and Cameron (2000) is an adequate starting point. This empirical model relates the amount of N lost by leaching (in each 100 L m_{-2} of lixiviate water) with the amount of potentially leachable nitrogen, by mean of a quadratic function. On the other hand, the amount of potentially leachable nitrogen is calculated as the sum of all N inputs (precipitation, nitrogen fixation, irrigation and input of organic fertilizer and seeds) minus the partial outputs (harvest, denitrification, ammonia volatilization and erosion). However, it should also be considered as an entry of nitrate that due to the net balance N mineralization and nitrification. Net N mineralisation and nitrification have been studied for grassland and pasture, forest ecosystems and agroecosystems, and depend heavily on the soil total N content. Generally, around 2 % of the soil organic N is nitrify to nitrate after being mineralised to ammonium. This percentage has been used by many authors to estimate the annual supply of available N from soil (see, for example Havlin et al., 2005). The total N content for different crops and rotations can be estimated from the most probable distribution of these crops in the soil map if available. Since the Di and Cameron model estimate the leaching nitrate for each 100 L m^{-2} of water lixiviated, the lixiviate water volume should also be estimated. This can be done from the water balances calculated from the meteorological information of the study area. Taking into account the monthly values of rainfall and evapotranspiration, and soil water content at 100% of water field capacity which is specific for each crop and rotation, the lixiviation volume can be estimated. Annual irrigation water volume should be added to rainfall for the irrigate cropland.

In Montefrio, since evapotranspiration (more than 800 L m^{-2} y^{-1}) exceed precipitation (654 L m^{-2} y^{-1}) nitrate leaching is relatively low. Values range between no N losses by leaching up to 2.8 Kg N ha^{-1} y^{-1} in the irrigate rotation of beans and wheat.

4.5. N, P and P losses throughout soil erosion

Significant amount of N, P and K might be lost out the farming by soil erosion. These losses should be estimated from the total contents of N, P and K of the top soil and annual soil loss rates.

Factors which play an important role in soil loss are the shape, texture and slopes of the relief, precipitation regime, lithology, soil texture and structure, and type of vegetation and its vertical and horizontal arrangement and, in case of agro-ecosystems, the management practices which include intensity, frequency and timing of tillage.

Currently, mapping soil erosion is performed through categorical and empirical models. The categorical models give a semantic or qualitative scale of erosion depending on the presence of symptoms of erosion (presence of streams, gullies and ridges, degree of removal of topsoil, exposure of the root system). However, these models are not suitable to reconstruct nutrient balances, because the various categories do not correspond to proportional numerical values. Among the various empirical models designed to estimate soil loss, probably the most used is the USLE (Wischmeier and Smith, 1958). This model quantifies soil lost according to several factors: rain factor (annual average of rain erosive potential), soil erodibility (which indicate the influence of chemical and physical properties of the soil), slope length, steepness of the slope, type of vegetation cover and main farming practices. Some of these factors get different values depending on a semi-qualitative assessment. However, if georeferentiation of the cropland is not possible and accurate meteorological information is lacking, the application of the USLE model became impractical.

Nevertheless is possible to have a rough estimate of annual soil lost rate from the knowledge of the most likely historic area occupied by the crops, the vegetation cover pattern of the crops and the current slope and landscape mapping of the studied area. Thus, in our study case, the annual soil lost should be negligible for the irrigated croplands because they usually are located in the plain of permanent or temporary streams. For these crops, they should be a net gain of soil particles from the river and soil erosion of the surrounded hills which have not been quantified in this nutrient balance model. Cereals and rotations of cereals with legumes likely occupied small valley areas with low-moderate slopes and, therefore, the annual rate of soil lost should be relatively small. Nowadays there are some remnants of these cropping which occupied the smooth valleys of Montefrío. Olive grove and vineyard occupied the less productive sites in areas of moderate to high slopes. Soil erosion should be higher than for the others crops.

Soil total N, P and K for each crop, rotation and woody cropland is that of the soil map (LUCDEME) when overlapping with the most likely area position of the crops. Total nitrogen losses for Monterío cultivated land ranged 0.0 for irrigated cropland to 4.2 Kg N ha^{-1} y^{-1} for olive groves, whereas values for P and K were, 0.0 to 1.3 (vineyard) Kg P ha^{-1} y^{-1} and 0.0 to 32.2 (olive groves) Kg K ha^{-1} y^{-1}, respectively.

Table 2. Livestock distribution (number of head), ready-to-apply available manure (on fresh basis) and manure nitrogen, phosphorus and potassium for Montefrìo in 1752.

	No heads	Annual fresh manure production (Kg head-1)	Annual fresh manure production (tons)	Annual manure N production (tons)	Annual manure P production (tons)	Annual manure K production (tons)
Cattle	1776	1500	2664	13.3	4.04	31.6
Horses	226	1500	339	2.03	0.61	4.83
Mules	64	1500	96	0.57	0.17	1.36
Donkeys	913	862.5	787	4.72	1.44	11.3
Working animals	2979		3886	20.6	6.27	49.16
Sheeps	21322	75.0	527.7	4.38	1.33	10.42
Goats	14565	75.0	360.5	2.99	0.90	7.11
Pigs	6860	1570	10770,2	48.4	14.7	115.2
Revenue producing animals	42747		11658.4	55.7	16.9	132.8
Manure (tons)1			15544,4	76.42	23.2	181.9

Table 3. Annual inputs and outputs and net balance for nitrogen (Kg N ha^{-1}) for the crops and rotation of Montefrio in 1752. Calculations for the uncultivated land were based on the soil type for the one third rotation.

Inpur/output processes	Main variables considered for calculations	Irrigation vegetables	Bean-wheat rotation	Ruedo (bean-whear-chickpea-barley rotation)	One third rotation	Olive grove	Vineyard	Uncultivated land
Rainfall	Annual average rainfall (m-3 ha-1) and total N in rainwater (g m-3)	3.48	3.48	3.48	3.48	3.48	3.48	3.48
Formation of new soil	Annual soil meteorisation (ton ha-1) and soil total N	-	-	-	-	-	-	-
Non symbiotic N fixation	4 as starting point value and reducing the rate according to tillage intensity	1.5	3.0	3.0	3.0	3.0	3.0	4.0
Symbiotic N fixation	Harvested grain and straw taking into account the belowground biomass and rhizodeposition	5.4	38.7	10.1	8.33	20.0	0.0	20.0
Irrigation	Irrigation volume and total N in streamwater	7.0	6.0	0.0	0.0	0.0	0.0	0.0
Fertilisation	Manure application rate and total N content in manure	33.7	38.0	12.7	0.0	0.0	0.0	0.0
Seeds	Seeds application rate and seeds content of N	10.6	4.5	1.9	0.6	0.0	0.0	0.0
Input		61.7	93.7	31.3	15.4	26.5	6.5	27.5
Harvest	Harvest and total N of the harvested considering if the case those for grain and straw	52.1	51.1	19.3	3.2	1.5	3.2	0.0
Denitrification	Basal soil denitrification and fertilised associate denitrification depending on soil clay content	14.0	18.4	7.7	6.7	4.5	4.5	6.7
Ammonia volatilisation	Basal ammonia volatilisation and fertiliser associated ammonia volatilisation	8.3	9.5	4.1	1.6	1.7	1.5	1.6
Lixiviation	Potential lixiviate N, net annual N mineralisation/nitrification and annual water balance	0.9	2.6	0.3	0.2	0.6	0.0	1.6
Soil erosion	Soil erosion rate and soil total N	0.0	0.0	3.5	3.2	4.2	3.3	1.0
Output		75.3	81.6	34.9	14.9	11.3	12.5	10.9
Net balance		-13.6	12.1	-3.7	0.5	15.2	-6.1	16.6
Aggregated net balance (tons)		-0.84	0.100	-0.09	3.67	1.79	-0.32	

Table 4. Annual inputs and outputs and net balance for phosphorus (Kg P ha^{-1}) and potassium (Kg K ha^{-1}) for the crops and rotation of Montefrio in 1752. Calculations for the uncultivated land were based on the soil type for the one third rotation.

Input/output processes	Main variables considered for calculations	Irrigated vegetables		Irrigated beans-wheat rotation		Ruedo (bean-wheat-chickpea-barley rotation)		One third rotation		Olive grove		Vineyard		Uncultivate land	
		P	K	P	K	P	K	P	K	P	K	P	K	P	K
Rainfall	Annual average rainfall (m-3 ha-1) and total P and K in rainwater (g m-3)	0.61	3.0	0.61	3.0	0.61	3.0	0.61	3.00	0.61	3.00	0.61	3.0	0.61	3.00
Formation of new soil	Annual soil meteorisation (ton ha-1) and soil total P and K	0.16	10.1	0.20	10.1	0.17	2.71	0.17	2.71	0.17	3.21	0.17	3.21	0.17	2.71
Irrigation	Irrigation volume and total P and K in streamwater	1.80	7.00	1.50	6.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fertilisation	Manure application rate and total N content in manure	10.2	31.8	11.5	35.9	3.85	12.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Seeds	Seeds application rate and seeds content of P and K	4.20	9.70	0.70	1.20	0.36	0.72	0.19	0.21	0.00	0.00	0.00	0.00	0.00	0.00
Input		16.9	61.6	14.5	56.2	4.99	18.5	0.97	6.00	0.78	6.30	0.78	6.30	0.78	5.71
Harvest	Harvest and total P and K of the harvested biomass considering if the case those for grain and straw	20.1	52.4	10.0	33.2	3.53	13.0	1.11	3.62	0.20	2.0	0.83	6.22	0.00	0.00
Soil erosion	Soil erosion rate and soil total P and K	0.00	0.00	0.00	0.00	0.67	10.9	0.67	10.9	1.08	32.2	1.30	25.7	0.21	3.23
Output		20.1	52.4	10.0	33.2	4.20	23.9	1.78	14.5	2.00	34.1	2.18	32.0	0.21	3.23
Net Balance		-3.9	9.19	4.45	23.0	0.80	-5.38	-0.81	-8.5	-1.22	-27.8	-1.40	-25.7	0.57	2.48
Aggregated net balance (tons)		-0.24	0.57	0.04	0.20	0.02	-0.13	-5.95	-62.4	-0.14	-3.27	-0.08	-1.48		

Figure 2. Annual net nitrogen (a), phosphorus (b) and potassium (c) balances for the different crops and rotation of Montefrio in 1752.

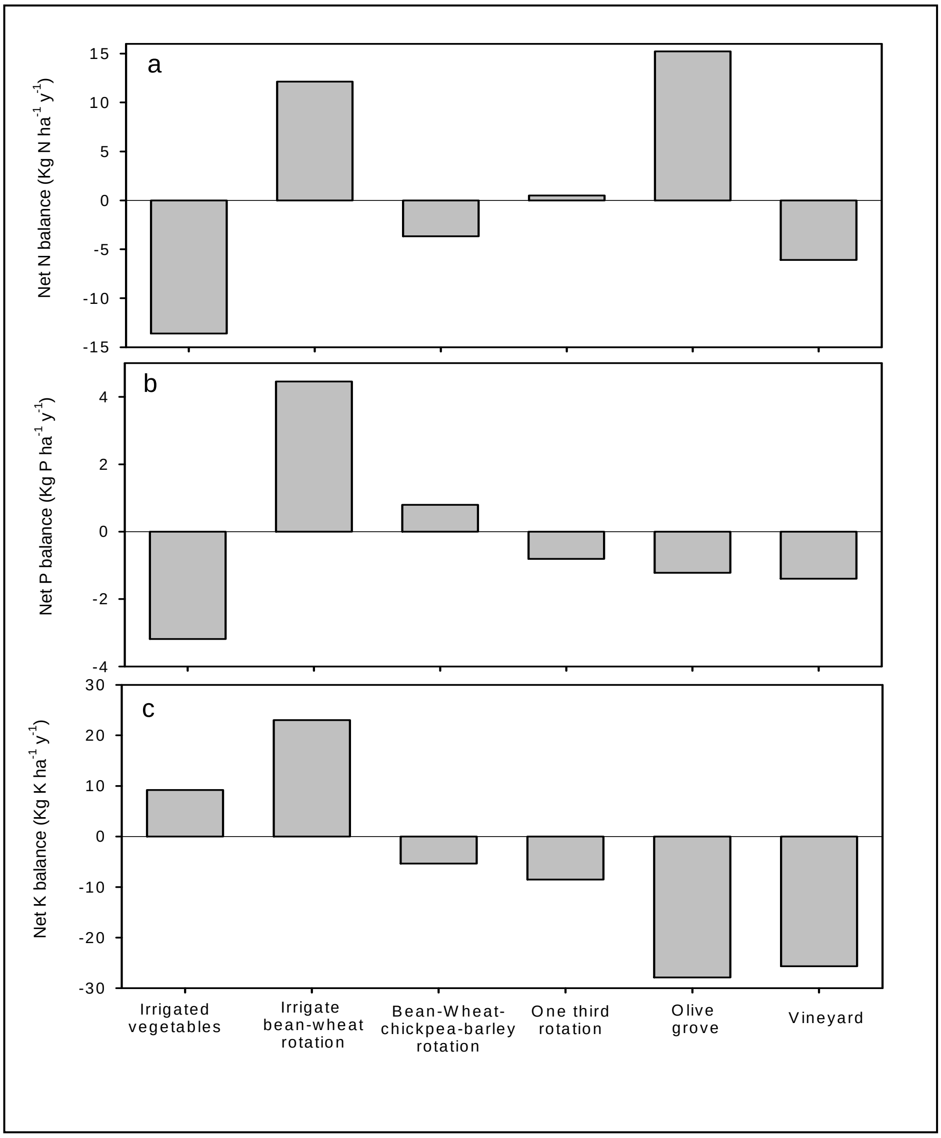
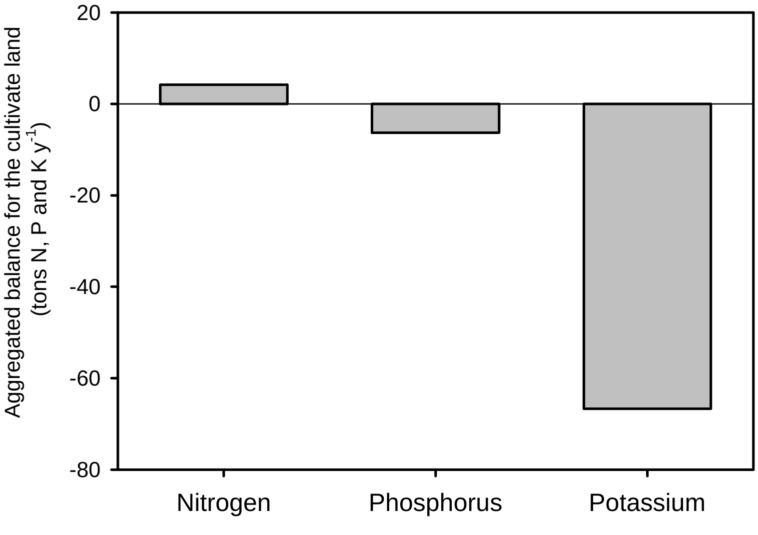


Figure 3. Annual aggregated net balance for the cropland at Montefrio in 1752.



5. Significance of the nutrient balance and model validation

Table 3 and 4, and Figure 2 show the net N, P and K balance for the various crops and rotation for Montefrío during the middle XVIII century whereas Figure 3 the aggregated balance for the whole parish. As expected, those crops or rotations which did not receive any organic fertilisation showed negative balance for P and K, and thus cropping was based on the so called "soil mining". These elements have not got a gaseous compounds of significance, and thus the only natural via to get into the farming are throughout rainwater and parent material meteorisation. When harvested P and K are higher than those natural inputs, net balance must necessarily be negative has shown for the one third rotation and the woody crops such as olive groves and vineyard. On the other hand, the soil reservoir of total P and K is huge compared to that harvested. However, most of the P and K are in an unavailable form for plants. Broadly less than 0.5 % of the total P and K are available in the soil solution. Any management practices which directly or indirectly lead to increase soil erosion has a great impact on the P and K balance, since the relative high soil total P and K content. Thus, P and K balance for those crops at moderate-high slopes and not fertilised or in low-moderate slopes but under a relatively high degree of intensification and yield should show negative balance for P and K.

In general, those crops or rotations which include legume (the four year rotation of Montefrío which included chickpea and beans) or allow for natural vegetation to growth (olive groves, one third rotation with a year of not tillage fallow) which usually contain natural legume within the plant community showed positive or near neutral balance for N. This was true even considering the removal of the legume residue of the rotation; the belowground N fixed and N rhizodeposition, not included in many others nutrient balance models, leave in the farming some of the fixed N not taken with the harvest. Taking into account the removal of the legume grain and straw of the crop, approximately the 30.0 % of the fixed N is left in the farming.

However, what consequences on the long-term stability of the harvest and on the system as a whole might have the magnitude of a negative balance? In other words, taking into account the lack of any indicator of deviation of the data and the possible inaccuracy of some of the estimations, what means from a point of view of the long term productivity for vineyard a net balance of -6.1, -1.4 and -25.7 Kg element ha^{-1} y^{-1}, for N, P and K, respectively? It is equally important for the long-term stability of the crop system a negative balance of – 6.1 for P and -25.7 for K? Where is the limit beyond which a magnitude of the balance is important from a productivity point of view?

The significance of negative (or positive) balance is highly dependent on the type of crop or rotation and of the nutrient involved. N deficiencies usually limit productivity at the short term and affect crops yield sooner, because proteins involved in the photosynthetic system is mainly made of nitrogen. This is specially true for annual fast-growing crops in which most of the nutrient demand occurred in one or two months, and with a root system with relatively low soil exploration potential, such as wheat, beans chickpea and barley. On the other hand, the only significant route of input is via atmosphere since bedrock usually contains no appreciable amounts of N. In addition, there are other additional processes of output of available nitrogen other than soil losses and yield, such as denitrification, ammonia volatilization and N leaching, not applied to P and K. P deficits, on the other hand, use to have medium term effects on yields because bedrock continuously supplied available P and the soil P retention capacity throughout complex processes (mainly adsorption/desadsorption and precipitation/ solubilisation) is high. In addition, P taken up by crop is much lower than that for N (typically at a ratio of 10 kg N to 1 kg of P). Negative balance for K can be viable in the long-term despite the harvested K is similar to that for N, because the potential for short, medium and long soil availability of K is high.

Theoretically, when the annual rate of withdrawal of a nutrient with the harvest exceeds the annual rate of supply of this nutrient, then the subsequent production is limited by this nutrient. According to the soil total nutrient content and considering the 30 cm topsoil and a given apparent density, the total amount of that nutrient in a hectare can broadly be calculated. However, as mentioned above, the pool of the plant-available form of a nutrient is much more lower than that of total. These are typically lower than 0.5 % for N, P and K. Annually, soil unavailable N, P and K is transformed to plant available N, P and K and the transformation rate is highly dependent on the pool of soil total N, P and K, among other biological, and geo-physico-chemical processes. Despite the proportion of unavailable nutrient, which is transformed to plant available form, is rather low, it is of significance for the yield. For instance as a general starting point value, that proportion is annually 2, 0.1 and 0.1 % of the total soil N, P and K. Thus, from the soil pool of total N, P and K, which can be estimated for each soil type and thus each crop and rotation, the amount of soil available N, P and K might be inferred.

Since negative balance for a given nutrient means a net removal of that nutrient, the available amount of that nutrient decreases. The number of years since crop demand for a nutrient is higher than the soil annual supply of that nutrient in indicative on the crop unsustainability. When the number of years is higher than 500 years, the crop system is sustainable from an agrarian point of view, despite soil mining.

Table 12 shows the number of years from which annual crops demand for available N, P and K meet that supply by soil from the pool of soil total N, P and K. Because irrigated vegetables, the bean-wheat, four year and the one-third rotations and the olive oil groves showed positive balance for N, these crops are N sustainable. However, this is not the case for vineyard. Under similar management and yield in four hundreds years, soil supply of available N will be lower that that taken up with yield. Any management addressed to increase vineyard yield without fertilisation should decrease significantly the sustainability of this woody crop at the long term. For P, although soil P mining was true, except for the fertilised bean-wheat rotation, the long-term sustainability (> 650 years) of the crops is guaranteed. Finally, the soil K mining, especially throughout losses by erosion, makes almost unsustainable at the long term the olive oil cropland.

There are mainly two ways for validation the nutrient balance model outlined here. The lack of any anthropogenic management practices should lead to neutral or positive balance for nitrogen and neutral or slightly negative balance for P and K. Indeed when the model have been run under the assumption of non-human alterations (removal from the model N, P and K inputs due to irrigation, fertilisation and seeds and outputs such as harvesting, and reducing the soil lost by erosion by 70 %) the balance for N was positive whereas that for P and K was almost neutral although slightly positive (Table 3 and 4). On the other hand, those crops or rotations that historically have been established during millenniums should show net values of the balance near the neutrality, as it is the case for the "ruedo" and one-third rotation for Mediterranean inland agriculture.

II. Second Section: Three Case-Studies from Andalusia (18th and 19th centuries).

The main aim of this section is to highlight the key importance of the replenishment of soil fertility on the sustainability of farming systems based on organic fertilization. The stability of crops and the sustainability of development and specialization of agricultural production in Europe during the 18th and 19th centuries depended, after centuries of continuous cultivation, on the adequate replenishment of soil fertility. It also underscores the importance of fertility replenishment at the beginning of the socio-ecological transition from agrarian metabolism towards industrialization.

To corroborate this hypothesis, soil fertilization techniques throughout the 18th and 19th centuries in farming systems of Southern Europe have been studied, immediately before the extensive use of synthetic chemical fertilizers. In such systems, soil fertility replacement was a critical factor for the long-term stability of harvests and the territorial equilibrium required in organic-based agricultures.

The low net primary production of Mediterranean agroecosystems reduced the chances of having plentiful livestock and, therefore, enough organic matter to replenish all the nutrients harvested. Some of the territory had to be devoted to animal feed and, therefore was not available for other uses. Food demands of the population forced this territory to be minimized, keeping livestock to a minimum and therefore the capacity to fertilize. Under these conditions, the soil fertility of a significant portion of the agricultural land had to be replaced by natural means i.e. through fallow. Both production of manure and fallow required a significant proportion of land i.e. high *land cost* (Guzmán Casado González de Molina, 2009) which 'had to be paid' by agricultural systems based on organic fertilization, especially in the Mediterranean region. As a consequence of this *land cost*, overall productivity per unit surface area had to be relatively low. Other options were severely restricted. The possibility to import food or feed or even manure from surrounding areas to save land was limited to short distances, except in areas with easy access to inland waterways or the sea, until the late 19th Century.

6. Three case-studies from Andalusia

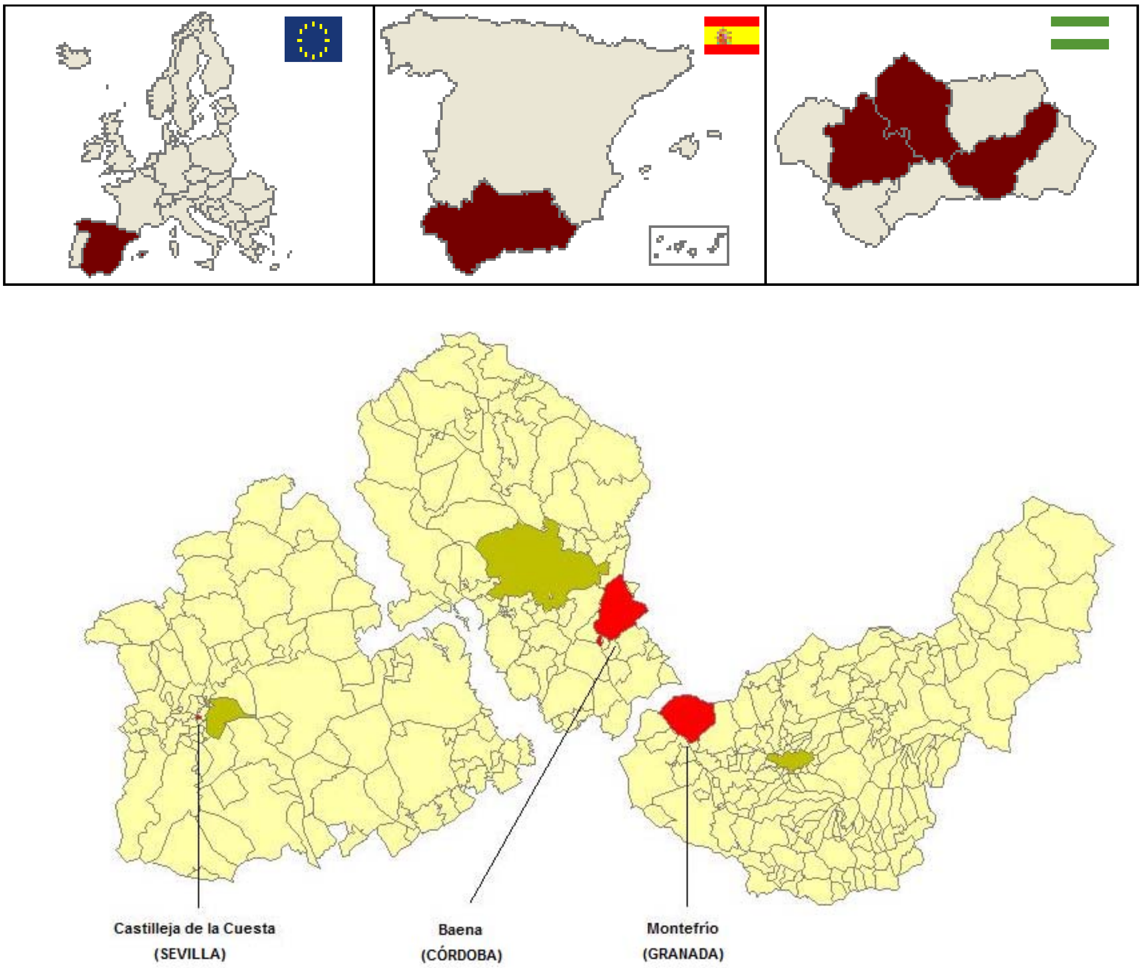
Demonstrating these hypotheses requires a detailed study, only possible at a local level. Therefore three case studies have been chosen: Montefrío (Granada), Baena (Cordoba) and Castilleja de la Cuesta (Seville) which are representative, from an edapho-climatic and socio-economic point of view, of three inland regions in Andalusia (Figure 1). Both Castilleja de la Cuesta and Montefrío were municipalities dominated by small peasant owners. Baena, however, was characterized by the predominance of large farms (*latifundios*), and renting was the main access to cultivation during the 18th and 19th centuries. Montefrío was a relatively isolated area over the study period, with limited communication possibilities and therefore cut off from the national market. This, in turn, limited the possibilities of exchanging energy and materials with the outside world and therefore agricultural expansion was highly dependent on domestic demand. Castilleja de la Cuesta, on the other hand, was a territory heavily linked not only to national demand but also to the American market due its proximity to the Seville river port. A significant portion of its production was sold outside its territory. Finally, Baena was in an intermediate position. Part of its production (mainly oil and wine) was sold elsewhere thanks to the proximity of the rail network developed during the second half of the 19th Century, although the possibility for exchange was more limited than in the case of Castilleja. Despite the diversity of situations, the similarities between the three areas are so significant that, from the mid 19th Century onwards, they displayed a common evolutionary pattern in land use and experienced a similar model of agricultural development. This model was broadly similar to that of the whole of southern Spain.

Baena covers an area of 362.51 km^2 and is located in the Guadalquivir valley, southeast of Cordoba province. Its municipality spreads over the countryside and borders the Sierras Subbéticas mountain range in Cordoba. The terrain is vaguely rugged: around a quarter of its surface has an average gradient of between 3 and 7 per cent and the remainder between 7 and 15 percent. The river Guadajoz, before flowing into the Guadalquivir, crosses the town (from southwest to west) and its tributary (river Marbella) also flows through the town. The climate is continental with average annual rainfall and potential evaporatranspiration (PET) of 641 mm and 1378 mm, respectively.

Montefrío (254 km^2) is situated in the central sector of the Béticas mountain ridges, northwest of Granada province. The climate is Mediterranean-continental, with annual precipitation similar to that of Baena, 654 mm, but with considerably lower PET (760 mm). The main feature of the Montefrío landscape is that the gradient of most of the territory is over 10 %. Agriculture management is typical of medium-mountain regions.

Finally, Castilleja de la Cuesta is situated in the western sector of Seville province, 5 km from the city of Seville itself. It has a surface area of just 2.23 km^2 spread over a small plateau near the right bank of the river Guadalquivir, 96 m above sea level. The climate is characterized as Mediterranean with oceanic influence, and with average annual rainfall and PET of 574 mm and 1392[2] mm, respectively. The gradient of most of the territory is less than 7 % and only 16 % has gradients of between 7 and 15%.

Figure 4: Location of the three case-studies.



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[2] Rainfall and PET data have been taken from: *Proyecto Lucdeme* (Montefrío-100; Ministerio de Medio Ambiente, 1997) for Montefrío; for Castilleja and Baena from *Monografía 22/98* by Consejería de Agricultura y Pesca (la Junta de Andalucía, 1998)

7. Changes in land use

The evolution of land use (Table 5) reflects the significant increase experienced in agricultural production between 1752 and 1897 (Table 6). In terms of dry matter, Baena increased its production by 70%, whereas it doubled and trebled in Castilleja and Montefrío, respectively. The data suggest that the widely-held idea in Spanish historiography that agriculture was developed extensively rather than intensively over this period (Llopis, 2004) should be rejected. The increase in productivity was only possible through the expansion of irrigated areas, the extension of more intensive crop rotations and the increase of the cultivated area (Table 5). Therefore the main strategy to increase productivity was a combination of extensification and intensification, although heavily restricted by the availability of labour and fertilizers (see below).

Figure 4: Location of the three case-studies.

	Montefrío			**Castilleja de la Cuesta**			**Baena**		
	1752	1852	1897	1752	1854	1897	1752	1858	1897
	Ha	Ha	Ha	Ha	Ha	Ha	Ha	Ha	Ha
Constant irrigation	62.2	145.3	39.3	1.7	2.1	5.0	132.1	314.0	314.0
Occasional irrigation	9.0	26.8	58.1				25.8	40.0	40.0
"Ruedo"	24.2	1324.3	2934.3			36.4	588.9	3267.9	3501.8
"Trasruedo"								3618.1	4958.8
"Año y vez"							3428.3	2666.7	3074.5
"One third" rotation	7348.0	11616.4	12311.0	74.2	28.8		21978.0	17673.6	15811.3
Olive groves	117.7	441.6	718.4	38.6	119.0	99.0	4897.6	9912.0	9912.0
Vineyards	57.8	196.4	246.1	69.3	20.1	10.2	1836.6	1569.0	1569.0
Fruit trees				6.8	31.0	14.9			
Cropland	7618.8	13750.8	16307.2	190.5	201.1	165.6	32887.3	39061.3	39181.4
Pastures	13047.7		7149.5				5326.1		
Woodland	3809.9		1019.7				49.0	543.0	543.0
Woodland and pastures		10725.5					3321.5	1979.7	1859.6
Agrarian Surface Area	24476.4	24476.4	24476.4	190.5	201.1	165.6	41584.0	41584.0	41584.0
Unproductive	1060.6	1060.6	1060.6	32.5	21.9	57.4	480.0	480.0	480.0
Total Area	25537	25537	25537	223	223	223	42064	42064	42064

The surface recorded as "woodland and pastures" indicates the impossibility of distinguishing between the two categories in historical sources.

The agroecosystems of the three municipalities were extensively exploited in the mid 18th Century, although to different degrees. The institutional reasons as to why, according to some authors (see Llopis, 2002; Amarilla, 2004), access to arable land was restricted during that Century are not applicable to our case studies. The main reason was the very low population density (around 20 inhabitants Km^2, in Baena and Montefrío) in the mid 18th Century (Table 6)[3]. The main limiting factors over this period were not the availability of arable land or fertilizer, but the shortage of manpower. A significant part of the arable land in Montefrío (28.8%), Castilleja (33.3%) and Baena (52.5%) was devoted to cereal crops in *one third rotation*, with very low yields. In addition, the area of permanent pasture, where wheat in shifting cultivation was grown irregularly, was relatively high in Montefrío (51.1%). In Baena 8.2% of the area was cultivated with wheat in an *año y vez* rotation (first year wheat, second year fallow). None of these rotations was fertilized. Fertilized-intensive production which took centre stage in the following Century, occupied much smaller areas. A combination of vegetables and fruits and in some cases cereals were the main crops grown on irrigated land. The *ruedos* (rings) rotation was located in dry land near the villages where the application of intensive work and fertilization was more feasible.

The greatest differences between the three sites were found in terms of woody crops. In Montefrío, vineyards and olive groves were marginal (0.7%) but represented almost half of the cultivated land in Castilleja (48.4%) and 16% in Baena. In Montefrío, olives trees were usually scattered and fruit-bearing (Calderón Espinosa, 2002), producing very small olive crops. However, in Castilleja de la Cuesta and Baena olive cropping was in an initial stage of transition from the above growing technique to a second phase that Calderón Espinosa (2002) termed subsistence olive groves. In this model, management was more intensive and part of the production was aimed at the market[4]. This process increased throughout the 19th Century.

The Liberal Revolution made the expansion of cultivated land and the decline of pasture land possible in several ways. In addition, population density increased due to the relative ease of cultivating new lands during the early decades of the 19th Century and the increased degree of specialization or intensification of areas already cultivated.

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[3] The population density of Castilleja de la Cuesta is higher due to its location. Most of the population worked outside Castilleja, in the *latifundios* of the Guadalquivir Valley.

[4] Historic sources point to a density per hectare in Baena of 100 olive trees, so relevant at that time. A similar density can be found for villages around Castilleja.

In Montefrío and Castilleja the population doubled, and rose by 82% in Baena (Table 6). Labour was no longer the main limiting factor of production. The increase in population density meant increased pressure on the land. Thus, liberal reforms and the food demands of growing populations stimulated the enhancement of production and productivity. Two mechanisms were responsible for the increase in production: firstly, the cultivation of new lands. The cultivated area multiplied by 2 and 1.2 in Montefrío in one Century and in just 45 years, respectively, and by 1.2 in one Century (from 78% to 93% between 1752 and 1858) in Baena (Table 6)[5]. Secondly, through the increase of rotations with more intensive labour and fertilization, which were uncommon in 1752. For instance, in the mid 19th Century, yields from the *one third* rotation were 621 Kg ha^{-1}, 781 Kg ha^{-1} and 874 Kg ha^{-1} in Montefrío, Baena and Castilleja de la Cuesta, respectively. These increases in yield were, most likely, due to the application of larger amounts of seed and labour.

Table 6: Population and agrarian production, 1752-1897

	Castilleja de la Cuesta			**Montefrío**			**Baena**		
	1752	**1854**	**1897**	**1752**	**1852**	**1897**	**1752**	**1858**	**1897**
Cropland (ha)	191	201	166	20667	13751	16307	32887	39061	39181
Production of dry matter (kg of harvested biomass)	127324	267503	254888	3157112	7386841	9470094	25718264	37782270	43419823
Production 100=1752	100	210	200	100	234	300	100	147	169
Number of inhabitants	920	1200	1852	5108	7938	10404	8000	13291	14539
Population 100=1752	100	130	201	100	155	204	100	166	182
Population Density (Km^2)	418	545	842	20	31	41	19	32	35
Production/inhabitants (kg dm)	138	223	138	618	931	910	3215	2843	2986
Production/inhabitants. 100=1752	100	161	99	100	151	147	100	88	93
Production/cropland (kg dm/ha)	668	1330	1539	153	537	581	782	967	1108
Production/cropland. 1752=100	100	199	230	100	352	380	100	124	142

"Harvested biomass" refers to food and feed production and industrial plants harvested in croplands. Biomass from pastures and forests is not included. Cropland in 1752 in Montefrío included permanent pastures through shifting cultivation management.

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[5] Castilleja de la Cuesta did not have pasture lands, obtaining its feed from the territories of nearby towns.

However, the expansion of land devoted to food was made at the expense of territory for feeding livestock (see Table 7). According to the low net primary production which characterized Andalusia's ecosystems, cattle density was already limited in the mid 18th Century. Except for Castilleja, cattle density was below the standard 20 livestock units, far from the stocking density described in humid areas of Europe. The case of Castilleja was due to the strategic location of this municipality within the region of Aljarafe. However, the trend for Aljarafe as a whole was similar to the other two cases (13.3 LU Km^2). The availability of manure per cultivated hectare was consistently low, except for Montefrío where the greater availability was due to 'revenue producing' livestock (sheep, goats and pigs). However, the manure produced by this livestock was much more difficult to collect due to their grazing management. Grazing was a viable alternative given the relative abundance of land.

Livestock size, which decreased significantly between 1752 and 1854 (Table 7), was severely affected by the expansion of cultivated land. The trend of a clear reduction in livestock size continued until the late 19th Century: it halved in Baena, dropped by a third in Montefrío and decreased slightly in Castilleja. However, there were changes in livestock composition. The number of working animals did not fall sharply because of the net increase in demand for animal traction and the increase in cultivated land. 'Revenue producing' livestock, however, was reduced by 60, 90 and 25% of the figures from 1752 in Baena, Montefrío and Castilleja, respectively, because this livestock used parts of the agroecosystem that could not be used for human food or working animals. Table 7 also shows a decrease in the density of 'revenue producing' livestock in pasture land, a phenomenon which seems contradictory. This apparent contradiction might be explained by the impact of the privatization of landmarks and commons, which almost ended the livestock income of the peasant economy, and the fact that the best lands for grazing were the first to be ploughed up.

Table 7: Evolution of livestock and manure production

Table 7

Evolution of livestock and manure production

	Baena (Co)			Montefrío (Gr)			Castilleja (Se)		
	1752	1858	1897	1752	1856	1901	1752	1854	1897
Cattle	2662	2531	1589	1776	318	770	36	7	22
Horses	551	470	470	226	86	460	55	71	65
Mules	237	290	292	64	1015	184	4	12	--
Donkeys	1860	1048	1004	913	169	569	29	86	37
Working animals	5310	4339	3355	2979	1588	1983	134	176	124
Sheep	14129	3460	2260	21322	6181	2069	15	--	--
Goats	828	235	663	14565	1883	921	--	42	15
Pigs	4368	2737	2337	6860	2475	1384	8	72	3
Revenue producing L	19325	6432	5260	42747	10539	4374	23	114	18
Total heads	24635	12629	8615	45726	12127	6357	147	290	142
LU (500 kg)[2]	4705.5	3379.1	2561.8	5147.1	1892.0	1586.9	77.3	102.8	72.9
LU wa[3]	3128.8	2734.0	2021.2	1820.9	1011.9	1187.0	75.2	88.9	71.4
LU r[4]	1576.7	645.1	540.6	3326.2	880.1	399.9	2.1	13.9	1.5
LU/ km2	11.32	7.64	5.76	21.03	7.73	6.48	40.46	51.16	43.92
LU/ cropland hectare	0.14	0.10	0.07	0.68	0.14	0.10	0.40	0.51	0.44
LU r/pasture land	0.18	0.10	0.09	0.20	0.08	0.05	--	--	--
LU wa/cropland ha	0.10	0.08	0.06	0.24	0.07	0.07	0.39	0.44	0.43
Manure (tons)[5]	19870	16221	12160	20440	11029	9263	283	457	261
Manure/cropland ha	0.6	0.5	0.3	2.7	0.8	0.6	1.5	2.3	1.6

Source: authors' own data, see text

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[2] Live weight figures for every type of cattle have been taken from the mean values given by García Sanz (1994): cattle (371 kg); horses and mules (326 kg); donkeys (172 kg); pigs (77 kg); goats (34 kg) and sheep (30 kg)

[3] Large units of working animals

[4] Large units of revenue producing livestock (sheep, goats and pigs)

Historical Sources: In order to assess surface areas, cattle, yields and production costs, the following sources were used: for 1752 The Ensenada Cadastre, both the General and Specific Responses. For the 19th Century Amillaramientos de la riqueza rústica were used [similar to a cadastre for the payment of land taxes], Cartillas Evaluatorias [Assessment Notebooks] and Trabajos Agronómicos de la Comisión Central de Evaluación y Catastro [Agronomic Reports by the Agrarian Advisory Board]. All of these sources are kept at the Public Archives of Castilleja de la Cuesta, Montefrío and Baena. In addition, we used Notary Documents included in the Provincial Historical Records of Seville and Cordoba, Granada. We also used the wealth documents of the Servicio Agronómico Provincial [Provincial Agronomic Service, 1880-1916]. To compare land uses and agrarian surface areas we took into account data from the Instituto Geográfico y Estadístico (Geographic and Statistical Institute, 1871-1873), published in the Statistical Yearbook of Spain (1888).

The decline of working animals (per hectare of cultivated land) also seems contradictory given the increase in agrarian production recorded in the three case studies. From relatively high figures (0.10 to 0.40 Large Units of livestock, LU, per ha cultivated land), it dropped to 0.06 and 0.08 LU per ha cultivated land. It is likely that working animals, especially cattle, were affected by the decline in pasture, whereas horse-type livestock (horses, mules and donkeys) adjusted their numbers according to the need for traction and transport, always minimizing any competition with cereal food).

As a result of the general reduction in livestock size, there was a net reduction of the fertilization capacity, which decreased particularly in Montefrío (54%) and Baena (39%) but remained almost unchanged in Castilleja. Therefore, the rise in production in the 19th Century could not have been more intense due to the clear drop in organic fertilization capacity. The decline in agrarian production per capita shown in Table 6 is explained by this fact. It seems clear that the imbalance between cultivated land and land dedicated to animal feed, at a time when large shipments of grain, straw and manure were limited, had this effect on fertilization capacity.

The potential development of agriculture practiced in the 19th Century in the agroecosystems of Baena, Montefrío and Castilleja de la Cuesta was close to its limit in the last decade of the 19th Century. The possibilities of increasing cultivated land were very limited in Montefrío and almost impossible in Baena and Castilleja. In general terms, there was a stagnation or even a reduction in yields, with the exception of the woody crops.

Perhaps the most obvious case was that of the *ruedos*, in which rotations de-intensified and yield dropped off. In Baena and Montefrío yield decreased to 1719 kg of dry matter ha^{-1} y^{-1} and 1344 ha^{-1} y^{-1}, respectively. The most likely reason lies in the need to increase human food production at the expense of forage legumes. In Montefrío, for instance, there was a change from a two-year rotation in 1858, alternating wheat and beans, to a four-year rotation, less productive and for food, in which two years of wheat alternated with one of chickpeas and another of beans. Similarly, in Baena, a three-year rotation (beans, wheat and barley) was replaced by another of fallow, wheat and barley in which production focused on wheat despite a decrease in annual production. So, how can the aforementioned rise in production between 1854 / 8 and 1897 be explained? It is quite likely that it was achieved at the expense of the pool of soil nutrients. The decline, except for Castilleja, in the amount of available manure per hectare of cultivated land, which was half and one fifth in Baena and Montefrío, respectively, confirm the above consideration.

8. Methodology and sources used

To assess the effects of the temporal trend in production, a nutrient balance study was performed at two different scales: a crop or rotation scale to determine their level of sustainability throughout the observed variability in land use, and at an aggregate scale (whole territory) to test for the degree of sustainability of the whole system. We have described in the first section the methodology used to build the nutrient balances.

Assessing nutrient balance for the past is complex because of the difficulty estimating values for some variables. Therefore, results can only be taken as tendencies and trends and not as exact values. In addition to the uncertainty related to complex processes of the nitrogen (N), phosphorus (P) and potassium (K) cycles, the literature on nutrient replacement in edapho-climatic conditions similar to those of Andalusia is scarce. However, many of the values for the variables needed to perform the nutrient balance assessment have been taken from various field experiments currently taking place in organic farming. Elsewhere, we have insisted on the utility of studies dealing with pre-industrial farming systems (González de Molina & Guzmán Casado, 2006; Guzmán Casado & González de Molina, 2007 and 2009) for the adequate management of current organic agroecosystems because of the similarity between the two. Similarly, data from current field studies performed in organic farming systems with organic fertilization might improve our knowledge of traditional agricultural systems. Data which cannot be provided by historical sources or reconstructed by current simulation models might be given through experimentation. The crop extraction of N, P and K of traditional varieties, or symbiotic N fixation by natural weeds in olive groves or during fallow periods of cereal rotations are clear examples.

Table 8: Methodology used to asses nutrient balances

		INPUTS AND OUTPUTS	MAIN VARIABLES INVOLVED	MAIN SOURCES OF INFORMATION
INPUTS	Natural	Rainfall	Mean historic records (site-specific). Total N, P and K. concentration in rainfall.	Weather station (data > 25 years). Current data (rainfall collectors) from non-polluted sites.
		Non symbiotic N fixation	Bibliographic mean (depending on intensity and frequency of tillage).	Scientific review.
		Symbiotic N fixation in cultivars with seeded legumes and/or weed legumes	Total N in aboveground plant biomass. Total N in belowground plant biomass. Percentage of total N of atmospheric N origin. Rhizodeposition. N fixed by weed legumes.	Harvest and total N in harvest (traditional cultivars). Root biomass (scientific review) and total N content. Scientific reviews. Scientific reviews. Results from field experiment on comparable sites.
		Soil formation de novo	Soil meteorization rate. Weighted average of total soil P and K content.	Estimated (climate conditions and main soil type). Soil map (LUCDEME).
	Anthropogenic	Irrigation	Estimated historic water flow. Water concentration of total N, P and K.	Estimated (historic records). Current mean concentrations of permanent non-polluted streams.
		Organic fertilization	Weighted average of total N, P and K content in made-manure. Made-manure application rate.	Historic records. Historic records.
		Seeds	Seed content of total N, P and K. Seed application rate.	Historic records. Historic records.
OUTPUTS		Crop harvest	Harvest. Total crop content of N, P and K.	Historic records. Historic records plus results from current field experiments.
		Denitrification	Soil silt content. Total N applied with manure.	Current model. Soil map. Historic records.
		Ammonium volatilization	Bibliographic mean. Total N applied with manure.	IPPC model. Historic records.
		N lixiviation	Estimated lixiviated water volume. Partial net balance. Estimated annual N mineralization.	Current model. Weather station (data > 25 years). Current data.
		Soil losses	Soil losses rate. Weighted average of total soil content for N, P and K.	Estimated. Soil map (LUCDEME).

9. Nutrient balances: results

Results of the nutrient balances seem in general reasonable. Crops or rotations where manure was applied display a positive balance, whereas those without manure were negative for all or some of three elements. However, the magnitude was different for various crops or rotations with different significances from short, medium and long term viability. Another result which seems obvious but is important when testing the model is that crop types or rotations which include legumes and/or a year of fallow with natural weeds or woody crops with natural weeds for most of the year (such as olive and fruit groves) displayed a positive balance for N.

The strategy adopted for the organization of cultivated land had a significant impact on nutrient balance. In Castilleja de la Cuesta (Seville) there were two strategies. As mentioned before it was an area of relatively intensive production linked to the market of Seville and the River Guadalquivir. The presence of subsistence crops, especially cereals and legumes, was much lower than in the other two areas studied, which were typical of east Andalusia and west inland areas.

Agrarian territory was divided into farms with access to irrigation and dry lands where herbaceous crops coexisted alongside woody crops. The rotation of irrigated crops in the mid 18th Century included a predominance of vegetables that supplied the surrounding area and/or for self consumption, taking into account the lower surface area. There was an unknown number of orange trees scattered around some of these farms. Nutrient balance for the irrigated land showed strong deficits due to the lack of manure application (Table 9). Historic sources do not record any manure application. However, according to the yield (between 12 and 19 tons y^{-1}) it is feasible to assume that manure was applied. The same is true of the data for 1854. Yields were similar to those obtained in 1880 and 1897, periods for which historic sources recorded application rates of about 14.7 and 16.8 tons of manure per hectare per year. It is reasonable to think that in 1752 and 1854 management was similar, with comparable manure doses. Under these conditions, the balance would be positive.

Non-irrigated land was divided into three distinct parts. One was devoted to fruit trees, some of which had access to irrigation water and manure at the end of the 19th Century, in accordance with the increased level of specialization sparked by growing food demands from Seville. The fruit trees grown in the 30 hectares allocated in 1854 were highly diverse and included apples, plums, pears, apricots, cherries and peaches among others. Little is known about the density of plantation. In any case, the balances were negative, which is typical of non fertilized crops, except for 1897 when yield was around 7000 kg of fruit ha^{-1} y^{-1} and manure was applied at an annual rate of about 2.25 tons (Table 9). However, N fixation by natural legumes which grew during the winter and early spring outweighed the harvested nitrogen.

Table 9: NPK balances in kg element/ha*year in Castilleja de la Cuesta, 1752-1897

Table 9

Balances of nitrogen (N), phosphorus (P) and potassium (K) in kg/ha* year in Castilleja de la Cuesta (Seville) 1752-1897

	Constant irrigation	One third rotation	“Año y vez” rotation	Olive groves	Vineyards	Fruit trees
N						
1752	-25.7	-0.5	--	12.0	-5.9	14.7
1854	-32.6	-4.6	--	4.0	-16.6	10.7
1880	33.9	--	18.4	5.5	-18.8	8.7
1897	33.9	-17.6	--	7.3	-0.1	--
P						
1752	-16.3	-1.1	--	-0.9	0.7	-0.6
1854	-16.9	-2.7	--	-2.1	-3.4	-1.2
1880	8.3	--	5.1	-1.8	-3.9	-2.8
1897	8.3	-5.8	--	-1.6	3.5	--
K						
1752	-29.7	-12.9	--	-15.8	-13.7	-12.7
1854	-30.2	-19.5	--	-20.8	-35.4	-22.5
1880	46.2	--	-1.4	-24.6	-40.9	-29.0
1897	46.2	-39.4	--	-21.4	-22.1	--

“—“: means that such a crop or rotation did not exist for this year

Source: Catastro de Ensenada 1752, Amillaramientos 1854, 1866 y 1897. Respuestas Generales 1752, Cartillas Evaluatorias 1853-60, 1880, 1882, Trabajos Agronómicos de la Comisión Central de Evaluación and Catastro 1897 AMCC.

Another part of the dry land was used to grow cereals as the main subsistence crop. Their predominance was declining as the agroecosystem was specializing in woody crops, especially olive groves. In the middle of the 18th Century, *one third* of the rotation (with unseeded fallow) gave substantial yields (around 900 kg ha^{-1} or 9 kg per kg of seed). The balance for N was equilibrated but strongly negative for P and K. In about 1854, yield increased and thus the balance was even more negative. The rotation probably worked because of the removal of considerable amounts of P and K and, to a lesser extent, N. Perhaps the lack of nutrients explains why in 1880 the rotation system used was *año y vez con barbecho semillado* [first year wheat and second year seeded fallow] with manure applied early in the rotation at a rate of 16.8 ton. Yields increased significantly to over 1,500 kg of wheat and nearly one ton of beans and chickpeas in the rest year. The presence of legumes and manure explains the positive balance.

By the end of the Century (1897) rotation had changed again. Beans were followed by wheat and finally barley in a three year rotation. Despite the increase in intensification, the rotation was not fertilized. The sources explicitly record this assertion: "This land is not usually fertilized". Wheat yields decreased but were partially counterbalanced by the yields of beans and barley. Only the shortage of organic fertilizers could explain this type of rotation, which extract substantial amounts of phosphorus, potassium and, especially, nitrogen from the soil. It is possible that surplus manure produced by livestock was used for this rotation, alleviating, at least partially, their nutrient shortage, as explained below.

The rest of the dry land was used for dry wood crops including grapevines and olive groves. Throughout the period studied, they were becoming increasingly important. For both crops, historic sources do not record any fertilization, except for grapevines in 1897. The expansion of olive cultivation was greatly significant, almost 100 ha. However, during the 18th Century the degree of intensification was fairly low, with annual yields of between 300 and 600 kg ha^{-1}, mainly due to the management applied and low tree densities. Undoubtedly the cultivation of olive trees was not only directed at selling olive oil production. Yields (between 800 and 1500 kg ha^{-1} olives) were significant in the mid 19th Century, and even higher, according to the historic records, in 1880 (between 1200 and 2000 kg of olives) and 1897 (from 900 to 1600 kg). It is likely that the natural weeds which included forage legumes contributed to the replenishment of nitrogen removed by harvesting and pruning. Nitrogen balances were positive, although this was not true for phosphorus, which registered a significant although not very large deficit, and potassium with significant net losses.

Grapevines became important in terms of surface area in the mid 18th Century but significantly declined throughout the 19th Century to occupy a little over 10 hectares in

1897. In the latter period, this crop was no longer grown for the production of wine, but rather for table grapes. Yields doubled from 1752 (between 300 and 1100 kg ha^{-1}) to 1854 (2300 kg ha^{-1}) and increased by 250 % from 1854 to 1880 (5900 kg ha^{-1}). This clear intensification is only possible at the expense of a significant deficit in the balance of potassium, phosphorus and especially nitrogen. Not surprisingly, the new rise in yield (between 4400 and 6600 kg ha^{-1}) was only possible through the application of a significant amount of manure (32,000 kg) every five years. Except for the nutrient balance of this period, during the 18th and most of the 19th Century balances were negative, suggesting that this form of cultivation was linked with nutrient mining. In other words, this area of Seville decreased its *natural capital* at the expense of vine exportation. The specialization of vineyards to produce table grapes was only possible through the application of manure. Without a substantial increase in fertilization capacity, the competitive success achieved at the turn of the Century would have been almost impossible.

Since there was a relative abundance of useable cropland (20 and 19 inhabitants km^{-2} in Montefrío and Baena, respectively), in the mid 18th Century, this land was organized in Montefrío and Baena according to different levels of intensification. This vast territory was occupied on the basis of small and major villages and large units of population settlement around small clusters called *cortijos* or *cortijadas*. Intensification decreased as the distance from the cluster increased, following the model described by Von Thünen and more recently by Paul Krugman and others (Krugman, 1991; Fujita, Krugman and Venables, 2000). Closer to inhabited areas and near to watercourses, farming consisted of small plots of arable land with access to irrigation, used for vegetable, fruit, grain and legume crops. The surrounding land was occupied for the cultivation of cereals and legumes for both human and animal consumption. Any available manure was preferably applied to these croplands, because of the savings in transport costs and labour. Hence, the largest part of the cultivated area was devoted to wheat or barley in a *one third* rotation which included *barbecho blanco* (unseeded fallow) and with a fairly modest dose of seed and therefore yield. Modest seed dose and yield was not a problem because of the relative abundance of land. Finally, there were extensive areas dedicated to woody crops, most of them in reclaimed land from the bush or in arable land fairly unsuited to agrarian purposes, which included vineyards and olive groves, which received relatively little man or animal labour. Still in 1752, a very important part of both municipalities remained uncultivated. In both territories the livestock size was relatively high (21 and 11 LU km^{-2}, respectively). In both territories, trends in cropland tended towards intensification. The *ruedos* and vineyards expanded, as did the olive groves, which also increased their level of intensification. Unlike Castilleja, in Montefrío, the pressure for intensification was not stimulated by the regional and national market, but thanks to the population growth enhanced by access to land property (*repartos*) and by its own demographic dynamism. Baena sat somewhere in between the situations described in Castilleja and Montefrío. Cereal, vine and olive production was higher than local demand and the surplus was allocated to the national market and even exported abroad.

Despite the different strategies in arable land distribution and destiny of the yield, the nutrient balances in Montefrío and Baena show similar trends to those of Castilleja de la Cuesta. Crops or rotations with access to manure displayed, in general, positive balances (i.e. surplus of nutrients), and unfertilized areas tended to be negative, only alleviated in the case of N by the N-fixing of legumes or weeds (olive groves and cereals in the fallow third).

Table 10 shows the nutrient balances for Montefrío. The negative sign of the constantly irrigated crop (vegetable production only) in 1752 and 1856 is due, just as in Castilleja de la Cuesta case, to the lack of information available in historical sources. Assuming a similar fertilization dose to that recorded in the *Trabajos agronómicos* [Agronomic Reports] of 1901 (20,000 kg of manure ha^{-1}), the balance would have been positive. This assumption seems logical given that, between 1752 and 1852, there was no shortage of manure. Similarly, the balances in occasional irrigation crops, with similar yields and smaller manure application doses, were also positive. The main reason is that these crops were rotated on a biennial basis with cereals and legumes (except in 1752 where one year of fallow was added). In this rotation model, legumes were a key element of balance. Few data are available for the rotation of constant irrigation crops, except that vegetables were the main crop. Similar problems were found for Baena for both irrigation models, and in this case our estimates were based on data from Montefrío and Castilleja.

Table 10: NPK balances in kg element/ha*year in Montefrío, 1752-1897

Table 10

Balances of nitrogen (N), phosphorus (P) and potassium (K) in kg/ha* year in

Montefrío (Granada) 1752-1897

	Constant irrigation[1]	Occasional irrigation[2]	"Ruedos"[3]	One third rotation	Olive groves	Vineyards
N						
1752	-13.6	7.8	-3.6	0.7	15.2	-3.7
1852	-6.0	5.0	6.2	5.0	5.5	-8.9
1897	6.1	--	2.1	0.1	4.3	-8.9
P						
1752	-3.1	2.6	0.8	-0.6	-1.2	-1.1
1852	-1.2	1.9	-0.2	-1.5	-2.7	-3.4
1897	3.6	--	-0.4	-1.4	-2.9	-3.5
K						
1752	9.1	18.0	-5.3	-12.1	-27.8	-23.2
1852	13.0	7.1	-7.4	-17.2	-53.2	-53.4
1897	29.9	--	-12.8	-17.2	:-54.1	-53.4

"--":means that such a crop or rotation did not exist for this year

1. With an annual crop in a rotation of wheat and vegetables; 2. With a biennial rotation of beans and wheat; 3. With a four-year rotation of beans - wheat - chickpeas - wheat.

Source: Catastro de Ensenada 1752, Amillaramientos 1852 y 1897. Respuestas Generales 1752, Cartillas Evaluatorias 1856, 1887, Trabajos Agronómicos de la Comisión Central de Evaluación and Catastro 1901, Archivo Municipal de Montefrío

In Montefrío, the *ruedos*, also fertilized, displayed negative balances for N and K in 1752, though not very significant due to low intensification. The nutrient balances for Baena were more equilibrated (i.e. positive or near zero). The rotation systems used in both municipalities combined cereals with legumes, thereby increasing inputs of N to the soil and food per unit area for both man and livestock. We believe that this rotation, which eliminated fallow due to the application of manure, represented the specific "agrarian revolution" of southern Spain[6] and spearheaded the intensification of production experienced by Andalusia in the 19th Century.

In Montefrío in 1752, rotation consisted of wheat followed by beans and then chickpeas and, in the last of the four years, green barley and rye for livestock feed. As with constant irrigation crops, the deficit in nutrient balance could well be attributed to the quality of information contained in the *Respuestas Generales del Catastro de Ensenada* [General Responses of the Ensenada Cadastre, 1752]. We believe that the historical source of 1897 is much more reliable, because information was collected and recorded by agrarian officials from the Provincial Agricultural Advisory Board. In this case, the P and K deficits are probably due to a shortage of manure, which, as we shall discuss later, affected arable land in the area. Yields in this period were notable for that time and for dry arable land: 1900 kg ha^{-1}, 1200 kg ha^{-1}, 260 kg ha^{-1} and 1100 kg ha^{-1} for beans (first year), wheat (second year), chickpeas (third year) and green barley or rye (forth year), respectively. The balance for 1852 is more equilibrated (closer to zero) due to the higher dose of manure used (15.0 tons) and because of the alternation of wheat with beans, to the detriment of chickpeas (for human consumption only), which display a relatively limited symbiotic N-fixation capacity. Later, in 1897, chickpeas appeared again coinciding with the food shortages and social crisis of Montefrío.

In Baena, the rotation system, which was fertilized with manure at a rate of 1269 kg ha^{-1}, combined wheat and barley (year 1) and legumes (year 2) for both human consumption and animal feed ('yeros' --*Vicia ervilia*--, lentils…). Yields were relatively low and accounted for 700, 350 and 600 kg ha^{-1} of wheat, barley and legumes, respectively. Low yield with some manure and legumes explain the positive balances. In that period, nearly 600 ha were dedicated to this rotation system in Baena, indicating a higher degree of intensification than Montefrío where it only occupied 24 ha. In the mid 19th Century, the particular agrarian revolution of southern Spain had demonstrated its benefits and this rotation expanded 5.4 fold, accounting for 3268 ha. The yields had increased, ranging between 700 and 1000 kg for beans, 760 and 1135 for wheat and 900 and 1400 for barley (in a three-year rotation). Even though the manure application rate

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[6] The rotation could last two or three years and combined cereals (wheat and barley) with leguminous crops (beans or, in some cases, chickpeas), grown to feed both animals and humans. This rotation also entailed the suppression of fallow and a major increase in N through symbiotic fixation. It could be considered a Mediterranean adaptation of the 'mixed farming' system characteristic of the Agricultural Revolution.

remained unchanged, the presence of beans made the balance for N positive. At the end of the Century, the area allocated to this rotation had risen again, although only slightly (3502 ha), but not overall (three years) yield because the year in which beans were grown was replaced with a year of fallow. As a consequence of this strategy, wheat (between 900 to 1600 kg ha^{-1}) and barley (between 800 to 1600 kg ha^{-1}) production increased. Even though overall yield decreased, the balance was negative, probably due to the reduction in the manure application rate to 6.0 tons.

For the 19th Century, the historic sources described another type of rotation not indentified for Montefrío: *trasruedos*. The *trasruedo* was a three-year rotation system that occupied arable land immediately after the *ruedo*, alternating two years dedicated to barley or *escaña* (*Triticum spp*., a primitive wheat) with a third year of fallow. Manure was not added. Consequently, yields in the mid to late 19th Century were low, ranging from 350 to 700 kg of barley ha^{-1} in each of the two years.

The existence of the *año y vez* model of rotation in Baena, which alternated wheat and barley without fertilization with fallow in the second year, can be explained by the increasing interest in intensification. Yields were low (560 and 250 Kg ha^{-1} for wheat and barley, respectively). However, during the mid 19th Century, yields had increased to 719 Kg ha^{-1} for wheat. Yield remained unchanged until the late 19th Century. Due to the lack of fertilization, this rotation could only be maintained with the reservoir of soil nutrients; i.e. by mining. Recognition of this mining is important because many politicians and scholars have argued, since the end of 19th Century, that this rotation was the peasant alternative to the extensive *one third* rotation of large farms in Andalusia, given its high labour intensity. We strongly believe that this rotation was not sustainable, at least in Baena. This rotation existed in Castilleja de la Cuesta as well, but demanded manure which was severely limited by livestock size.

The rotation which occupied the most arable land was dedicated to grain production and was managed on a *one third* basis, combining wheat, rest and seeded fallow in a three-year cycle. Yields in Montefrío were rather low (around 400 kg ha^{-1}) and slightly higher in Baena (700 kg ha^{-1}). This form of management was the consequence of a manure shortage, which was offset at the expense of a high land cost. The low population density in 1752 could explain the large scale and extensive nature of this system, as shown by its poor yields. Under these conditions, the N balance attains equilibrium or an insignificant deficit. Nevertheless, from the very beginning this rotation displayed a negative balance for phosphorus and potassium. This fact might explain that the sole application of superphosphates during the early 20th Century significantly increased yields. In the mid 19th Century, this rotation occupied less land due to the expansion of *ruedos*. Population growth explains the intense increase of rotation and yields, which reached 900 kg ha^{-1} of wheat every three years for both sites. This situation must have been fairly common throughout the dry cereal lands of Andalusia: an equilibrated N balance, mainly due to the legumes of the natural weeds in the year of rest, and significant deficits for P and K. A rotation as widespread as this was only possible due to the soil's P and K reservoir; i.e. through mining.

Montefrío and Baena are representative of the edapho-climatic conditions of inland Andalusia, where specialization in woody crops gained importance during the 19th Century, a prelude of the main productive orientation of the 20th Century. Therefore, it is interesting to know the nutrient viability and sustainability of this mode of cultivation. At the beginning, this specialization in Montefrío was marginal with a limited presence in cereal farms and rarely grouped to form a farm. Historic sources record a density of about 22 olive trees per bushel, about 46 per ha, half the density registered two centuries later, with yields always below 250 kg ha^{-1}. Cultivation was scattered with low labour, as described by Esther Calderon (2002). In the mid 19th Century, yield increased (to between 450 and 1050 kg ha^{-1}) for the same reasons mentioned above for Castilleja: increasing tree density and labour. This process of improvement, and also intensification, continued during the second half of the century, as suggested by the further increase in yield (between 650 and 1300 kg ha^{-1}) recorded in the Agronomic Report of 1897.

Table 11: NPK NPK balances in kg element/ha*year in Baena, 1752-1897

Table 11

Balances of nitrogen (N), phosphorus (P) and potassium (K) in kg/ha* year in

Baena (Córdoba) 1752-1897

	Constant irrigation	Occasional irrigation	"Ruedo"	"Trasruedo"	"Año y vez" rotation	One third rotation	Olive groves	Vineyards
N								
1752	-1.33	--	1.2	--	-3.3	-0.3	0.7	-7.1
1858	9.79	2.98	-4.7	-4.4	-2.9	1.5	0.3	-9.1
1897	-7.78	-1.96	-9.8	-4.4	-3.4	-0.9	-3.4	-16.8
P								
1752	1.74	--	3.6	--	-2.4	-1.5	-2.8	-1.5
1858	-12.40	-2.25	0.1	-1.3	-2.9	-1.6	-2.8	-2.0
1897	-3.26	6.91	-2.1	-1.3	-3.3	-2.1	-3.4	-3.5
K								
1752	15.95	--	3.4	--	-16.5	-13.1	-38.3	-30.6
1858	13.12	15.36	-12.6	-10.6	-16.5	-12.8	-38.7	-34.4
1897	27.22	30.34	-21.8	-10.6	-22.9	-23.5	-42.3	-45.8

"--": means that such a crop or rotation did not exist for this year.

Source: Catastro de Ensenada 1752, Amillaramientos 1852 y 1897. Respuestas Generales 1752, Cartillas Evaluatorias 1856, 1887, Trabajos Agronómicos de la Comisión Central de Evaluación and Catastro 1901, Archivo Municipal de Baena

Olive grove management was more intensive in Baena, mainly because of the special suitability of this are to olive farming. Over a thousand hectares were occupied by a highly productive olive farm (between 1100 and 1600 kg olives ha^{-1}) for that period. The remainder, up to 4897 ha, according to the Ensenada Cadastre (1752), was planted with less productive olive trees, although with production levels (500 kg ha^{-1}) which doubled that of Montefrío. In the mid 19th Century, Baena had just over 3000 ha of olive groves, following a sharp decline at the end of the Old Regime, when the monopoly of two aristocratic-owned mills in the town choked production. The unchanged yields (between 780 and 1600 kg ha^{-1}) suggest that by the middle of the century, the intensity of cultivation remained unchanged. However, in the second half of the century intensification increased. By 1872, Baena had almost 10,000 hectares of olive farms, according to the Geographic and Statistical Institute (1872). The density of olive trees was around 100 per hectare with yields between 1000 and 2200 kg olive ha^{-1} (Agronomic Reports, 1897).

The nutrient balances show a trend similar to that of Castilleja de la Cuesta, in spite of the differences pointed out above. This fact strengthens the conclusions outlined previously. The balance was positive for N (except for Baena 1897) but showed significant deficits for both P and K. The intensification of olive farming not only increased the net extraction of soil P and K, but the balance for N also changed from positive to negative. The N surplus of previous periods, despite receiving no manure, can be explained by the symbiotic N fixation of natural weeds. Results of current field experiments[7] have allowed us to quantify this process at 20 kg N ha^{-1} y^{-1}.

This was not the case for grapevines. Natural weed cover is much less common in a crop such as the grapevine, with relatively high plant density. There is no space for the proper development of natural weeds. In Montefrío, yields in the 18th Century were roughly consistent with those of Castilleja (between 200 and 1100 kg of grapes per ha), showing that the fifty hectares allocated to vines at that time only met the needs of the owners. In contrast, the vineyard of Baena displayed a significant level of specialization. Two thousand hectares of land was occupied by a vineyard with relatively high yields (between 500 and 1300 kg of grapes ha^{-1}). By the mid century, this area had increased fourfold in Montefrío and was reduced slightly in Baena. Yields at both sites were similar (between 900 and 2600 kg ha^{-1}), but much lower than that of Castilleja and the surrounding area, which clearly specialized in wine production (between 2000 and 4000 kg ha^{-1}). The increase in production (and intensification) in Baena was in response to its growing integration into the national market, whereas in Montefrío, somewhat isolated from the regional and national markets, intensification was still related to the increase in local demand due to a growing population. There were no changes by the end of the century, with unchanged yields for Montefrío and a slight increase in Baena (up to 3400 kg of grapes ha^{-1}). Historic sources do not mention any fertilization for grapevines, as in olive farming. No changes in labour were observed for vineyards at the turn of the century. Yield remained unchanged and

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[7] Results obtained in tests carried out by the research team led by Gloria Guzman. In short, over the last six years, the increase of total N in the soil has been monitored (with natural weed cover that was cleared during the month of March) in an olive grove with comparable edapho-climatic conditions to those of Montefrío. The annual increase in total N has been used to estimate the amount of N fixed by weed vegetation cover.

adjusted to resident demand. The vineyard nutrient balances confirm the findings for Castilleja. Production of this crop was based on the net extraction of soil N, P and K (i.e. mining) and as the intensification of crops increased (higher yields) so did mining. It is reasonable to argue that nutrient mining, as observed since mid century and especially at the end of the century in Baena, could not in all probability be maintained indefinitely.

Summarizing, the results of nutrient balances suggest that rotations and crops that were fertilized, in general more intensively managed, could have been maintained over time. However, extensive arable and woodland, which receives no input of organic matter, could be maintained through the soil nutrient reservoir, resulting in nutrient mining. This was particularly intense in woody crops, such as olive groves and more significantly, especially for N, in vineyards. The magnitude of mining became greater with time, as crop intensity increased.

10. Significance of net nutrient extractions

What were the consequences of the nutrient deficits for most balances on harvest stability and the system as a whole? The significance of deficits is largely dependent on the type of rotation and the nutrient concerned. N deficiencies usually limit productivity in the short term and affect crops yield sooner, because the only significant route of input is via the atmosphere (bedrock usually contains no appreciable amounts of N). Furthermore, there are other output processes in addition to soil loss and yield, such as denitrification, ammonia volatilization and N leaching, not applied to P and K. P deficits, on the other hand, had medium term effects on yields because bedrock continuously supplied available P and soil has high P retention capacity through complex processes (mainly adsorption/desadsorption and precipitation/solubilization). In addition, the amount of P taken up by crops is much lower than for N (typically at a ratio of 10 kg N to 1 kg of P). Negative balances for K can be viable in the long-term even though harvested K is similar to that for N, because the short, medium and long available pool of soil K is usually vast[8].

The significance of deficits in P and K are, in relative terms, similar as one hectare of soil (30 cm deep) contains about 1.0 tons and 19.0 tons of P and K, respectively. In this

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[8] For further information about the biological and physical/chemical processes involved in the mobilization of N, P and K, see Carreira and García Ruiz (2008).

respective, negative balance values indicate total annual net losses outside the system of approximately 0.12 and 0.14%, for P and K, respectively. However, negative values for P, in spite of lower absolute values than for K, might affect the yield earlier and to a greater extent. Available P is relatively scarce (most soil P is unavailable in the short term) and low available soil P generally affects the N-fixation capacity of legumes negatively. Negative values of K balance are greater, but their significance relatively lower because of the vast amounts found in soil. In addition, most crops have the capacity to store K when it is found in excess in the soil. Summarizing, a continuous net extraction of P might affect production earlier (fall in yields, symptoms on leaves …) than that of K. One indication is that a widespread K deficiency in Andalusia's olive crops has only been detected in the last 20 years[9]. However, as mentioned previously, limited P has a negative effect on the N fixing capacity of legumes (in this sense, it is likely that the application of chemical P fertilizer had a synergistic effect). Therefore, we believe that P deficiencies would have been significant in the medium term, and in the long term for K.

To get a rough idea of the consequences of such deficits, for the case of Montefrío (Table 12), the number of years in which nutrient deficiencies affected crop yields (i.e. the number of years in which soil available N, P and K met crop demand for nutrients) were calculated. The possibility that certain crop symptoms of nutrient deficiencies manifested earlier was not ruled out. Most of the values included in the table exceed 500 years and some a thousand years, a much longer period than the meaningful agrarian timescale. Agrarian History teaches us that significant socio-economic changes in the agrarian world take place in shorter periods of time and therefore, from the perspective of sustainability, a time period in excess of 500 years is considered a sustainable crop in terms of nutrient balance.

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[9] Due, among other things, to deficiencies in fertilization with potassium maintained over time.

Table 12: Number of years after which the deficit of N, P and K might start to threaten the culture of Montefrío

Table 12

Years as of which the deficit of N, P and K might start to threaten the culture of Montefrío[1]

Rotation	N			P			K		
	1752	1852	1897	1752	1852	1897	1752	1852	1897
Ruedos	--	--	--	--	--	1734	--	1.599	939
One third rotation	--	--	--	1325	516	551	1070	1205	1205
Olive groves	--	--	--	668	293	271	551	452	277
Vineyards	443	179	179	724	231	221	657	281	281

"--": This sign means a positive result for the balance

[1] Calculations have been made taking into account the annual soil availability of N, P and K needed to replenish the N, P and K harvested, and the results of the balance. Annual soil N, P and K availability have been estimated according to the weighted soil (one hectare, 30 cm depth) total N, P and K content and the annual rates of soil supply for available N, P and K. As an example, 231 years for N mean the number of years from which the supply of soil available N will replenish the N harvested in that rotation or crop. In other words, a number of years higher than 231 for that rotation or crop means that the rate of soil supply for N is lower than the rate at which N is harvested. We assume that a crop or rotation with values higher than 500 is sustainable with respect to the nutrient balance and from an agrarian point of view.

Source: authors' own date

This exercise is relevant because *one third* cereal rotations or more intensive crops such as the *ruedos* of Montefrío, with net nutrient extractions, were nutrient-sustainable (> 500 years, Table 12) from an agrarian point of view.

However, for woody crops such as olives and especially vines, the period from which annual flux in soil available P and K was lower than nutrient yield removal was shorter. For both crops, if chemical P and K had not been applied early in the 20th Century, it is probable that symptoms of nutritional deficiencies would have appeared today or even earlier. We mentioned previously the current effects of negative K balances on olive crops, highlighting inadequate K management. The grapevine was the only crop in the three case studies which showed a clear negative balance for N. It was the only crop without an input of organic matter and no N inputs from atmospheric N. As a direct consequence, the soil nitrogen pool progressively dwindled. The decline in organic matter has a greater impact on the soil than the capacity to supply nutrients. The decrease in the soil's water holding capacity, cation exchange capacity (related to nutrient retention), resistance to erosion and the soil's biological activities, all directly related to soil fertility, involve much deeper soil degradation. In short, the results clearly suggest that the vineyards of Baena, Montefrío and Castilleja de la Cuesta can be considered unsustainable without the aid of fertilizers.

11. The aggregate balance: towards unsustainability

One of the most important attributes that should be taken into account when measuring the sustainability of agricultural systems is stability. This roughly encompasses the long-term maintenance of an agroecosystem's net primary production. One of the main indicators of this stability is the yield per unit area. We have already explored one of dimensions of this problem by analyzing the results of nutrient balance at a crop and/or rotation scale. Now we need to explore the possibilities the territory as a whole had to maintain or even expand the aforementioned rotations – especially the most intensive ones – with its own resources. Thus, a balance of the territory as a whole is required (González de Molina and Guzmán Casado, 2006). This is particularly relevant for periods in the past, when importing nutrients from outside was still heavily restricted and harnessing available biological energy required certain amounts of land (land cost) to replenish the harvested nutrients. The following exercise estimates, based on the overall balance, whether the agroecosystems of these three case studies may or may not provide the nutrients needed and examines their temporal trend between 1752 and 1897.

This exercise involves, first, establishing a relationship between available manure, calculated through the potential production of livestock size, and manure actually used. Secondly, an estimation of capability to offset the weighted nutrient deficits with surplus manure is required. This dual exercise allows us to assess the actual possibilities of these agroecosystems to intensify production using their own territorial resources, either through the introduction of crops or rotations with higher yields or by increasing the specialization of some crops thereby also increasing nutritional requirements.

The amount of manure produced in each territory was compared with requirements according to the manure application rate for each crop or rotation. At the same time, an aggregate balance for N, P and K was calculated, taking into account the results of the crop specific balances and the area. Finally, these data were compared with the potential input of N, P and K from surplus manure in order to assess possibilities for compensation. The results are shown in Table 13. In 1752, the availability of manure was not a problem to sustain crop demand. Therefore, these results indicate that other factors, such as economics, led to an underutilization of abundant organic matter produced by livestock. The intensification of production that took place between the mid 18th and 19th Century was possible through an increased use of manure. Consequently, manure availability declined significantly. At a certain point in the mid 19th Century, the maximum use of available manure was reached. Data clearly indicate that in the last few decades of the 19th Century, all three territories had practically reached their limit for further crop intensification based on the resources of the agroecosystem.

Table 13: Aggregate nutrient balance, 1752-1897

Table 13

Aggregate nutrient balance, 1752-1897 (in tons of manure and kg of N, P and K)

		Total demand[1] (A)	Available manure (B)	Remaining manure (B-A)	Balance[1]		
	Year				N	P	K
Baena	1752	5489	19870	14381	48273	-36466	-519647
	1858	16697	16221	-476	-56373	-76522	-790110
	1897	12682	12160	-522	-147372	-98968	-1065366
Montefrío	1752	710	20440	19730	9325	16742	-148451
	1856	9617	11029	1412	3526	-16157	-273995
	1897	9803	9263	-539	-13427	-22446	-332232
Castilleja	1752	43	283	240	891	29	-1833
	1854	96	457	361	1456	51	-2823
	1880	489	510	20	-237	-269	-3844
	1897	175	261	(*) 0	-169	-254	-3834

Source: authors' own data

[1] Total demand is the total amount of manure required by crops or rotations where manure is added. [2] The balance is the result of subtracting (in kg of N, P and K) the macronutrient content of surplus manure from the aggregate nutrient deficit (produced by crops and rotations with negative deficits). (*) Assuming surplus manure (86 tons) was added to cereal rotation with high yield this year, since nutrient deficits were so significant that it would not have been possible to produce without manure (see table 5).

Data for 1897 confirm this idea. In Castilleja, intensification even regressed with respect to 1880, which was probably due to the reduction of its fertilization capacity by almost half. This fact might have contributed to the drop in yields and the negative balances of these three nutrients, in spite of lower yields. The agroecosystem of

Castilleja de la Cuesta was unbalanced in the late 19th Century, having exceeded the limit for replacing fertility with its own resources.

From a theoretical point of view, the presence of legumes in some rotations meant that there was no shortage of N in either 1752 or 1854. However, this was not the case for P, with slightly higher losses than the inputs, and K, with clear mining. When a territory specialized in fruit trees, olive groves and grapevines, nutrient removal not compensated with manure was generalized for all nutrients. In Castilleja de la Cuesta, chemical fertilizers were essential to further progress in terms of crop intensification and specialization and also to maintain the productive effort achieved in previous decades. This circumstance is rather significant in the midst of the crisis at the turn of the century, just prior to the extension of chemical fertilization in Spain.

The results for Baena and Montefrío (Table 13) confirm the findings for Castilleja: a decline in fertilization capacity over the time period studied, which was deeper for Baena and Montefrío, probably due to the reduction of land allocated to livestock feed. As a consequence, the territorial balance which had been maintained previously was broken. It was also found that, as in the case of Castilleja, in the late 19th Century, both Montefrío and Baena reached maximum possible crop intensification with their own resources and available technology. In fact, the balance deficit observed for 1897 in Montefrío reveals that this capacity had been exceeded and that the level of intensification had to be reduced without the aid of synthetic chemical fertilizers, which only became fully available in Montefrío in the second decade of the 20th Century (oral information).

The intensification of cereals and specialization in olive groves and vineyards were responsible for the deficit of nutrients. The net reduction of nutrient availability resulting from the decrease in livestock size meant that intensification was based on the soil pool of nutrients (i.e. mining), especially for P and K. Even the effect of forage legumes in weed cover, which until the mid 19th Century made it possible to sustain a positive nitrogen balance, could not be maintained in subsequent years. The soil nutrient reservoir was the key to increasing yields and maintaining the productive effort during the 19th Century.

12. Conclusions

This research has highlighted the usefulness of what we call *experimental history* for the study of traditional agricultural systems based on organic fertilization. On the one hand, the experiments conducted to measure N fixation by weed cover in current organic olive groves have given reliable values, essential when estimating nutrient balances with some degree of rigor. On the other hand, the experimental approach taken in collaboration with a research team from the University of Granada in order to characterize the nutrient content of traditional cereal varieties (Guzman, Garcia-Ruiz, Sanchez and Garcia del Moral Martos, 2009) has helped to refine and modify the values of extractions given in the literature, generally for current varieties. The traditional varieties extracted fewer nutrients (lower N, P and K grain and straw contents), especially for crop residues. This and other evidence indicate that they were better adapted to nutrient shortages than the current varieties. These features[10] make it difficult and meaningless to draw comparisons between traditional and organic agriculture and conventional farming, as practiced today in terms of yield per unit area.

Taking into account the structural shortage of manure, extensive crop land, the presence of fallow and low yields can be interpreted as an adaptive strategy of farmers to provide their crops with necessary long-term stability. Thus, nutrient extraction was minimal for crops and rotations that were not fertilized. Nevertheless, the increase in demand from the national market and population growth put pressure on the agroecosystems, which shattered territorial balance. Arable land for food expanded at the expense of land used to produce animal feed, leading to a clear decline in the size of livestock and net reduction in the capacity to fertilize. As a result, the possibilities for further crop intensification were severely limited. It is clear that the intensification of unfertilized crops and rotations was based on the extraction of nutrients from the soil reservoir.

Moreover, the reduction of the net fertilization capacity even led to a less intensive management of some crops (the *ruedos* for instance) and stagnation in production *per capita*. During the final few decades of 19th Century, Baena, Montefrío and Castilleja de la Cuesta had reached or were close to the upper limit in terms of their possibilities for further intensification of agrarian production. Human and livestock carrying capacities

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[10] Together with others such as different crop coefficients, different land costs of fertilization, etc...

were exceeded for the three territories studied. The drop in yields of some rotations is clear evidence in this respect. In some crops where production increased, especially woody crops, this was only possible at the expense of the soil nutrient reservoir, making them even more unsustainable in the medium to long term.

During the 18th Century, net nutrient extraction for vineyards and olive groves had remained within tolerable limits through low intensity management. Nutrient extraction rose, however, as crop farming became more intense, fuelled by the opening of new markets, including the international market (López Estudillo, 2002). The scope of these deficits was in conflict with the sustainability of woody crop specialization, which has been proposed as a plausible strategy for agrarian growth during the 19th Century[11]. However, it was based on the export of *natural* capital. The fact that the expansion of land allocated to vineyards and olive groves was preferably made on uncultivated land, which had a virtually untouched reservoir of nutrients, might explain why this phenomenon was not noticed by contemporaries.

In any case, this study confirms that the replacement of soil fertility has become the key factor in the sustainability of agrarian metabolism based on solar energy. In addition, we firmly believe that this replacement also played a key role in the start of the transition towards the industrial metabolism in agriculture (Fischer-Kowalski and Haberl, 2007). The crisis experienced at the turn of the century, based on productive specialization and in the rise in yields per unit area, was only possible once the structural shortage of fertilizers had been overcome, as argued elsewhere (González de Molina and Pouliquen, 1994 , González de Molina and Guzmán Casado, 2006), through the manufacture of synthetic chemical fertilizers with fossil fuels.

The main results and conclusions of this study are in line with the two studies presented at 1st World Congress of Environmental History, hold in Copenhagen, August 2009 (Tello, et al., 2209; Cunfer and Krausmann, 2009). On the basis of all three studies it is possible to draw an important conclusion: the turn of the century crisis could be explained not only by the entry of cheaper grain into Europe, but also by friction between two types of farming systems with different mechanisms for the replacement of soil fertility. The land cost of European agriculture, and particularly in

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[11] In the recent debate about the backwardness of Spanish agriculture, it has been suggested that specialization in woody crops was a viable productive alternative (Llopis, 2002; Pascual and Sudriá, 2002; Carreras and Tafunell 2004). In this context Gallego and Pinilla (1996) and Gallego (2001) maintain that restrictions in international demand limited the expansion of woody crops.

the Mediterranean, was higher than in America and Australia. In the absence of chemical fertilizers, the replacement of soil fertility required land devoted to producing manure or plant legumes. Since European agriculture has continuously cultivated soil for hundreds of years, agrarian growth could not be based on the soil nutrient reservoir for much longer. Moreover, the intensification in production experienced by European agriculture during the 18th and 19th centuries decreased the capacity to replenish all the nutrients harvested. So, productive specialization and the rise in yields obtained during first agricultural revolution were progressively exhausted. This was not the case in other countries such as the United States or Australia, where the soil nutrient reservoirs of arable land cultivated recently were high. In these areas, the land cost of replacing soil fertility was much lower. The turn of the century crisis reflected in lower prices for overseas agrarian products occurred when the revolution of sea transport confronted two types of agricultural systems with somewhat different land costs. Hence, the relative scarcity of nutrients, exacerbated by the territorial imbalance resulting from production growth in 19th-Century Europe, is one of the major reasons behind the turn of the century crisis, leading to the agrarian socio-ecological transition.

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APPENDIX

INPUTS

NATURAL		FOUR YEARS ROTATION			
		Surface of the crop	0,94	(ha)	
		crop year 1 Wheat	crop year 2 Chickpea	crop year 3 Barley	crop year 4 Beans
RAINFALL					
Mean annual rainfall (L m-2)		612	612	612	612
Total N concentration in the rainfall (mg L-1)		0,57	0,57	0,57	0,57
Calculated annual input (Kg N ha-1 y-1)		3,49	3,49	3,49	3,49
Calculated input of the rotation (4 years, kg N ha-1)	**13,95**				
Calculated input for the 4 years and at the surface of the cro	**13,12**				
Non symbiotic N fixation	n. of times				
Tillage intensity (number of tillage events from 0 to 4	2	3	3	3	3
Calculated annual input (Kg N ha-1 y-1)		3	3	3	3
Calculated input of the rotation (4 years, kg N ha-1)	**12**				
Calculated input for the 4 years and at the surface of the cro	**11,28**				
Symbiotic N fixation					
Crop 1; Beans					
Grain harvested (fresh weight; Kg ha-1))					394
N content of the grain (% fresh weight)					4,06
Inputs by the grain (Kg N h-1)				0	16,00

Produced straw (fresh weight; Kg ha-1)				0	267,92
N conent of the straw (% fresh weight)					1,63
Inputs by the straw (KgN ha-1)				0	4,37
Inputs by symbiotic N fixation			0	0	23,26
Crop 2; Chickpea					
Grain harvested (fresh weight; Kg ha-1))			372		
N content of the grain (% fresh weight)			4,06		
Inputs by the grain (Kg N h-1)			15,10		
Produced straw (fresh weight; Kg ha-1)			0		
N conent of the straw (% fresh weight)			1,63		
Inputs by the straw (KgN ha-1)			0		
Inputs by symbiotic N fixation		0	17,25		0
Crop 3;					
		0	0		0
		0	0	0	0
		0	0	0	0
	0	0	0	0	0
Calculated annual input (Kg N ha-1 y-1)		0	17,25	0	23,26
Calculated input of the rotation (4 years, kg N ha-1)	**40,51**				
Calculated input for the 4 years and at the surface of the cro	**38,08**				
ANTROPOGENIC					
Irrigation					
Volume of irrigated water (m3 ha-1)		0	0	0	0
Riverine/stream N concentration (mg L-1)		5,6	5,6	5,6	5,6
Calculated annual input (Kg N ha-1 y-1)		0	0	0	0
Calculated input of the rotation (4 years, kg N ha-1)	**0**				
Calculated input for the 4 years and at the surface of the cro	**0**				

	FERTILIZATION					
	CHEMICAL					
	Rate of annual addition of the product 1 (kg ha-1)		0	0		0
	N content of the product (%)					
	Input by this chemical (kg N ha-1)		0	0	0	0
	Rate of annual addition of the product 2 (kg ha-1)					
	N conrent of the product (%)					
	Input by this chemical (kg N ha-1)		0	0	0	0
	Rate of annual addition of the product 3 (kg ha-1)					
	N conrent of the product (%)					
	Input by this chemical (kg N ha-1)		0	0	0	0
	Calculated annual input (Kg N ha-1 y-1)		0	0	0	0
	Calculated input of the rotation (4 years, kg N ha-1)	**0**				
	Calculated input for the 4 years and at the surface of the cro	**0**				
	ORGANIC (manure)					
Manure 1	Rate of annual application (kg ha-1, wet weight)		5000		5000	
	N content (%) (in wet weight)		0,51		0,51	
	Annual input by this manure (kg N ha-1)		25,5	0	25,5	0
Manure 2	Rate of annual application (kg ha-1, wet weight)					
	N content (%) (in wet weight)					
	Annual input by this manure (kg N ha-1)		0	0	0	0
Manure 3	Rate of annual application (kg ha-1, wet weight)					
	N content (%) (in wet weight)					
	Annual input by this manure (kg N ha-1)		0	0	0	0
Manure 4	Rate of annual application (kg ha-1, wet weight)				0	
	N content (%) (in wet weight)					
	Annual input by this manure (kg N ha-1)		0	0	0	0
	Calculated annual input (Kg N ha-1 y-1)		25,5	0	25,5	0
	Calculated input of the rotation (4 years, kg N ha-1)	**51**				
	Calculated input for the 4 years and at the surface of the cro	**47,94**				

Calculated annual input by chemical/organic fertilisation (Kg N ha-1		25,5	0	25,5	0
Calculated input of the rotation (4 years, kg N ha-1)	**51**				
Calculated input for the 4 years and at the surface of the cro	**47,94**				
SEEDS					
Crop 1; Beans					
Rate of seeds annual application (Kg ha-1)					44
N content of the seed (%)					4,06
Annual N input by crop seeded			0		1,79
Crop 2; Wheat					
Rate of seeds annual application (Kg ha-1)		111			
N content of the seed (%)		2,02			
Annual N input by crop seeded		2,24		0	0
Crop 3; Chickpea					
Rate of seeds annual application (Kg ha-1)			41		
N content of the seed (%)			4,06		
Annual N input by crop seeded		0	1,66		0
Crop 4; Barley					
Rate of seeds annual application (Kg ha-1)				112	
N content of the seed (%)				1,77	
				1,98	
Annual N input by crop seeded		0	0		
Calculated annual input (Kg N ha-1 y-1)		2,24	1,66	1,98	1,79
Calculated input of the rotation (4 years, kg N ha-1)	**7,68**				
Calculated input for the 4 years and at the surface of the cro	**7,22**				
TOTAL INPUTS					
Calculated annual inputs (Kg N ha-1 y-1)		34,23	25,40	33,97	31,53
Calculated input of the rotation (4 years, kg N ha-1)	**125,13**				
Calculated input of the rotation (4 years, kg N ha-1)	**117,63**				

OUTPUTS

HARVEST				
Crop 1; Beans				
Annual grain harvested (wet weight Kg ha-1)				394
N content of the grain (%)				4,06
Output by harvested grain (Kg N ha-1)		0	0	16,00
Annual straw harvested (wet weight Kg ha-1)				267,92
N content of the straw (%)				1,6
Output by havested straw (Kg N ha-1)				4,29
Annual output by the harvest of the crop		0	0	20,28
Crop 2; Wheat				
Annual grain harvested (wet weight Kg ha-1)	798			
N content of the grain (%)	2,02			
Output by harvested grain (Kg N ha-1)	16,12		0	0
Annual straw harvested (wet weight Kg ha-1)	1117,2			
N content of the straw (%)	0,29			
Output by havested straw (Kg N ha-1)	3,24			
Annual output by the harvest of the crop	19,36		0	0
Crop 3; Chickpea				
Annual grain harvested (wet weight Kg ha-1)		372		
N content of the grain (%)		4,06		
Output by harvested grain (Kg N ha-1)		15,10		
Annual straw harvested (wet weight Kg ha-1)		0		
N content of the straw (%)		1,6		
Output by havested straw (Kg N ha-1)		0		
Annual output by the harvest of the crop	0	15,10		0
Crop 4; Barley				
Annual grain harvested (wet weight Kg ha-1)			894	
N content of the grain (%)			1,77	
Output by harvested grain (Kg N ha-1)	0	0	15,82	

Annual straw harvested (wet weight Kg ha-1)				1519,8	
N content of the straw (%)				0,45	
Output by havested straw (Kg N ha-1)				6,84	
Annual output by the harvest of the crop				22,66	
Calculated annual input (Kg N ha-1 y-1)		19,36	15,10	22,66	20,28
Calculated input of the rotation (4 years, kg N ha-1)	**77,41**				
Calculated input for the 4 years and at the surface of the cro	**72,76**				
DENITRIFICATION					
Soil clay + Silt content (%)	15				
Soil basal N losses by denitrification (Kg N-N2O ha-1 y-1)		1,72	1,72	1,72	1,72
Soil N losses by denitrification linked to fertilisation (Kg N-N2O ha-1		0,51	0	0,51	0
Total N lossess by denitrification (Kg N-(N2O+N2) ha-1 y-1)		8,67	6,69	8,67	6,69
Calculated input of the rotation (4 years, kg N ha-1)	**30,73**				
Calculated input for the 4 years and at the surface of the cro	**28,89**				
AMMONIUM VOLATILISATION					
Total N lossess by ammonia volatilisation (basal + fertiliser linked) (		6,6	1,67	6,6	1,73
Calculated input of the rotation (4 years, kg N ha-1)	**16,61**				
Calculated input for the 4 years and at the surface of the cro	**15,61**				
N LIXIVIATION					
Soil total N (%)	0,173				

Annual N supply by mineralisation and nitrification (Kg N ha-1 y-1)		124,56	124,56	124,56	124,56
Potential leacheable N (Kg N ha-1 y-1)		172,16	174,50	168,59	175,39
N lixiviation (Kg N ha-1 y-1 100 mm-1)		0,30	0,36	0,20	0,38
Calculated input of the rotation (4 years, kg N ha-1)	**1,24**				
Calculated input for the 4 years and at the surface of the cro	**1,17**				
SOIL LOSSESS					
Annual soil losses (Tn ha-1 y-1)		2	2	2	2
Total N content of the erosed soil (%)		0,173	0,173	0,173	0,173
Annual N losses by soil erosion (Kg N ha-1 y-1)		3,46	3,46	3,46	3,46
Calculated input of the rotation (4 years, kg N ha-1)	**13,84**				
Calculated input for the 4 years and at the surface of the cro	**13,01**				

TOTAL OUTPUTS

Calculated annual outputs (Kg N ha-1 y-1)		38,09	27,28	41,40	32,55
Calculated output of the rotation (4 years, kg N ha-1)	**139,32**				
Calculated output of the rotation (4 years, kg N ha-1)	**130,97**				

SUMMARY

	Kg N ha-1 y-1
INPUTS	
RAINFALL	3,49
NON SYMBIOTIC N FIXATION	3,00
SYMBIOTIC N FIXATION	10,13
IRRIGATION	0,00
FERTILISATION	12,75
SEEDS	1,92
TOTAL	**31,28**
OUTPUTS	
HARVEST	19,35
DENITRIFICATION	7,68
AMMONIA VOLATILISATION	4,15
N LIXIVIATION	0,31
SOIL LOSSES	3,46
TOTAL	**34,96**
NET BALANCE	**-3,67**