Nutri2Cycle

D.1.3 Driving forces of farming systems and their impacts on CNP ratios and flows

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Summary

Carbon, nitrogen and phosphorus have numerous functions in plants, animals and humans, and hence in food production, and in the interactions between food production systems and the wider environment. Ecological stoichiometry concerns the way that the elemental compositions of organisms shape the interactions between organisms and in the end all life on earth. It deals with the balance of elemental ratios and how these affect organism growth, nutrient cycling, and the interactions with the biotic and abiotic worlds. While the C:N:P ratios of components of natural systems have been studied extensively, there are only few studies that have examined (changes in) C:N:P ratios of components of agricultural systems and the whole food production – consumption system in a comprehensive manner. Most studies focus on either yield (energy, C) and/or N and/or P. This report therefore reviews the changes in C:N:P ratios in pools, flows and losses of farming systems in Europe over time. The underlying hypothesis is that the relative proportions of C, N and P in pools and flows in farming systems affect the leakiness of these systems. Understanding the stoichiometry of C:N:P in farming systems may help to identify options to decrease the leakiness.

This report focusses on (i) describing and understanding the conceptual/mechanistic relationships between driving forces of agricultural systems and their possible/likely impacts on C:N:P ratios and C, N and P coupling, and (ii) the simulation of the likely impacts of main driving forces on C:N:P ratios in agriculture. First an overview of the current farming systems is provided in terms of farm type characteristics, livestock numbers, manure management and crop production.

Chapter 4 provides a qualitative description of the driving forces of farming systems, based on a literature review, and a semi-quantitative analyses of the changes over time in farm structure. The main driving forces of European agriculture (markets, science & technology and policy) have led to the specialization, intensification, upscaling (enlargement) of farming systems, and to the introduction of treatment technology in the food production – consumption chain. The more specialized, intensive, and large farming systems, with often similar farm types in concentrated areas, are producing relatively N and P rich products, and have decreased the C:N and C:P ratios of soil organic matter. The narrowing of the C:N and C:P ratios have made the systems more leaky and vulnerable to external changes.

Figure S.1 provides a summary to illustrate the C:N:P ratios and the changes in CNP for the main compartments of agriculture (crop products, livestock products, animal manure and soils). The C:N:P ratios were estimated as the average of all crops, livestock products and manures for the EU-28, using weighted averages based on the total amount of nitrogen. The review of C:N:P ratios in Chapter 6 shows that the variation in C:N:P ratios can be large among crops, livestock products, manures and soils. Nevertheless, the overall averages provide a good picture of how CNP stoichiometry changes for the different compartments of agriculture.

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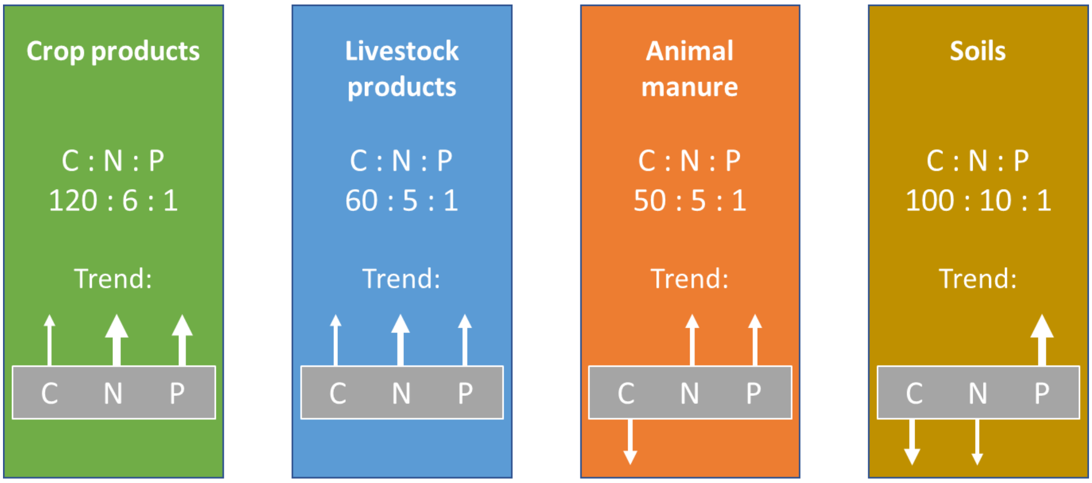

Figure S.1 Summary of the C:N:P ratios of crop products, livestock products, animal manure and arable soils. The arrows indicate the trend over the last decades in the overall amount of CNP for each compartment. The width of the arrow indicates an estimate of the size of the change relative to the trends for the other elements.

Managing C:N:P stoichiometry should be part of the solution of developing more leak-tight farming systems. It requires a better understanding of the linkages and delinking mechanisms of C, N and P in food production – processing – consumption systems. Currently, most studies are too disciplinary, often focused on just one nutrient element while neglecting the interactions with other elements and their functioning. This report must be seen as a first step as C:N:P stoichiometry is not much studied yet in agriculture. Variations in the contents of C, N and P are in general well understood and known, but how these contents are affected by crop rotations, crop and livestock management, food processing and storage throughout the food chain is less understood. Our knowledge of C:N:P stoichiometry in agriculture is fragmentary, in part because the focus has been mostly on yield (and protein contents), and much less on C:N:P ratios through the food production-consumption chain.

We recommend therefore to conduct more studies on the C:N:P stoichiometry in agriculture. These should determine both C, N and P contents in products and develop relationships between C:N:P stoichiometry in the inputs, outputs and leakiness of farming systems and soils. New manure treatment and other organic processed products could be utilized most beneficially from C:N:P stoichiometry and leakiness point of view. Recommendations for manure and fertilizer applications have to consider the soil-crop needs for both C, N and P. Meeting the P demand first is likely a good strategy in most regions, given the fact that P is retained both in manure and soil, and therefore is likely the element with the lowest demand. Topping up the C and N supply until soil-crop needs are met will require in many cases specific manure treatments products and/or synthetic fertilizers.

1. Introduction

1.1 Background

Food and animal feed contain on average 40 to 50% carbon (C), 2 to 5% nitrogen (N) and 0.1 to 0.5% phosphorus (P). The other part of the food and feed is made up of oxygen (O), hydrogen (H), essential nutrients (K, Ca, Mg, Na, S, Cl, Fe, Cu, Zn, Mn, Co, Mo, Se, I, Cr, F) and non-essential nutrients, metals and non-metals (e.g., Si, Al, Cd, Pb). The relative proportions of C, N and P differ between different food and feed commodities, while the relative availabilities of these commodities have changed over time due to changes in food preferences and in farming systems. The study of the relative proportions of elements in food and feed and other substances is termed *stoichiometry*. Stoichiometry has its basis in 'the law of definite proportions', which was founded by Joseph Proust by the end of the 18th century, and states that a chemical compound (or molecule) contains its elements in fixed ratios. Stoichiometry also deals with the 'law of conservation of mass and energy'. *Ecological stoichiometry* involves the balance of elements and energy in ecological interactions and processes (Sterner and Elser, 2003).

The saying 'You are what you eat' reflects 'ecological stoichiometry'; to be fit and healthy you need to eat good food. Though there is a truth in this saying, the reality is a bit more complex. In fact, the C:N:P ratios in humans and animal species are remarkably constant, and to a large extent independent of what we eat (but there are large differences in C:N:P ratios among animal species). The C:N and C:P ratios in humans and animal species are remarkably constant due to *homeostasis*, the physiological regulation of the humans' and animals' internal environment, which reduces changes in C:N and C:P ratios within humans and animals. Greater truth is in the saying 'You excrete what you eat', and even more in the saying 'You excrete what you eat, minus the fractions you respire or retain'. Indeed, C:N:P excretion by humans and animals equals C:N:P intake minus C:N:P retention minus C respiration. It reflects the laws of definite proportions and of mass conservation; the excreted C, N and P become available to other organisms.

Plants (and algae) are autotrophs and have not such a strict homeostasis as humans and animals. As a result, the C:N and C:P ratios of plants can vary substantially in response to the external environment, i.e., the incoming solar radiation and the availability of N and P. The growth, development as well as elemental composition of plants depend on the genotype and the balance of photosynthetic active radiation (energy) and the availability of N and P (and other essential nutrients) near plant roots. There is also variation in C:N:P ratios among plant parts and biomolecules within plants; the C:N and C:P ratios of proteins, nucleic acid, lipids, cellulose and cell walls differ one to two orders of magnitude.

The biomass of natural terrestrial ecosystems is carbon-rich with an average C:N:P ratio of about 50000:100:1. The 'new' N (derived from biological N_2 fixation) and 'new' P (derived from weathering) are recycled on average 100 to 200 times in these systems (Sterner and Elser, 2003). In contrast, marine biomass has on average a much lower (narrower) C:N:P ratio of 106:16:1 (so-called Redfield ratio; Falkowski et al., 1998). The average C:N:P ratio of the biomass of freshwater systems is in between that of natural terrestrial ecosystems and the marine system. Humans have greatly altered the C:N:P ratios and cycling through agriculture and fossil fuel combustion (Vitousek et al., 1997; Schlesinger and Bernhardt, 2014). Agriculture has more than doubled the annual inputs of 'new' N (through the Haber-Bosch process) and P (through P fertilizers derived from mined rock phosphates). Agriculture has also contributed to land use change, and has introduced new crop varieties and animal breeds. By doing so, agriculture also influences the C:N:P ratios of freshwater systems and marine coastal areas, as well as the ecological functioning of these systems. It has been suggested that the N and P loading of surface waters has exceeded critical boundaries (Steffen et al., 2015). More than half of the N and P input to surface waters is from agriculture, and this fraction is increasing (Beusen et al., 2016).

1.2 Objective

While the C:N:P ratios of components of natural systems have been studied in a comprehensive manner for decades (Sterner and Elser, 2003; Van der Waal et al., 2018), there are few studies that have examined (changes in) C:N:P ratios of components of agricultural systems and of whole food production-consumption systems in a comprehensive manner. Most studies focus on either yield (energy, C) and/or N and/or P. As a result, there are as yet no comprehensive reviews and overviews of the changes in C:N:P ratios in agricultural systems and in whole food production-consumption systems.

This report therefore reviews the changes in C:N:P ratios in pools, flows and losses of farming systems in Europe over time. The underlying hypothesis is that the relative proportions of C, N and P in pools and flows in farming systems affect the leakiness of these systems. A related hypothesis is that understanding the stoichiometry of C:N:P in farming systems may help to identify options to decrease the leakiness. This review is therefore based on a several compartmental reviews coupled through a discussion and synthesis at the end.

1.3 Outline of the report

Following this Introduction, Chapter 2 will present the analysis framework for this review of the driving forces of changes in farming systems and of their effects on CNP flows and their stoichiometry. Chapter 3 presents a brief overview of the main characteristics of current farming systems in Europe Union (EU). Chapter 4 provides a qualitative description of the driving forces of farming systems, based on a literature review, and a semi-quantitative analyses of the changes over time in farm structure. Chapter 5 briefly describes the concept of ecological stoichiometry as it is applied to natural ecosystems, and how it may be applied to agro-ecosystems. Chapter 6 presents results from a review on C:N:P ratios in agriculture, making distinction among crop and animal products, manures and soils.

Chapter 7 is a synthetic discussion, which links the driving forces of farming systems discussed in Chapter 4 to the changes in CNP stoichiometry of agricultural products and CNP losses discussed in Chapter 6. Next, chapter 7 identifies possible options and technologies to improve the CNP stoichiometry in agricultural products and to decrease CNP losses. The chapter concludes with some main findings and recommendations.

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2. Analysis framework

2.1 Introduction

Carbon, nitrogen and phosphorus have numerous functions in plants, animals and humans, and hence in food production, and in the interactions between food production systems and the wider environment. They make up significant fractions of plants, animals and humans, and of the various biological molecules and components in plants, animals and humans. They are essential, ubiquitous and often in short or excess supply, with contrasting implications. Yet, their functioning is suboptimal in the biosphere when one or more of the other essential elements are in short or excess supply, including sulphur (S), calcium (Ca), magnesium (Mg) and micronutrients such as iron (Fe), zinc (Zn), copper (Cu) and molybdenum (Mo). All essential nutrients, vitamins, light, and water have to be available at specific levels for proper functioning of plants, animals, humans and ecosystems, but C, N and P have very special roles here (Smil, 1997).

Why do C, N and P have these roles and why is this report focussed on C, N and P?

- C has the ability (i) to form four stable, high-energy covalent bonds with a number of elements, including N, O and S, (ii) to form diverse redox states (-4 to +4), (iii) to generate a flexible architecture, and (iv) to store energy.
- N has the ability (i) to form a diversity of redox states, (ii) store energy, (iii) form amine groups with is a core of amino acids, and (iv) is able to link to and associate with other elements (Fe, Mg, Mo).
- P has the ability to form strong linkages with other elements, and thereby to provide stability for polymeric molecules, and is ubiquitous in cellular metabolisms and biological structures. It is present in genetic polymers (RNA, DNA), coenzymes, intermediate metabolites, and is the principle vehicle of biochemical energy (ATP).

These three basic reasons explain why C, N and P have such important role in life on earth. In addition, C, N and P are essential ingredients of a whole range of industrial products. Further, C and N are also involved in the greenhouse gas effect, climate change, and the acidification of oceans, lakes and soils, while N and P are involved in eutrophication of natural habitats, including lakes and oceans. Evidently, C, N and P are key elements in the biosphere and food production systems, but due to human influences on the biosphere, 'there is often too much C, N and P, at wrong places'.

In the biosphere, C, N and P are intimately linked in organic matter, in a whole range of different organic molecules with different C:N:P ratios, but they occur as free molecules as well. Through plant metabolism, C, N and P are intimately coupled and decoupled, depending on growth stage. Plant metabolism is defined here as the complex of photosynthesis, respiration, and the synthesis of organic compounds. Photosynthesis produces the substrates for respiration and the starting organic

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compounds used as building blocks for subsequent biosynthesis of nucleic acids, amino acids, and proteins, carbohydrates and organic acids, lipids, and natural products. Plants are harvested and consumed by humans and/or animals, and thereby new couplings and decoupling of C, N and P occurs. The same occurs in food production systems, but two changes have occurred: (i) the relative proportions of C, N and P in main products have changed, and (ii) the coupling-decoupling mechanisms of C, N and P have changed (Schlesinger and Bernhardt, 2014; Smil, 2002).

The purpose of this chapter is to present an analytical framework for analysing changes in C:N:P ratios in food production systems.

2.2 Coupling and decoupling processes for C, N and P

The dominant coupling mechanism for C, N and P in the biosphere is through photosynthesis and subsequent biosynthesis of various organic molecules in photoautotrophic algae and plants (Table 2.1). In specific niches, there is chemosynthesis of organic molecules in nature (in anaerobic environments). Biosynthesis and coupling of C, N and P also occurs in animals and humans. And there is biosynthesis and chemosynthesis in reactors, in industry.

Basic decoupling processes are respiration, decomposition and mineralization of organic matter. Partial decoupling occurs via excretion of urine and faeces in animals and humans, with some specific differences between animal species. In faeces, most of the C, N and (part of) P are still coupled, while urine contains dissolved organic compounds, which are easily decomposed, and inorganic solutes. In ruminants most of the P (>90%) is excreted in faeces, in humans and pigs, most of the P is excreted in urine as solutes (Table 2.1).

Table 2.1 Overview of processes that lead to (partial) coupling of C, N and P and to (partial) decoupling of C, N and P. (Source: authors expert knowledge). Nr is reactive nitrogen.

	C-N-P coupling processes	Resources for coupling	C-N-P decoupling processes	Reactants of decoupling
Plants	Photosynthesis, biosynthesis	Light, H_2O, CO_2, Nr, P, other nutrients	Plant respiration and degradation, senescence	CO_2, H_2O, NH_4, PO_4
Bacteria and archaea	Chemosynthesis	CO_2/CH_4, H_2O, Nr, P, other nutrients	Respiration and degradation, senescence	CO_2, H_2O, NH_4, PO_4
Animals	Biosynthesis	Glucogenic energy, Nr, P, other nutrients, H_2O	Partial decoupling through selective grazing and harvesting Respiration, selective excretion via urine & faeces	N-rich and P-rich plant parts versus C-rich plant parts CO_2, H_2O, NH_4, PO_4, various organic molecules
Industry	Biosynthesis & chemosynthesis	Glucogenic energy, chemical energy, Nr, P, other nutrients	Refinery, fractionation, fermentation	Different components with different C:N:P

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Soil			Decomposition, mineralization of organic matter	CO_2, Nr, P

Via biosynthesis and chemosynthesis, various organic molecules and components are formed, which may differ in C:N:P ratios. Compounds with specific C:N:P ratios are harvested by animals and humans and consumed and digested elsewhere. Prior to consumption, the harvested compounds are often refined, fractionated and partly fermented, whereby again compounds with different C:N:P ratios are formed (Table 2.1).

2.3 Relative enrichment / impoverishment of N and P

Plant types respond differently to environmental conditions, as some plant types are better adjusted to poor soil fertility and/or cold and/or wet conditions while other plant types are better adjusted to high soil fertility and/or warm and/or dry conditions. As a result, there is site-specific variation in C:N:P ratios due to variation in plant types as well as variation within plant types. The background of this variation is further discussed in Chapter 5.

The responsiveness of plants to environmental conditions leads to competition and natural selection. Humankind has learned from this, first through trial and error, and later through improved mechanistic understanding, and have added further tools (i) to adjust plant types and environmental conditions, and thereby C:N:P ratios, (ii) to adjust and improve the utilization of plants for animal and human consumption, and (iii) to adjust the recycling of C, N and P from residues and wastes.

The main processes that contribute to relative changes in C:N:P ratios in plant and animal products, and to changes in coupling of C, N, P are summarized in Table 2.2. A distinction is made between direct and indirect effects; direct is defined here as a direct consequence of a process, and indirect as a likely implication of the process. The changes in C:N:P ratios and in C, N and P have been summarized in terms of increases or decreases relative to natural conditions, to what is or would have been the case in nature, or relative to the common/conventional situation. An increase in C:N:P ratios means a relative decrease of N and/or P relative to C, and vice versa. An increase in C, N and P coupling means that C, N and P are or remain increasingly associated/bound to each other.

Most of the processes and mechanisms listed in Table 2.2 decrease C:N:P ratios indirectly, meaning that the specific process/mechanism likely has as implication that the N and/or P contents in the plant and/or animal products increase relative to C. Plant selection and breeding has greatly influenced plant morphology and growth rate; the harvested fractions have increased and crop residues have decreased (harvest index has increased). Plant types and varieties with high chlorophyll content (for high photosynthetic capacity) and with sufficient protein (for high food quality) have been favoured and these plants typically have relative high N and P contents. The implication of these changes is that C:N:P ratios likely have decreased compared to natural conditions. And because of the relative enrichment of N and P in the harvested crop products, there is a relative large risk of decoupling of C, N and P later on in the food production – consumption chain. Hence, coupling of C, N and P decreases

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in the food production – consumption chain; it is an indirect effect (implication) of the selection and breeding towards faster-growing, higher-yielding, and protein-richer crops.

Animal selection and breeding has also resulted in fast growing animals with relatively high carcass weight and relatively low fat deposition (with low N and P contents). As will be shown later, the N and P contents of animal components is remarkable constant, but the relative proportions of these components changes through selection and breeding. Though cattle dominate the world in terms of animal biomass, there is a relative increase in poultry and pork production in the world because the latter require relatively less feed (have higher feed conversion coefficients). The relative carcass weight (the usable portion of animals) changes in the order poultry > pigs > cattle. In summary, animal selection and breeding has contributed indirectly to a relative decrease in C:N:P ratios, and indirectly also to a decrease in coupling of C, N and P in the food production – consumption chain.

Fertilization with N and P has a direct effect on crop growth and C:N:P ratios. As uptake of N and P proceeds growth (photosynthesis and biosynthesis), there is in general a relative enrichment of plants with N and P following fertilization. Indirectly, this leads to less coupling of C, N and P in the food production – consumption chain.

Table 2.2 Human induced processes and mechanisms in food – production – consumption chains, which may lead to changes in the C:N:P ratios of crop and animal products, and to coupling of C, N and P in de food – production – consumption chain. (Source: authors expert knowledge).

Processes/mechanisms	Effects on C:N:P ratios	Effects on C, N, P coupling
Plant selection and breeding	Indirect - decrease	Indirect - decrease
Animal selection and breeding	Indirect - decrease	Indirect - decrease
Fertilization	Direct - decrease	Indirect - decrease
Irrigation	Indirect – neutral to increase	Indirect - neutral
Drainage	Indirect – neutral to increase	Indirect - neutral
Soil tillage, weeding	Indirect – neutral to increase	Indirect - neutral
Mechanization	neutral	Neutral
Mixed crop-animal production	neutral	Indirect - Neutral to decrease
Specialization in specific crops	Indirect – neutral to decrease	Indirect - decrease
Specialization in specific animals	Indirect – neutral to decrease	Indirect - decrease
Intensification	Indirect - decrease	Indirect - decrease
Conglomeration	Indirect – neutral to decrease	Indirect - decrease
Food processing & refinery	Neutral	Direct - decrease
Residue processing & refinery	Neutral	Direct - decrease
Composting	Direct - neutral to decrease	Direct - neutral to decrease
Manure digestion	Direct - decrease	Indirect - decrease
Manure separation/filtration	Direct - neutral	Direct - decrease
Manure incineration	Direct – partial decrease	Direct – full uncoupling
Reverse osmosis	Direct - neutral	Direct - neutral
Sewage treatment	Direct - neutral	Direct - decrease

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2.4 Framework for analysing changes in C, N and P ratios and coupling

Paragraphs 2.2 and 2.3 have indicated that C:N:P ratios of crop and animal products, and C, N and P coupling in the food production – consumption chain are influenced by many processes and mechanisms. In addition, there will be interactions, for example between plant breeding and fertilization, in C:N:P ratios of crop products, and in C, N and P coupling in the food production – consumption chain. Evidently, there is a myriad of processes and mechanism that affect C:N:P ratios.

Examining the effects of each of the processes and mechanisms separately and in detail is beyond the scope of this study. Rather, this study focusses on (i) describing and understanding the conceptual/mechanistic relationships between driving forces of the food production – consumption chain and their possible/likely impacts on C:N:P ratios and C, N and P coupling, and (ii) simulation of the likely impacts of main driving forces on C:N:P ratios and C, N and P coupling in the food production – consumption chain. This paragraph presents the conceptual framework for analysing relationships between driving forces of the food production – consumption chain and their possible/likely impacts on C:N:P ratios and C, N and P coupling.

The processes/mechanisms listed in Table 2.2 are directly and indirectly fuelled by the three main external driving forces of the food production – consumption chain, namely markets, technology and policy. Markets include the whole of demand and supply of food products, and are in turn influenced by population growth, economic growth, globalization, culture, as well as by external disturbances (climate change, diseases, pests, war). Technology represents the whole of scientific and technological progress, including processing technology, mechanization, information technology, and new production designs and products. Policy encompasses production and market support/control, and regulation of production methods by governments. These three external driving forces determine how farmers and suppliers, processing industries and retail respond, and how farming systems and the food production - consumption chain develop.

The responses of farmers to markets, technology and policy greatly varies across countries, due to differences in socio-economic and environmental conditions, and education and culture. Again, examining the differences in responses between individual farmers is beyond the scope of this study. Rather, we focus on overall main responses, which can be summarized by four main factors, namely (i) specialization, (ii) intensification, (iii) up-scaling, and (iv) treatment. Specialization includes the selection of only few main activities, crops or animals, and often includes outsourcing (transfer of activities to others). Intensification refers to increasing the output per unit of land, labour and animal, through increasing knowledge, management and non-factor inputs (e.g. fertilizers, irrigation, mechanization). Upscaling refers to increasing total output of a farm or firm, often through enlargement of the farm/firm, mechanization and often also through specialization/outsourcing. Treatment encompasses a whole range of activities aimed at increasing the value of crop and animal products at the farm, firm and/or processing industry. These four factors basically capture the influences of all processes/mechanisms listed in Table 2.2 that contribute to changes in C:N:P ratios of crop and animal products, and in C, N and P coupling in the food production – consumption chain.

The possible influences of the driving forces (markets, technology and policy) on the possible responses of farming systems, processing industry and retail, and their impacts on C:N:P ratios of crop and animal products, and in C, N and P coupling and losses in the whole food production – consumption chain are summarized in Figure 2.1. The driving forces and possible responses are at the top of Figure 2.1; these influence the development of farming systems. Three main systems are shown, namely specialized crop production systems, which include vegetable, fruit and nut production systems, specialized animal production systems, and mixed systems. These systems produce crop products and residues, and animal products and residues (manures). The main crop and animal products go to the processing industry and retail and then to the consumers, who leave food waste and sewage. The crop residues and animal manures are used to amend and fertilise soils. Losses of C, N and P are ultimately the result of the driving forces and of the responses by actors in the food chain; the losses are the result of partial enrichment of crop and animal products by N and/or P, and by various partial or complete N, N and P coupling decoupling mechanisms. This scheme also presents the flow of information of this review.

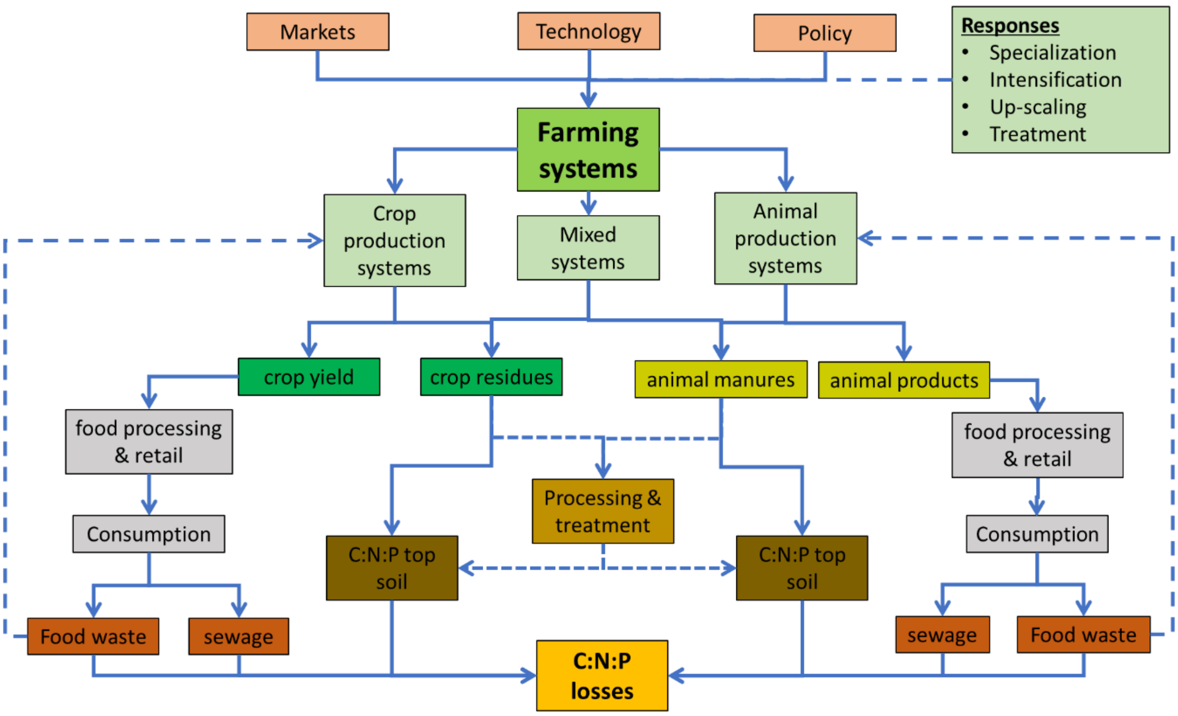

Figure 2.1 Conceptual framework of the review. The main driving forces of farming systems are shown on the top. The responses in terms of farm structural changes are presented at the right hand box, while the responses in terms of changes in C:N:P flows are presented at the bottom.

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3. Overview of current farming systems

This chapter presents a brief overview of the main characteristics of current farming systems in Europe Union (EU). This overview aims to illustrate what EU agriculture looks like nowadays, including its diversity among Europe. We will present data on farming systems, livestock numbers and distribution, information about manure management and crop areas and fertilisation. The data are derived from Eurostat and FAOSTAT databases, literature and results from the MITERRA-Europe model (Velthof et al., 2009; see also Nutri2Cycle Deliverable 1.5).

3.1 Farming systems

European scale data about farming systems are collected by Eurostat through the Farm Structure Survey (FSS) and presented as “agricultural production systems”. The classification of farm types is detailed with 62 particular types, which are aggregated to 22 principal types and 9 general types (EC, 2008). In 2013, 29% of EU-28 farms were specialised in field crops and 18% in permanent crops (Table 3.1). Specialist grazing, pig, poultry and mixed crop-livestock holdings account for 45% of the holdings. While specialist field crops and specialist grazing livestock together account for 46% of the holdings, they account for 74% of the land.

Table 3.1 Eurostat Farm type and the number of holdings, utilized agricultural area (UAA) and livestock unit (LSU) numbers for the EU based on the Farm Structure Survey of 2013

Farm type	Holdings	UAA (ha)	Livestock	Holdings	UAA	LSU
	million	million ha	million LSU	% of total	% of total	% of total
Specialist field crops	3.20	74.1	2.6	29.5	42.5	2.0
Specialist horticulture	0.21	1.2	0.1	1.9	0.7	0.1
Specialist permanent crops	1.89	10.7	0.3	17.5	6.1	0.2
Specialist grazing livestock	1.86	54.8	62.2	17.1	31.4	47.8
Specialist granivore	1.02	4.2	44.1	9.4	2.4	33.9
Mixed cropping	0.52	4.8	0.5	4.8	2.8	0.4
Mixed livestock	0.48	4.1	7.1	4.4	2.3	5.4
Mixed crops-livestock	1.50	19.9	13.3	13.8	11.4	10.3
Non classifiable	0.16	0.9	0	1.5	0.5	0.0

Maps with the distribution of the main farm types can be found in Nutri2Cycle Deliverable 1.4 (Ros et al., 2020). In Figure 3.1 the average farm size as reported in standard output, which is the average monetary value of the agricultural output at farm-gate price, is shown. In eastern and southern Europe the farm size is relatively small, especially in Romania and Greece, whereas in NW Europe the average farm size is relatively large, in terms of economic output.

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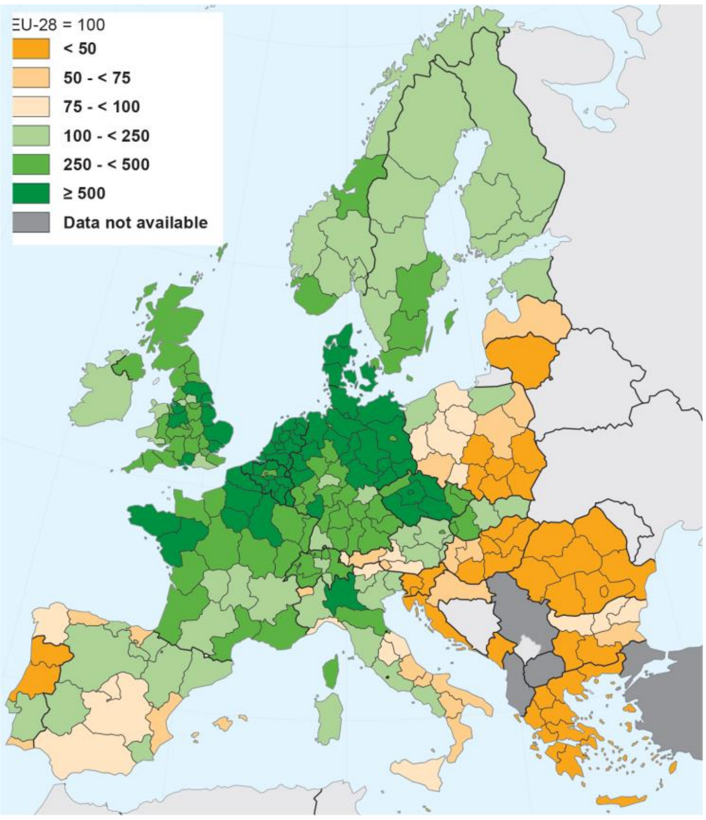

Figure 3.1. Distribution of farm size in Europe in 2016, the average for the EU-28 is set at 100 standard output (~€35000) (Source: Eurostat (ef_m_farmleg))

Table 3.2 presents economic characteristics for the main farm types in the EU. The numbers should be interpreted with care as the data only represent one year (2017) and the yearly variation can be large as shown in paragraph 4.3.1. Granivore farms (pigs and poultry) are on average the largest farms in economic terms, followed by horticulture and dairy farms. Mixed farms have the lowest net farm income, however, this is a bit biased, as most of the mixed farms are located in the new Member States, which are in general smaller farms with lower incomes. The direct payments contribute a substantial part to the gross income, for the field crops, mixed and other grazing farms about one third, for dairy 20% and for pig and poultry farms on average 8%.

Table 3.2 Economic characteristics for average EU27 farm types for 2017 (data derived from aggregated FADN statistics)

Farm type	Economic size	Total UAA	Total livestock units	Total output	Total Inputs	Gross income	Net Income	Total direct payments
	k€	ha/farm	LSU/farm	k€/farm	k€/farm	k€/farm	k€/farm	k€/farm
Fieldcrops	58	51	2	65	62	40	17	13
Granivores	450	39	342	377	320	136	72	11
Horticulture	174	6	1	196	155	103	44	2
Dairy	90	34	48	109	92	57	32	11
Mixed	43	27	23	48	47	24	10	7
Other grazing	45	46	43	48	48	29	16	12
Permanent crops	35	13	0	45	30	35	21	5
Wine	84	15	0	91	63	60	32	3

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3.2 Livestock farming

Europe maintains one of the highest livestock densities in the world (Lesschen et al., 2011). In 2017, the EU member states produced 25% of the world's milk production, 12% of the beef, 14% of the pork and 9% of the poultry and eggs production (FAO, 2017). These high numbers put pressure on the environmental system. Livestock farming is responsible for greenhouse gas emissions, eutrophication of surface waters and nutrient imbalances. Nutrient imbalances are especially visible in landless animal production systems, because feed is often imported (e.g., soybean from South America) and the produced manure is not transported back (Naylor et al., 2005).

According to data from the National Inventory Reports of 2019, France has highest number of beef cattle and poultry, and second highest number of dairy cows (Table 3.3). Spain and Germany have highest number of pigs, followed by France. Germany also has the highest number of dairy cows, and second highest number of beef cattle, followed by the United Kingdom. Italy and Poland also end up in the top three of highest number of poultry.

Table 3.3 Number of animals (x1000) per EU member state in 2017

Country	Dairy cows	Beef cattle	Pigs	Poultry
Austria	543	1400	2820	15772
Belgium	458	2061	6425	43668
Bulgaria	262	287	605	14228
Croatia	161	310	1121	10429
Cyprus	29	36	352	3261
Czech. Republic	370	1051	1491	21494
Denmark	571	976	12308	21484
Estonia	86	165	289	2763
Finland	275	618	1108	13136
France	3594	15416	13003	306189
Germany	4199	8082	22921	173574
Greece	97	458	694	35823
Hungary	245	618	2848	43091
Ireland	1388	5882	1587	17387
Italy	1791	4158	8571	199981
Latvia	150	255	321	4944
Lithuania	279	425	638	11196
Luxembourg	48	154	86	124
Malta	6	8	34	776
Netherlands	1672	2351	12401	104090
Poland	2374	3769	11353	197537
Portugal	240	1393	2189	35226

Country	Dairy cows	Beef cattle	Pigs	Poultry
Romania	1160	832	4406	73294
Slovakia	130	310	614	13354
Slovenia	109	371	257	6410
Spain	824	5703	29328	130771
Sweden	322	1179	1362	21142
United Kingdom	1901	7936	4969	181811
EU-28	23284	66204	144101	1702955

The amount of livestock in 2017 was compared to the amount of livestock in 1990. Most member states did not show a significant difference between the livestock numbers of 1990 and 2017. However, it became clear that the livestock numbers decreased most in the member states of eastern Europe and the number of dairy cows decreased in all EU member states except Cyprus and Ireland. The number of beef cattle increased most in Spain and Portugal, and also the number of pigs almost doubled in Spain between 1990 and 2017. The number of poultry increased in half of the member states, of which Luxembourg showed highest increase.

Livestock density (in # LU/ha) differs within and between EU member states (Figure 3.2Figure 2.1). The figure shows the distribution of the main livestock types in the EU member states as calculated by MITERRA-Europe (Lesschen et al., 2011). Overall, livestock density is highest in north-western Europe. Certain regions in Spain and Italy have also high livestock densities, and some regions in Poland have high density of dairy cows and poultry as well.

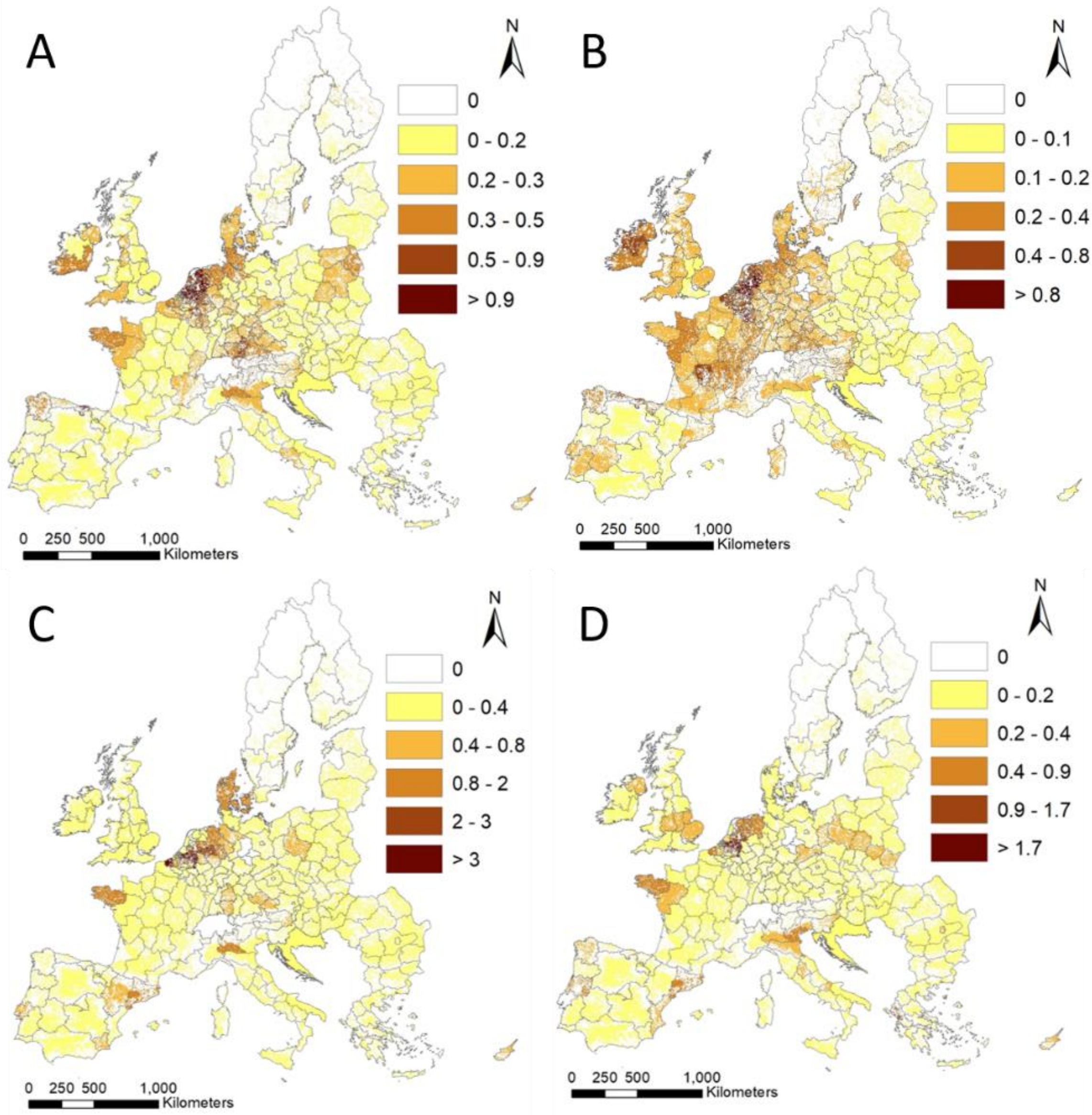

Figure 3.2 Livestock density of dairy cows (A), beef cattle (B), pigs (C) and poultry (D) in livestock units/ha UAA.

3.3 Manure management

3.3.1 Manure storage systems

Data on manure management are often not harmonised across EU member states and often obtained during single surveys. In the Eurostat survey of agricultural production methods (SAPM) also data on manure management was collected in 2010 including information on: manure application, manure storage, manure management and treatment facilities. Additionally the Manure Management Inventory was carried out by Eurostat in 2012. Also the obligatory country reports on the Nitrates

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Directive are used as the basis for a 4-yearly report by the EU commissions on the implementation of the Directive (EC, 2013). In addition countries report in the National Inventory reports on GHG emissions on the usage of manure management systems following the IPCC classification. Although this information might lack detail, it is probably the most comprehensive source for trends in manure management. Figure 3.3 shows the use of manure management systems, based on the amount of N excreted of all livestock, for the EU member states. Most of the manure is excreted in pasture and paddock, followed by liquid systems and solid storage. These three systems account for 83% of the manure. Digestion of manure has become relevant in some countries as well, whereas daily spread, anaerobic lagoons and composting are hardly used in the EU.

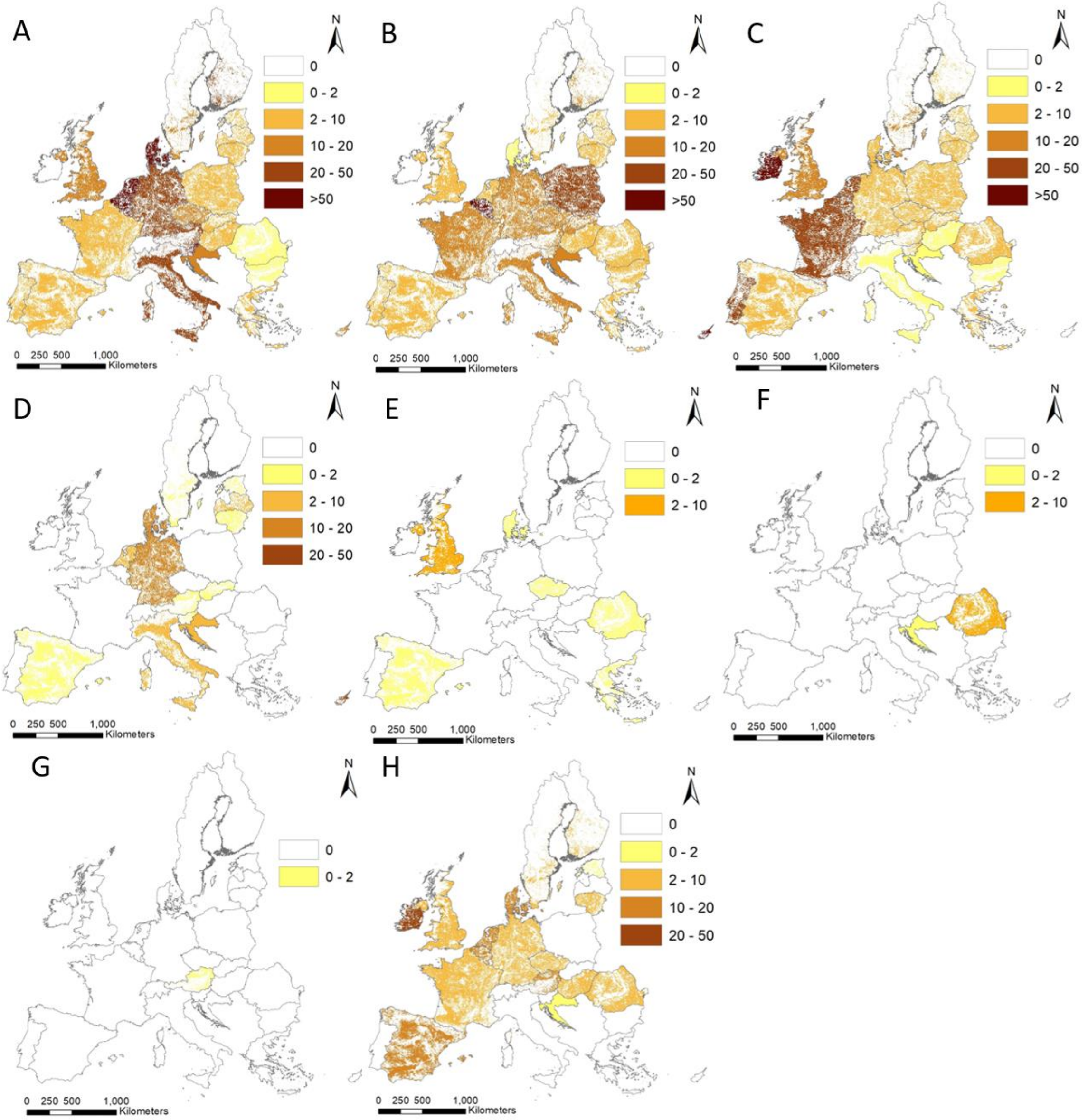

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Figure 3.3 Nitrogen excretion (in kg N/ha UAA) of eight manure management systems in 2017: liquid system (A), solid storage and dry lot (B), pasture range and paddock (C), digesters (D), daily spread (E), anaerobic lagoon (F), composting (G), and other systems (H). Data are derived from the National GHG Inventory Reports.

Manure management is relevant for the emissions of ammonia, but also for nitrous oxide and methane (GHG) and for the leaching and runoff of nutrients to groundwater and surface water and consequent eutrophication. The current uptake of Best available technology by European farmers is only patchy (Loyon et al., 2016). Only a number of indicators: the capacity for manure storage, the cover of storage facilities for manure (Table 3.4), and ammonia emissions are collected in a uniform manner. In some EU countries all holdings with liquid manure storage facilities us a cover (Belgium, Germany, the Netherlands, Slovakia) while in Romania, Bulgaria and Cyrus respectively 28%, 27% and 15% of the holdings with storage for liquid manure are covered.

Table 3.4 Percentage share of holdings with manure storage facilities in EU28 in 2010 (Source: Eurostat, aei_fm_ms dataset)

	Total number	With cover	Share with cover
Solid manure storage	1,890,770	262,930	14%
Liquid manure storage	812,410	703,720	87%
Slurry storage	719,530	493,740	69%
Holdings with storage facilities	2,309,410		
Total number of holdings with livestock	6,943,320		

3.3.2 Manure processing

A survey by Foged et al. (2011) estimated that 7.8% of the manure was processed (

Table 3.5), this is likely to be higher by now, but new survey data are lacking. The total estimated amount of processed livestock manure was 108 million tonnes, containing 556,000 ton N and 139,000 ton P. The most important treatments are separation and anaerobic treatment. In total 3.1% of the total livestock manure is separated, and 6.4% of the livestock manure in EU are anaerobically treated. In Germany 29% of the livestock manure is treated anaerobically. Separation is most used in Italy where 24% of the livestock manure is separated. (Foged et al., 2012). These treatments of livestock manure can have relevant effects on agriculture production, GHG emissions and soil quality (Möller & Müller, 2012).

Besides the data in Eurostat and data from EU project also relevant data are gathered in the National Inventory Reports (NIR)(UNFCCC, 2019). These reports present the percentage of manure that is digestated and composted. However, not all member states report in a similar approach. For example, it is well known that the Czech republic (https://www.eurobserv-er.org/biogas-barometer-2017/) has many digesters for manure but they report no contribution of digesters in the NIR.

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Table 3.5 Treatment of livestock manure in EU (Foged et al., 2011)

	Nr of installations	Million tonnes	% of total manure
Separation	11130	49	3.1
Additives and other pretreatments	668	7.5	0.5
Anaerobic treatment	5256	88	6.4
Treatment of soild fraction	1486	10.4	0.8
Treatment of liquid fraction	587	9.4	0.7
Air cleaning	69	4	0.3
Total amount of treatment		108	7.8

Digestates are produced from animal manure and crops. There are a few recent surveys in which the amount of digestate has been calculated. The study of Foged et al. (2011), JRC (Saveyn & Eder, 2014) and Wood (Corden et al., 2019) have assessed the digestate production in member states. In 2010 it was estimated that 88 million tonnes or 6.4% of the livestock manure production is used for anaerobic digestion (Foged et al., 2011). Corden et al. (2019) estimates that a digestate production of 176 million tonnes/year of which Germany produces 87 million tonnes/year (Table 3.6). The German NIR reports that of 17% of all N from animal manure is digested in 1664 biogas plants. Digestate might be an indicator for many manure-products in case it involves large plants with an interest to producing more advanced fertilisers. This is especially relevant in member states and regions with a surplus of manure. In a similar manner biogas production from agriculture, as given by Eurostat (Corden et al., 2019) might be an indicator for manure products.

Table 3.6 Estimated amount of digestate produced in EU member states in million tonnes/year (Wood, 2019)

Belgium	1.6	Greece	0.7	Lithuania	0.2	Portugal	0.6
Bulgaria	0.4	Spain	1.7	Luxembourg	0.1	Romania	0.1
Czechia	4.3	France	5.4	Hungary	0.6	Slovenia	0.2
Denmark	1.6	Croatia	0.3	Malta	0.1	Slovakia	1.1
Germany	87.0	Italy	30.0	Netherlands	2.9	Finland	0.8
Estonia	0.1	Cyprus	0.1	Austria	2.2	Sweden	7.2
Ireland	0.4	Latvia	0.6	Poland	1.3	United Kingdom	18.5
						EU28	176

Compost has a rather specific composition with a relative high amount of C and a low amount of N and P. Trends in compost (Eurostat) show an increase during the period in which it is being registered by Eurostat. The growth comes from several members states and dominantly Italy and Denmark. In some member states with a relative high amount of compost (France, Belgium, United Kingdom), see Figure 3.4, there is no growth between 2010 and 2016. A total amount of 20 million tons of compost was produced in the EU28 in 2016, which is respectively about 2 million ton C, 120 kton N and 15 kton P, using the values from JRC (2014) as an approximation of the average composition.

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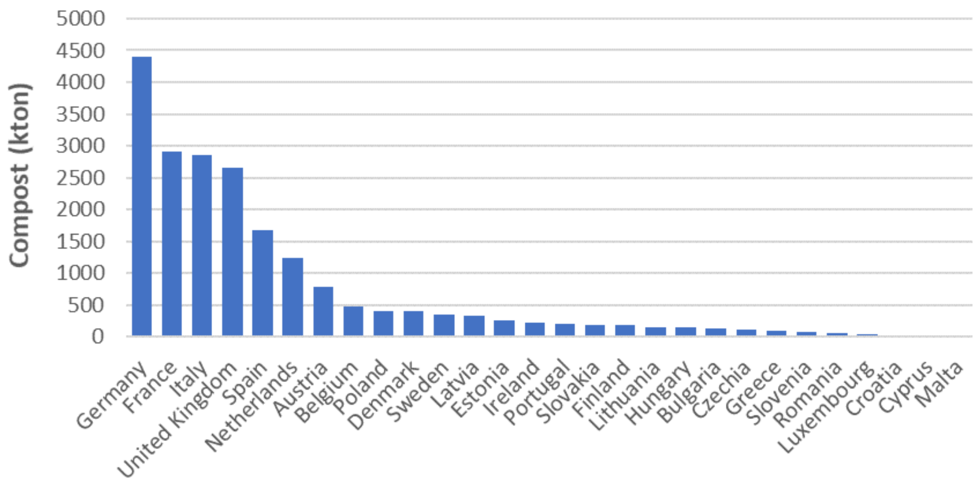

Figure 3.4 Compost production per member state for 2016 based on Eurostat data (env_ac_mfadpo)

3.3.3 Manure export

Only two EU countries, the Netherlands and Belgium, have large scale export of animal manure or processed manure products, as these countries have a manure surplus at national scale. Other livestock intensive regions, such as Bretagne in France and the Po region in Italy, will have manure processing and export, but these will mostly be used in other parts of the country. The available statistics (Table 3.7) show that in The Netherlands most of the exported manure is solid manure (mainly poultry) or the solid fraction of manure separation. The phosphate surplus is the main driver for manure exported in the Netherlands. In Flanders the export of composted manure is the source of exported nutrients. Due to processing and export of manure, the CNP stoichiometry of manure application changes, as further elaborated in Chapter 6.

Table 3.7 Exported and manure treatment in the Netherlands and Flanders in 2018 in kton N and P_2O_5 (source: NCM, 2019 and VLM, 2018) (NCM, 2019)

		Netherlands		Belgium	
		N	P_2O_5	N	P_2O_5
Mineral concentrate	Production	2.0	0.1		
Scrubbing salt	production	3.7	0.0	0.3	
Spent mushroom compost	export	3.1	1.8	4.3	2.2
Composted manure	export	9.2	11.5	23.1	22.0
Co-materials	export	1.4	1.4	1.0	0.7
Solid fraction of separated manure	export	0.5	0.6		
Liquid manure	export	6.2	4.1		
Liquid fraction of separated manure	export	0.3	0.1		
Digestate	export			1.1	1.6
Solid manure	export	18.5	15.1		
Livestock manure	export			9.2	5.6
Pelletized manure	export	7.8	6.0		
Ash	export	0	5.2		
Total export		37.1	34.4		

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3.4 Crop farming

There is a large diversity in crop farming systems in Europe. To analyse the spatial distribution of cultivated crops, we divided the crops into four main categories: grassland, cereals, perennials and other arable crops. Other arable crops include highly intensified crops, such as sugar beet, potato, rapeseed and vegetables. The share in area of agricultural land that these four classes cover within a NUTS2 region is visualised in Figure 3.5. Grassland dominates in Ireland, the United Kingdom (UK), some provinces in France, Romania and Austria. Cereals are dominating in northern and eastern Europe. The Mediterranean countries cultivate most dominantly perennial crops (e.g. olives, fruits and vineyards), and the other arable crops are more dominant in eastern UK and the Netherlands.

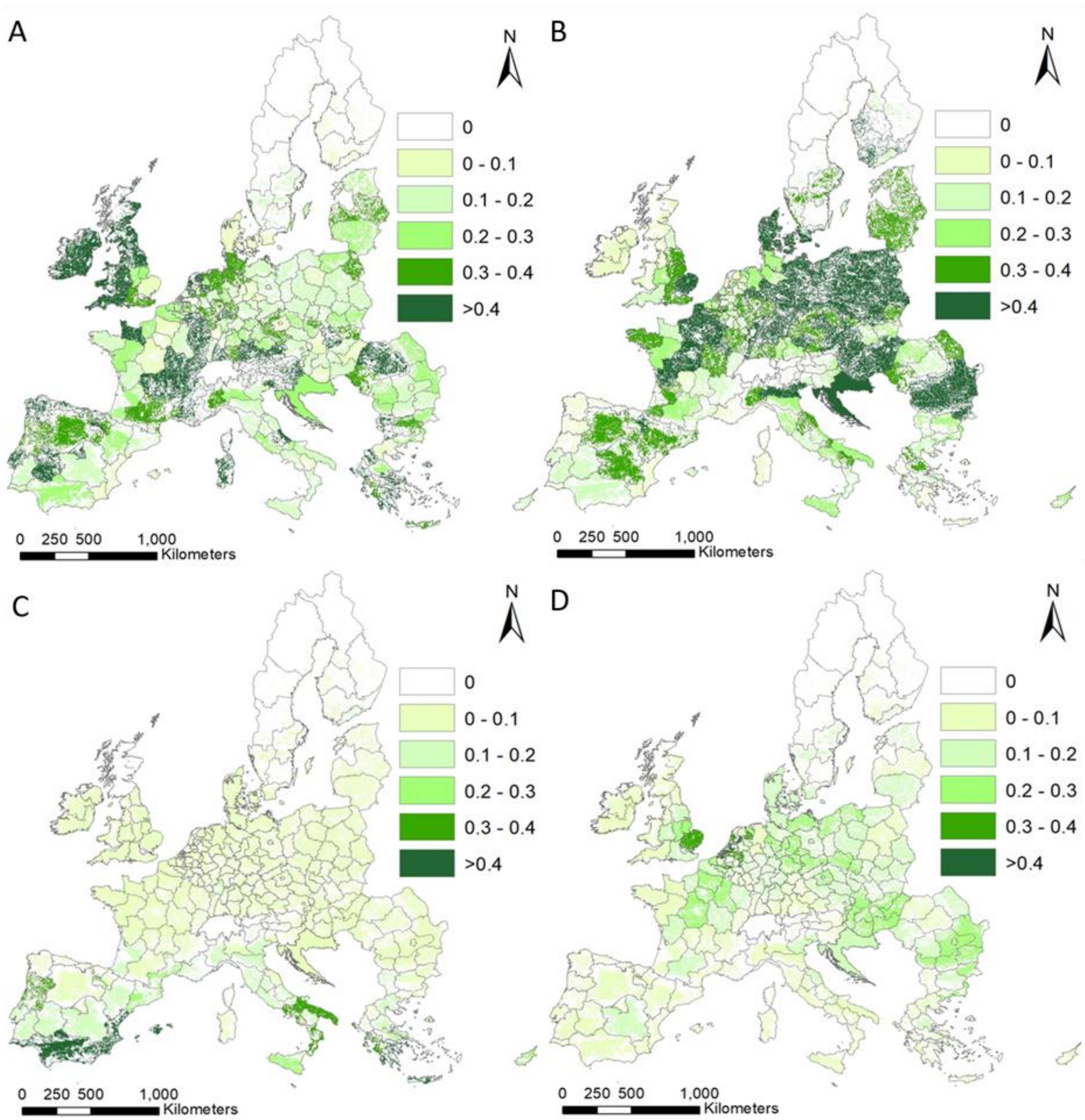

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Figure 3.5 The proportion of agricultural area that is covered by grassland (A), cereals (B), perennials (C) and industrial crops (D) per NUTS2 region (Source MITERRA-Europe data)

France and Spain cover about 15 and 12% of the total agricultural area of the EU. Selecting the crops that dominate at the EU market, identifies that 34% of the total agricultural area is used for cereal production, followed by grassland that covers about 26% of the total agricultural area (Table 3.8).

Table 3.8 Area (in 1000 ha) of a selection of crops for each EU member state (Source: Eurostat)

Country	Cereals	Potato	Sugar beet	Pulses	Fruit and vegetables	Oil crops	Fodder	Grassland	Other	Total
Austria	794	20	39	15	27	156	213	894	144	2301
Belgium	2075	11		3	84	1072	121	1151	227	4744
Bulgaria	359	73	73	1	67	14	251	415	28	1280
Croatia	579	10	9	2	61	157	149	226	66	1257
Cyprus	37	5		0	18	11	16	13	21	122
Czech Rep.	1616	22	55	19	32	517	474	850	187	3772
Denmark	1477	34	39	0	17	188	584	163	145	2649
Estonia	313	4		13	6	92	177	278	54	937
Finland	1079	21	12	12	21	58	642	11	371	2226
France	9300	158	314	125	357	2379	4913	7572	1536	26654
Germany	6422	234	325	76	215	1531	2584	3838	717	15942
Greece	749	18	9	12	310	900	831	1105	344	4278
Hungary	3077	19	8	13	172	974	288	324	355	5230
Ireland	245	7		1	9	13	570	2695	39	3581
Italy	3482	55	51	76	1144	1429	2457	2732	1675	13101
Latvia	565	27		9	19	117	451	356	64	1607
Lithuania	1039	11	5	39	27	239	620	810	108	2898
Luxembourg	25	1		0	4	4	24	48	1	107
Malta	3036	700		397	5849	35	221	2	1659	11899
Netherlands	229	165	107		106	3	400	540	140	1691
Poland	8165	323	192	212	677	1127	1008	2770	1326	15799
Portugal	279	29	2	13	295	411	612	645	773	3059
Romania	5331	208	6	55	308	1440	888	3726	1129	13092
Slovakia	792	7	8	2	16	269	230	504	83	1911
Slovenia	84	2		0	10	13	64	188	16	379
Spain	6033	64	26	403	1447	3550	1052	4971	4761	22307
Sweden	928	25	10	33	32	132	1001	377	391	2929
United Kingdom	3048	133	92	134	134	808	1320	8904	371	14944
Total	61156	2388	1381	1667	11466	17638	22160	46109	16732	180697

The regions in Europe with the highest crop yields, mainly countries in Northwest Europe, also have high nutrient inputs. Figure 3.6 shows the input of N and P for mineral fertilisers and animal manure. The N and P that is applied as manure is strongly related to the animal density, with high inputs in The Netherlands, Belgium, Cyprus, Brittany, Cataluña and the Po region. Mineral N fertilizer input ranges from less than 25 kg N/ha UAA in Romania to over 150 kg N/ha UAA in Northwest Europe. Mineral P fertilizer is less variable with in many countries inputs of 5-10 kg P/ha UAA. The Netherlands is an

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exception with very low levels, due to the already very high input of manure P and high P status of the soils.

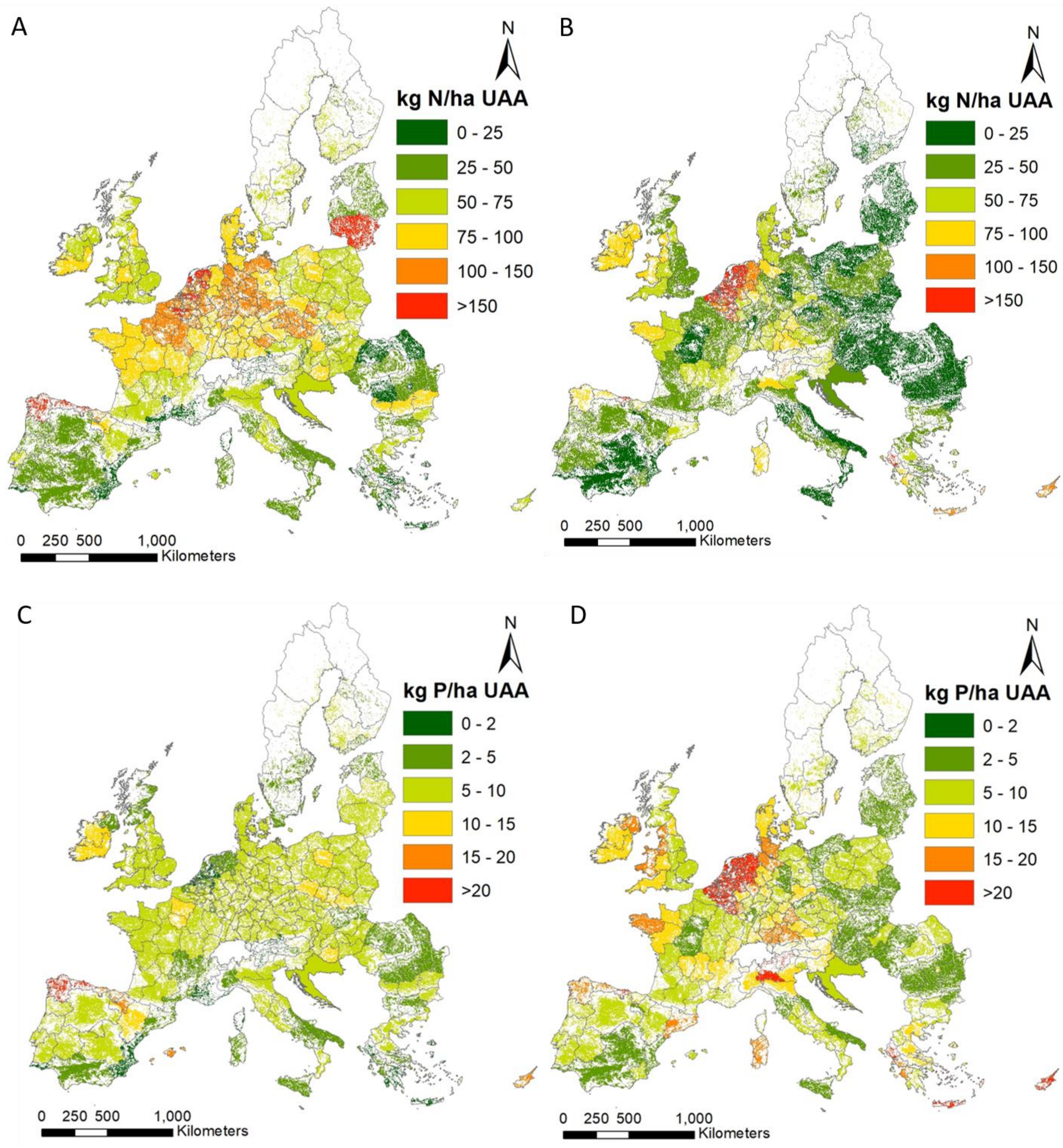

Figure 3.6 Application of nitrogen as synthetic fertilizer (A) and as manure (B), and the application of phosphorus (P) as synthetic fertilizer (C) and as manure (D). (Source MITERRA-Europe data)

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4. Driving forces and responses of farming systems

This chapter provides a brief qualitative description of the driving forces of farming systems, based on a literature review, and semi-quantitative analyses of the changes over time (last few decades) in farm structure. The influences of changes in markets, technology, and governmental policies on farming systems are discussed, in terms of responses by actors in the food production – consumption chain, i.e., (i) specialization, (ii) intensification, (iii) up-scaling and (iv) treatment, as briefly introduced already in Chapter 2.

4.1 Brief history of agricultural developments

Expansion of agricultural area was for ages the only way to supply sufficient food for the increasing European population. At the beginning of the Middle Ages more than 80% of the population was working in agriculture using the land in the best possible way given the limited external resources that were available to increase productivity and the absence of labour replacing machinery (Slicher van Bath, 1964; Rabbinge and Van Diepen, 2000).

In their seminal book 'A History of World Agriculture', Mazoyer and Roudart (2006) describe the many changes that have occurred in agriculture in different places in the world from the Neolithic age until the beginning of the 21st century. There have been series of agricultural revolutions that have changed and (re)shaped agricultural practices and systems. Much of these changes were the result of 'trial and error' and basic circumstantial evidence, and with different success rate. These changes largely developed independent of each other in different parts of the world. The initial successes were related to site specific conditions, to the presence of basic resources (fertile land, genotypes, water) (Diamond, 1999; 2006). The success of improved agricultural methods increased the output and allowed populations to increase in number and relative prosperity. The agricultural output has had a strong influence on the total human population throughout history (Hardin, 1993; Smil, 2000; Mazoyer and Roudart (2006). Access to land and ownership of land has been a critical factor for the success of agricultural production and the stewardship of the land and surrounding environment (Linklater, 2013; McNeil and Winiwarter, 2006).

Progress through 'trial and error' was slowly replaced by progress through scientific research and understanding from the 18th century onwards. Agricultural production became increasingly based on science-based insights and technology. This is commonly called the second agricultural revolution of modern times (the advent of sedentary agriculture some 10,000 years ago is commonly called the first agricultural revolution; Mazoyer and Roudart, 2006). The industrial revolution from the end of the 18th century and the associated urbanization have directly and indirectly facilitated the modernization of agricultural practices. It resulted in to new crop rotations, soil tillage methods and animal husbandry practices. Synthetic fertilizers, new energy sources and fossil energy fuelled machines came on the market. The agricultural output increased as did the global population.

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Major changes occurred in the 20th century, and especially in the second half of the 20th century. This is commonly called the third agricultural revolution, and includes the so-called 'green revolution' of the 1950s to 1970s (Mazoyer and Roudart, 2006; Evenson and Gollins, 2003). Agricultural output greatly increased through new crop and animal breeds, fertilization, irrigation, pest and diseases control, and mechanization and industrialization (Evans, 1998; Hazell and Woods, 2008). It has also led to division of labour and to an extension of the food production – consumption chain. The role of suppliers, processing industry & retail, research, advisors and governments have increased in agricultural production, while farmers have become more dependent on the other actors, both in terms of information, inputs and economic returns.

In the last chapter of their book, Mazoyer and Roudart (2006) hypothesize and explain the 'agrarian crisis', which is roughly a result of the increase in agricultural production, globalization and the uneven distribution of resources and wealth across the world. Large food companies, processing industries and retail increasingly define product quality and price and production methods. These pressive conditions resulted in the specialization, intensification and up-scaling of farming systems. This increased the productivity per ha, per animal and per unit labour increases. As a consequence, the prices for agricultural commodities decrease. At the same time, cost of living increase due to increasing standards of living, especially in developed countries, and because of inflation. As a result, farmers with low productivity drop out, while new, higher productive farms develop further on the other side of the spectrum. These lines of thoughts are visualized in Figure 4.1. For decades, this agricultural model was seen as the only way to compete in this highly competitive production system. Farmers in the EU are supported financially through direct payments (Table 3.2) and through Rural Development Programs (e.g., OECD, 2020; Michalek et al., 2020). Also farmers in many other affluent (OECD) countries in the world receive governmental subsidies (OECD, 2020). This provides farmers in affluent countries a competitive advantage relative to farmers living in countries with little financial support.

Over the last decades, the awareness for sustainability gained increased attention across the value chain and across scales. Intensive production systems are increasingly constraint by social and governmental acceptability (e.g. Pollan, 2006). Society's interest in regionally or environmentally friendly produced products increased. Whereas policy initiatives aim to reduce nutrient leaching (e.g., the Nitrates Directive), greenhouse gas emissions or waste streams (e.g., the European Green Deal) to support the transitions towards sustainable and circular agriculture. The transition requires investments in innovative techniques. For example, valuable bio-based fertilizers can be produced from manure through digestion plants (Sigurnjak et al., 2019) and energy can be recovered from bio-waste through anaerobic digestion or combined heat and power systems (Purdy et al., 2018). Emissions can reduce when emission-poor stables are introduced or separate solid and liquid manure in stables (Aguirre-Villegas et al., 2019) and precision agriculture has proven its potential to increase the water and nutrient use efficiency (Balafoutis et al., 2017). To realize the transition, upscaling (i.e., increase of the technology in terms of numbers) and outscaling (i.e., geographical spreading) of innovative techniques that stimulate sustainable and circular agriculture will become important in the next few decades (Wigboldus et al., 2016). That aspect just indicates the relevance of the Nutri2Cycle project as it analyses different technologies that promote better nutrient (C, N and P) recycling and help balancing nutrient stoichiometry in order to investigate which technologies are ready for upscaling and outscaling.

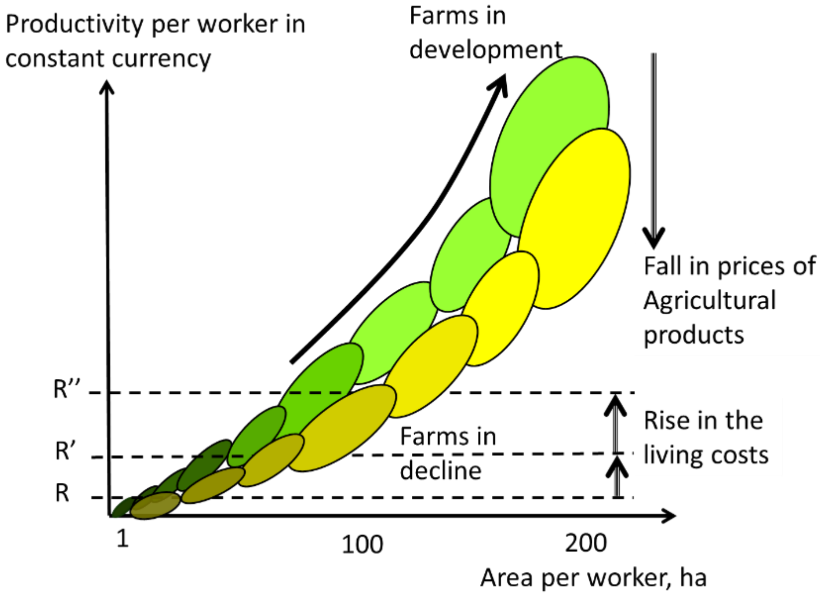

Figure 4.1 Comparison of productivity per worker for various farming systems in the world. Subsistence farms and small farms are situated in the lower left corner, highly mechanised large farms in the upper right corner. Over time, the productivity per worker expressed in constant currency drops down, due to a fall in the prices of agricultural products, visualised by a change from green coloured to yellow-coloured farming systems. At the bottom, farms are in decline, because the cost of living goes up from R to R' and R'', i.e. the point of marginalisation moves upward (after Mazoyer and Roudart 2006).

4.2 Driving forces of agricultural systems

Every agricultural transition over the past 10,000 years can be associated with one or multiple driving forces. Examples of these driving forces are the introduction of mineral fertilizer, agriculture quota, changes in policies. Changes have been most profound from the second half of the 20th century, especially in affluent countries where the output per unit of land, animal and labour has strongly increased. It is the interplay between markets, technology and governmental policy that have shaped European agriculture and its farming systems. Changing farming systems towards sustainability also needs to be a common effort of all three. For example, farmers who get a better price for their products, can be stimulated by investing in sustainable farming techniques. Another example, policies that subsidize sustainable farming technologies will stimulate the development of new technologies and the adoption of these techniques. This chapter will discuss in more detail the role of markets, technology and governmental policy as driving factors for change

Markets

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Markets are briefly defined by the demand, supply and prices of products. Changes in the demand for food emanate from changes in the global population and in the composition of the diets (Tilman et al., 2011). Changes in the supply of food result from a combination of changes in crop and animal productivity through technological and managerial advances, but also from temporal changes in weather and climate, trade conflicts, and pest and diseases (Evans, 1998). Changes in the price of food products reflect changes in the balance between food supply and demand, but may also reflect market interventions by individual governments and by international agreements between different governments (e.g., through tariffs, subsidies, regulations).

Markets as physical meeting places for exchange of goods have existed for as long as humans have engaged in trade, i.e. for millennia. Over time, markets have greatly developed, especially following the introduction of money, banks and information technology. On one hand, markets influence the decisions of farmers on which product to produce (demand driven) and on the other hand markets influence the decision of consumers on which products to buy (supply driven). This largely influences product prices. When demand of specific products is larger than supply, prices go up and vice versa. This is theory; in practice, there are often many constraints, which lead farmers to respond differently. Possible constraints include (i) lack of sufficient information about markets, (ii) lack of knowledge about the production of new products (with higher prices), (iii) lack of capital for investing in new production methods, (iv) large investments (with loans from banks) in existing production capacity, which have not been depreciated yet. As a consequence, farmers may try to produce more when prices go down, in order to get sufficient income. This may lead to further distortion of markets and to the collapse of farms with the highest cost of production and least financial reserves. Ultimately, it also leads to re-adjustment of the supply to better match demand.

The cyclical fluctuations in livestock markets have been described by the term pork cycle, following the observation of cyclic variations in the supply and prices of pork in United states and Europe in the beginning of the 20th century. When prices are high, more investments are made. However, the effect of these investments is delayed due to the investment and breeding time - the production lag. Eventually, the market becomes saturated, leading to a decline in prices, and production is thus decreased. This also takes time, leading to increased demand and again increased prices (Holst and Cramon-Taubadel, 2011). Globalization resulted in a fast increase in production (Mellor, 1992). To keep up the market position during the industrialization and mechanisation of the agriculture, most farming systems within the European Union intensified production. The use of mineral fertilizer increased exponentially and most farming systems were specializing in a single crop or livestock product (Ilbery and Bowler, 2003).

Technology

Technical progress is driven by developments in markets, technology and policy and has effect on the farm structure and price ratios (Figure 4.2). Changes in farm management were for example driven by political decisions on land consolidation that eased the use of bigger machinery on land (Vitikainen, 2004), the industrialization that stimulated farming systems to intensify and specialize on a single crop (Ilbery and Bowler, 2003), and the development or discovery of new farm management techniques that made farming systems more efficient (e.g., the discovery of an industrial method for producing mineral fertiliser, Global Positioning System (GPS)). De development of more resistant breeds made it possible to overcome pests, diseases and climatic changes. Together with the development of chemical pesticides, this reduced the need to adopt to the changing environment. Recent decades, the attention for soil exhaustion and environmental pollution gained increased attention.

From the 1950s onwards, mechanization in agriculture have enlarged and globalized markets. The increased availability of cheap fossil energy and the introduction of information technology were major driving forces of this change (Smil, 2000; Pimentel and Pimental 2008; Smil, 2017). Most recent techniques focus dominantly on the reduction of greenhouse gasses (e.g., solid-liquid separation systems, emission poor stables), the reduced spill of nutrients and water, and the recycling of waste flows. These techniques make use of GPS and sensor technologies (Balafoutis et al., 2017), machine learning techniques (Liakos et al., 2018), chemical processes like anaerobic digestion (Sigurnjak et al., 2019). The Nutri2Cycle project explores and tests newest technological innovations that stimulate recycling waste streams.

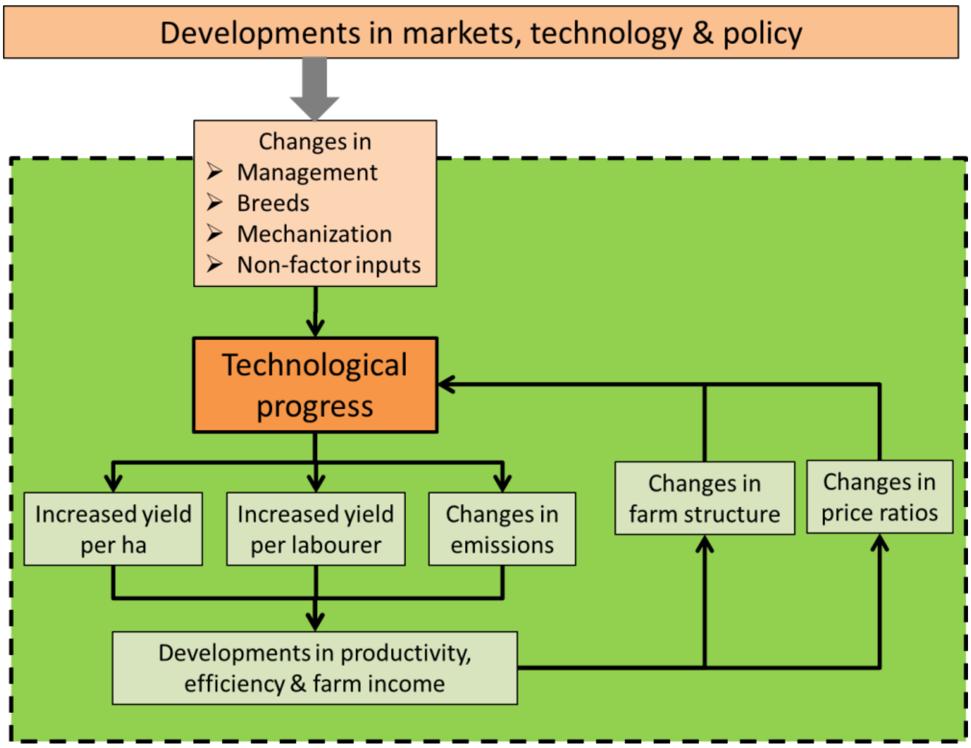

Figure 4.2 Driving forces for technological progress in farming systems. The developments in productivity efficiency and farm income lead to changes in price ratios and farm structure and thereby also to technological progress (internal driving forces), fuelled also by education and entrepreneurship of farmers.

Governmental policies

The phenomena of the pork cycle, the cyclical fluctuations in crop production, due to variations in weather conditions and the incidence of pest and diseases (and wars), and the low education level, innovation capacity, and incomes of rural farmers have led governments to support farmers and markets, especially from the 20th century onwards (Ilbery and Bowler, 2003). Indeed, the establishment of the common agricultural policy by the predecessors of the European Union in 1962 has provided strong incentives to the modernization of agricultural practices. The initial objectives of the common agricultural policy were (i) to increase agricultural productivity by promoting technical progress, (ii) to ensure a fair standard of living for farmers, (iii) to stabilize markets, (iv) to ensure stability of supplies, and (v) to ensure that supplies reach the consumers at reasonable price. The EU policy supported markets of agricultural products and the modernization and agricultural production methods, through subsidies and research. Side effects of this policy (surplus production and environmental pollution), and discussions in the world trade organization (WTO) and its predecessors initiated a series of policy reforms in the EU. These led to production quota, a change from market support to direct farm payments, series of environmental regulations, rural development programs, and the need for innovations (Recanati et al., 2019; Détang-Dessendre et al, 2018).

4.3 Driving forces of nutrient cycling

In natural, terrestrial systems, nutrients cycle between soils, plants and animals, and then back to soils again. Some nutrients cycle also through the atmosphere (e.g., N and S), while fractions of basically all nutrients are transported to groundwater bodies and/or the sea and then to sediments. The cycling occurs because of driving forces, of energy sources (Liu et al., 2020). Four primary *energy* sources are distinguished in natural systems (Figure 4.3). These four primary driving forces fuel a number of secondary driving forces, which subsequently fuel nutrient transformation and transport processes. Sunlight fuels photosynthesis, the hydrological cycle (evapotranspiration) and wind and water currents (in combination with gravitational energy and internal particle energy). Natural gravity and the internal energy of particles govern the earth motion (seasonal and diurnal cycles), the physical interaction between elementary particles, including diffusion, and the physical transport of particles, following the laws of thermodynamics. The heat (energy) in the core of the earth governs tectonic uplift and volcanic activity (Smil, 2017).

Wind, rain and evapotranspiration are considered secondary driving forces for nutrient transformation and transport because they are fuelled by the energy from the sun, gravitation and the internal particle energy. This holds as well for the orbital motion of the earth and the other so-called secondary driving forces. These secondary driving forces, alone or in combination, drive a large number of nutrient transformation and transport processes. This includes heterotrophy, i.e., bacteria, animals and humans which utilize the energy derived from the sun in the carbohydrates and protein and the nutrients in plants, for growth, development and (re)production (Schlesinger and Bernhardt 2013). Biological N_2 fixation is indirectly also fuelled by the sun; microorganism utilizes carbohydrates from plants or other sources to cleavage the triple bond between atmospheric N_2 and to produce ammonia and amines (Smil 2001).

The transport and cycling of nutrients in ecosystems depend also on the reactivity and mobility of the nutrient elements (related to the internal particle energy). Some nutrient elements (e.g., N, S, Fe, Mn) are involved in reduction–oxidation processes, and thereby change in valence, reactivity, and acidity. Nitrogen and sulphur (S) are termed 'double mobile' because these elements are mobile in the gaseous phase (e.g., NH_3, N_2, N_2O, NO, NO_2, H_2S, SO_2) and aqueous phase (e.g., NO_3, NH_4, SO_4), while some N and S species occur in non-mobile solid phase (organically bound N, elemental sulphur (S°)).

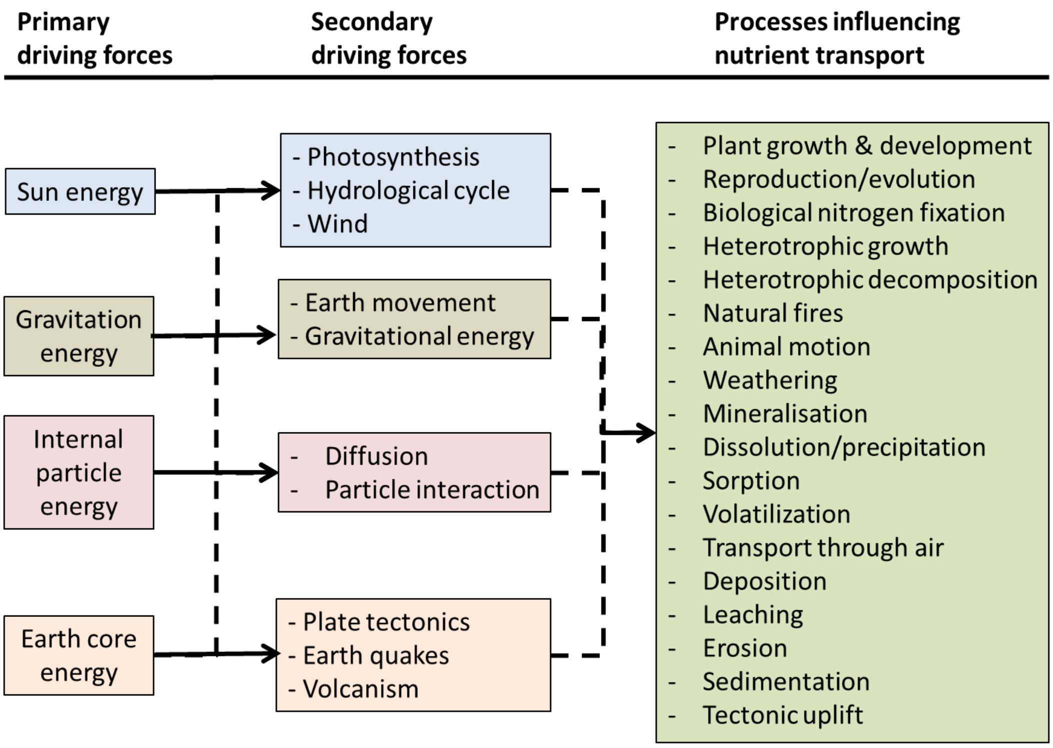

Figure 4.3 Driving forces of nutrient transformations and transport in natural systems. There are four primary energy sources (first column), which fuel the secondary driving forces and subsequently the nutrient transformation and transport processes in nature (Liu et al., 2020).

The change from natural systems to agricultural and food systems, which started some 10,000 years ago, has greatly altered nutrient cycles. The main driving forces for this change are the increasing and agglomerating human populations and the increasing prosperity (of at least part of the population), which lead to an increasing food demand and to changes in food choices and nutrient cycling (Figure 4.4). The change has been greatly facilitated by scientific and technological developments, such as the invention of inorganic fertilizers (the Haber-Bosch process; Smil 2001; Erisman et al 2008), high-

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yielding crop and animal breeds, improved pest and disease management, mechanization, irrigation, processing, storing and transport. These have greatly contributed to the increased crop and animal productivity and to improvements in the processing, storage and marketing of food, feed, fibre and fuel products, especially during the last century.

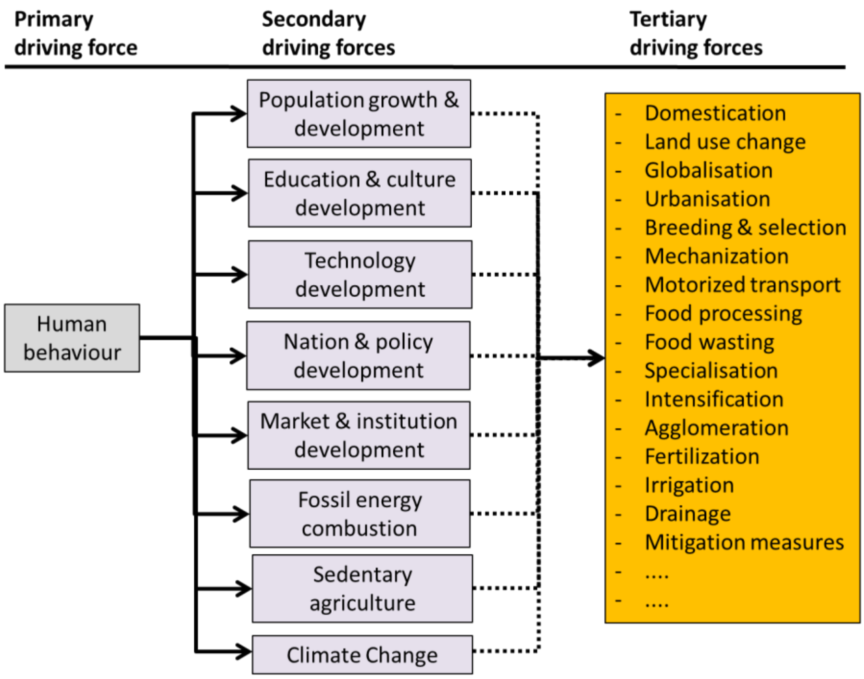

Figure 4.4 Anthropogenic driving forces for changes in nutrient transformations and transport in agriculture and food systems. A distinction is made between primary, secondary and tertiary driving forces, which all influence the nutrient transformation and transport processes indicated in Figure 4.3 (Source: Liu et al., 2020).

Liberalization and internationalization of markets combined with relatively cheap transport facilities have opened-up and enlarged markets, increased competition and decreased prices. As a result, nutrients embedded in food and feed products are transported across the world in all sorts of transport vessels (Galloway et al 2008; Lassaletta et al 2014a,b). Governmental policies have supported agricultural production in many countries, through the facilitation of the build-up of a good knowledge and physical infrastructure, through the market and product support and through subsidies on inputs (including fertilizers). The alterations in global nutrient cycles through land use change, agriculture, food processing and transport have increased especially from the 20th century onwards (Vitousek et al 1997; Smil 2000). Finally, climate change is also increasingly seen as a driver of changes in the global cycling of nutrients, as changes in temperature regimes and rainfall patterns affect biological processes and the transport of nutrients.

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As indicated in Chapter 2 of this report, C, N and P are coupled and decoupled at various stages of nutrient cycling in natural and agricultural systems, and the C:N:P stoichiometry of crop and animal products is influenced by changes in cycling and the relative importance of the driving forces of this cycling. Photosynthesis, chemosynthesis and biosynthesis lead to coupling of C, N and P, while respiration, senescence, fermentation, grazing, harvesting, decomposition, mineralization, refinery, and fractionation lead to (partial) uncoupling of CNP. The single, biggest event in history that has contributed to decoupling of CNP is the advent of synthetic fertilizer production, notably the production of synthetic N fertilizers. Fertilizers have become the largest sources of 'new' N and P in the terrestrial biosphere during the 20th century. It has allowed to greatly increase food production, through increased capture of solar radiance, also through the availability of high-yielding cultivars. It has also allowed to greatly increase animal feed production and thereby to increase animal production. This has subsequently contributed to increased manure production, with decreased C:N and C:P ratios in feces and urine. As a result, of the increased productivity and manure production, and the changed CNP stoichiometry, the susceptibility of crop and animal production systems to N and P losses has increased.

Evidently, a combination of primary and secondary driving forces have contributed to the changes in agricultural systems and to changes in nutrient cycling and in CNP stoichiometry. The total flow (input) of nutrients in agriculture has increased, the C:N and C:P ratios of crop and animal production have decreased, and the balance between C, N, P coupling and decoupling has changes. There is more uncoupling, because of the greater abundance of N and P compared to C. If the process of photosynthesis (and chemosynthesis and biosynthesis) could be improved per unit of incoming solar radiation, the coupling would be improved again.

Low-input systems have low productivity, but a relatively tight coupling of C, N and P, and hence low losses of N and P. Systems relying on N input via biological N_2 fixation have inherently a more tight CNP coupling than systems relying on N inputs via chemical N_2 fixation (N fertilizers). Low-protein animal feeding also reduces the uncoupling of CNP, as a much greater fraction of the ingested CNP is excreted in dung as coupled CNP, and little N and P (in case of pigs and humans) is excreted via urine in uncoupled forms.

Food processing and fractionation commonly leads to some uncoupling of CNP and/or to food fractions with different C:N:P stoichiometry. The use of these food fractions ultimately defines the fate of the CNP in these food fractions. Examples include the polishing of cereal grains; during polishing the most nutritious parts of the grain, i.e., the bran and the germ is removed. The only part that remains is the endosperm, which is primarily rich in carbohydrates (C) and devoid of N and P (and other nutrients). Hence, consumption of whole-cereal and multigrain brain leads to less uncoupling of CNP than consumption of bread made from polished grains.

Manure treatment is a way to reduce the manure volume (by reducing the water content), to improve the manure quality and biosecurity (by composting, pasteurization), to fractionate manure in fractions with different C:N:P ratios, and to manipulate the C:N:P ratio of these fractions. This may allow a more complete utilization of the manure CNP in crop production. The emphasis in manure treatment is quite

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often on one or two elements in manure, e.g., in manure digestion the focus is on C (energy), in slurry separation the focus is on obtaining a N-rich and P-poor fraction, and the C and P rich fraction, in NH_3 stripping the focus is on removing NH_3-N, in incineration the focus is on C (energy) and P (and some other nutrients in ashes). Evidently, the challenge for manure treatment is to combine treatment combinations and management approaches that lead to (i) a high utilization of both C, N and P jointly, and (ii) to identify options for greater coupling of CNP.

4.4 Main changes in agricultural systems

The changes in the driving forces of European agriculture (paragraph 4.3) have led to the specialization, intensification, upscaling (enlargement) of farming systems, and to the introduction of treatment technology in the food production – consumption chain. Specialization includes the selection of only few main activities, crops or animals within a farm, and often includes outsourcing (transfer of activities to others). Intensification refers to increasing the output per unit of land, labour and animal on a farm, through increasing knowledge, management and non-factor inputs (e.g. fertilizers, irrigation, mechanization). Upscaling refers to increasing total output of a farm or firm, often through enlargement of the farm/firm, mechanization and often also through specialization/ outsourcing. Treatment encompasses a whole range of activities aimed at increasing the value of crop and animal products at the farm, firm and/or processing industry.

This chapter provides a brief qualitative description of the driving forces of farming systems, based on a literature review, and a semi-quantitative analyses of the changes over time in farm structure. The influences of changes in markets, technology and governmental policies on farming systems over the last few decades are discussed, in terms of specialization, intensification, and up-scaling. Most of these data were derived from FAOSTAT, which has for many indicators data since 1961.

4.4.1 Farming systems

Detailed data per farm type for the EU is only available in the FSS and FADN statistics, where FADN have yearly values available. However, these statistical data are not available for such a long period as the FAOSTAT data. For FADN for most countries data is available since 2004. Although the period since 2004 is relatively short, it clearly shows that the trend of upscaling is still continuing, especially in the intensive livestock sector, where the number of pigs and poultry per farm doubled in the period 2004-2017 (Figure 4.5). For the dairy and mixed farm types, a slight increase in number of livestock per farm occurred, whereas in other grazing farms (i.e. beef and sheep) the number of animals per farm remained stable.

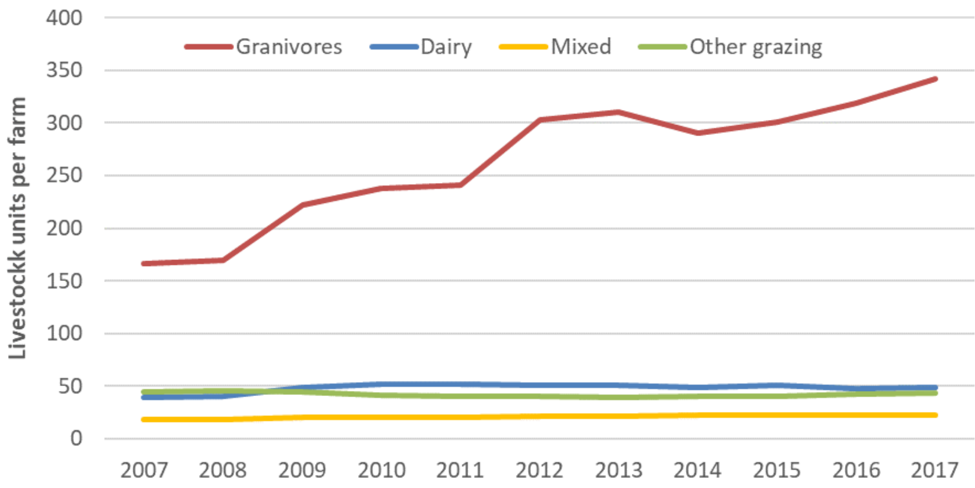

Figure 4.5 Trend in number of livestock units per farm for EU-27 (data derived from FADN statistics)

This increase in number of pigs and poultry per farm resulted also in a higher output per farm, which also doubled in the period 2004-2017 for these granivore farms (Figure 4.6). The average total output for dairy farms increased in this period by 20%. Also farms with permanent crops showed a large increase in total output. This can be partly explained by the change in farm size, which increased from about 9 ha per farm in 2004 to almost 13 ha per farm in 2017. For pig and poultry farms this increase in total production also resulted on average in a higher net income over the last years (Figure 4.7). For most other farm types the average net income remained more or less stable, although even at EU27 level large variation between years can be observed.

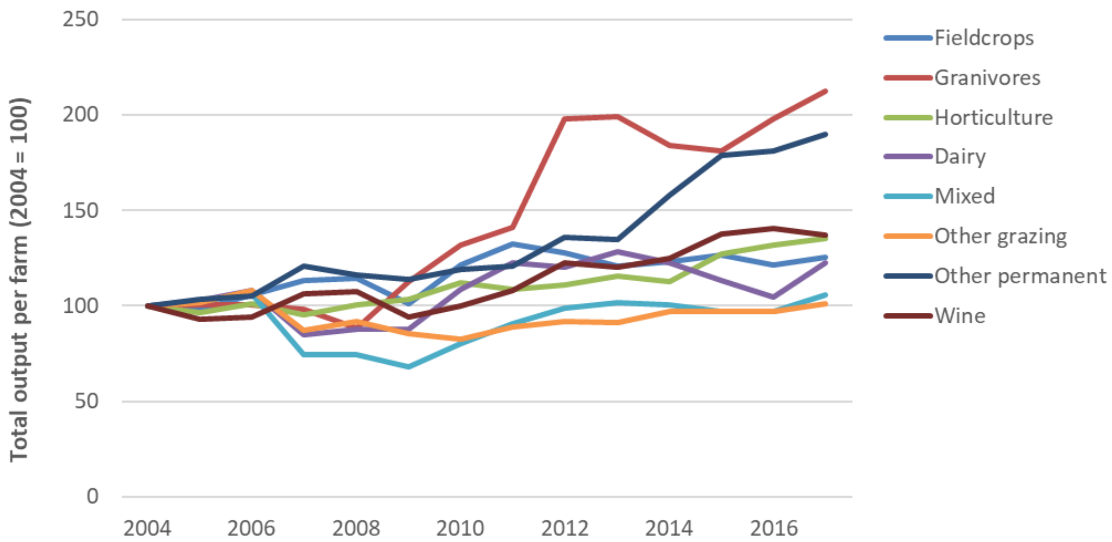

Figure 4.6 Trend in total output per farm (standardised to output of 2004 that set at 100) for the main farm types in the EU27 (based on aggregated FADN data)

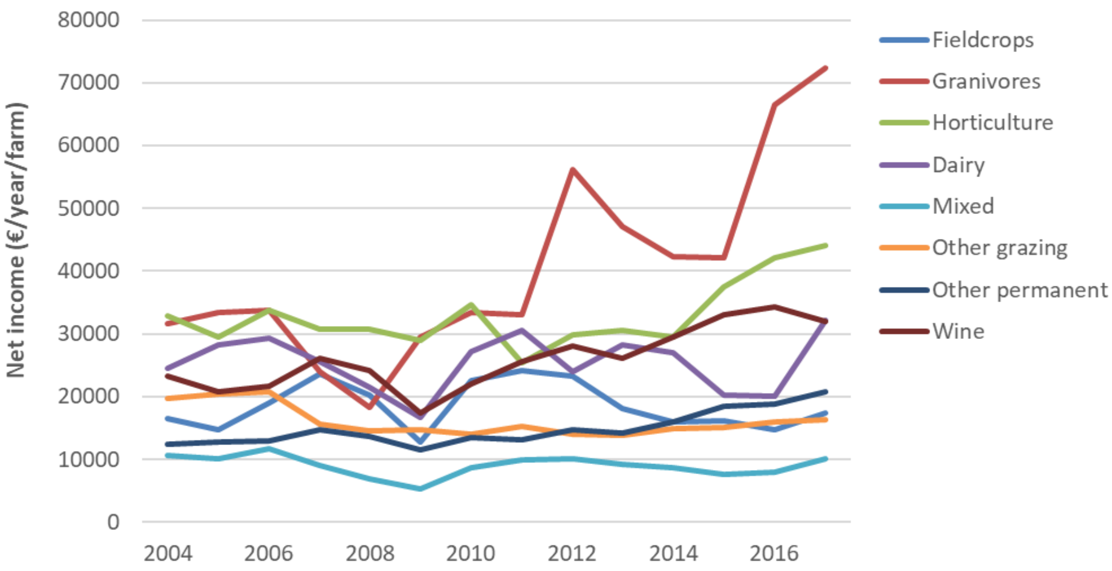

Figure 4.7 Average net income per farm for EU27 (based on aggregated FADN data)

4.4.2 Crop production

The total area of arable land (incl. fodder crops and temporary grassland) decreased from 123 million ha in 1961 to 106 million in 2017. This decrease can be explained by conversion of agricultural land to settlements, but also because of abandonment of marginal areas, mainly in Southern and Central Europe. Figure 4.8 shows the trend in harvested area for the main crop categories. For most crops the harvested crop area decreased, especially for pulses and potatoes, such as potato and sugar beet. Only the area of oil crops, mainly rapeseed and sunflower and olives. Also the permanent grassland area decreased from about 76 million ha in 1961 to 64 million ha in 2017. The area of permanent crops remained rather stable around 12 million ha. In these data the values of the countries that were part of the former USSR are not included for the period before 1991, this has a slight effect on the total numbers and means that the decrease in areas since 1961 is even a bit larger.

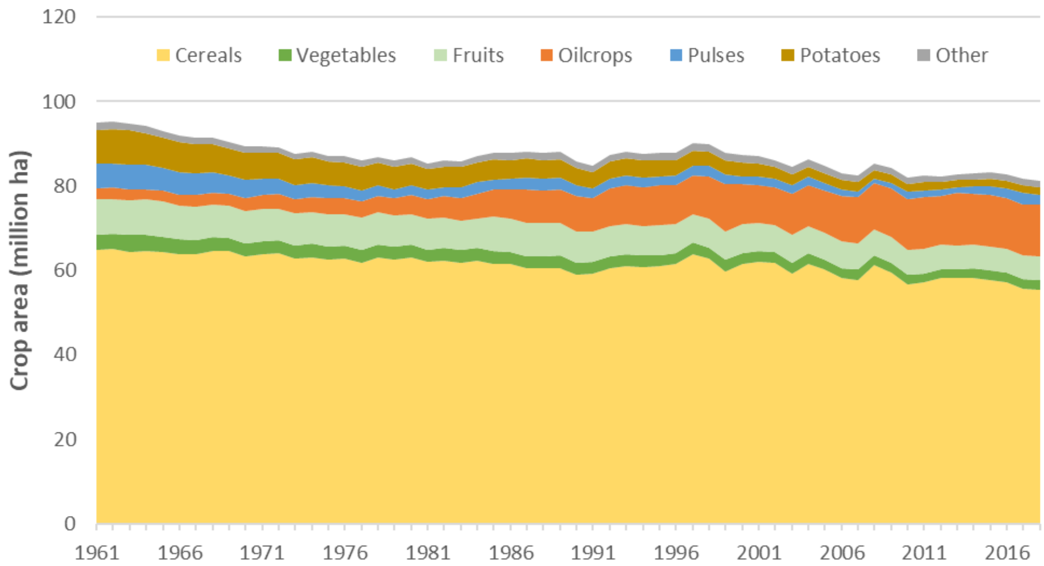

Figure 4.8 Trend in harvested crop areas for the main crop categories for the EU28 (source: FAOSTAT)

Despite the decrease in cropland, the total crop production increased, due to the increase in yields. For example, the average cereal yield increased from about 2 ton/ha in 1961 to more than 5 ton/ha in 2018 (Figure 4.9). The average crop yield increase for the EU28 member states was about a factor 2.5 for cereals and vegetables, 1.6 for fruits, 2.0 for potatoes and 2.7 for oil crops. The total cereal production increased from about 140 million ton in 1961 to about 300 million ton in 2017. For most other crops the total production also increased, only for potatoes the total production decreased from 130 million ton to 60 million ton, due to the sharp decrease in harvested area.

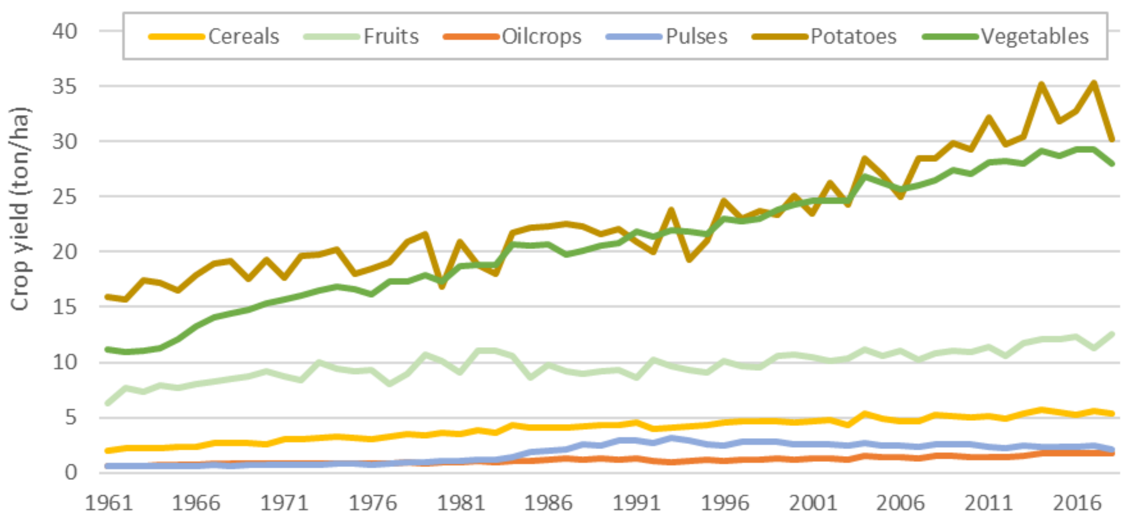

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Figure 4.9 Trend in crop yields for the main crop categories for the average of the EU28 (source: FAOSTAT)

The intensification of crop farming systems is linked to the access and availability of science-based insights and technological developments, but also to population growth. To feed a growing population, more food had to be produces at smaller area of agricultural land. The intensification of crop farming systems was stimulated by the introduction of new seeds, synthetic fertilizers, irrigation, pests and disease control and mechanization and industrialization. As a result, several EU member states rank within the top ten of highest production levels per hectare (e.g. the Netherlands, Belgium, Germany). Yield gaps (i.e., the difference between actual and potential yield) differ between member states (Schils et al., 2018), but overall crop yields of EU member states are about 2.5 times higher compared to the rest of the world (FAO, 2018).

The EU agricultural outlook for the agricultural markets and income 2017-2030 expects the utilised agricultural area and arable area a to decline and the share of permanent grassland remains stable (European Commission, 2017). Global sugar consumption is expected to decrease by 5% by 2030 due to increased health concerns. However, the end of the sugar quotas will increase sugar production by 12% by 2030. Cereal production is also expected to grow because of the increase in food demand, good export prospects and increasing use of cereals in industry. Oilseeds are expected to decrease because of lower demands. The increase in poultry and dairy products foresees an increase in fodder production.

4.4.3 Livestock production

Animal production is strongly influenced by market developments and by changes in agricultural and environmental policies. Before 1984, dairy farmers had been guaranteed a price for their milk regardless of market demand. This resulted in an overproduction of milk and milk products. Therefore, the Common Agricultural Policy (CAP) decided in 1984 to introduce a milk quota system in the European Union. This reduced the overproduction and stabilised farmer's revenues. The upheaval after the end of the Soviet Union caused a strong decline in animal numbers between 1990 and 1995. In 2009, the EU decided to lift the milk quota, which resulted in the expansion and intensification of livestock farming systems.

Livestock production in the EU member states shows in general an increasing trend (Figure 4.10). Total milk production increased since 1961 till 160 million ton in 1984. In that year the milk quota were introduced and milk production remained constant around 150 million ton per year. With the abolishment of the milk quota in 2015, milk production increased again. Beef production increased in the period 1961 till 1990 and afterwards steadily decreased, whereas pig and poultry meat production strongly increased. Egg production is more or less stable around 7 million tons per year. In terms of nutrients the total amount of N in livestock products increased from about 1200 kton in 1961 to 2200 kton in 2018 and for P from 230 kton in 1961 to 410 kton in 2018. Over time the N:P ratio slightly

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increased from 5.2 in 1961 to 5.3 in 2018, due to an increasing share of milk and chicken meat, which have a higher N:P ratio compared to beef and pork.

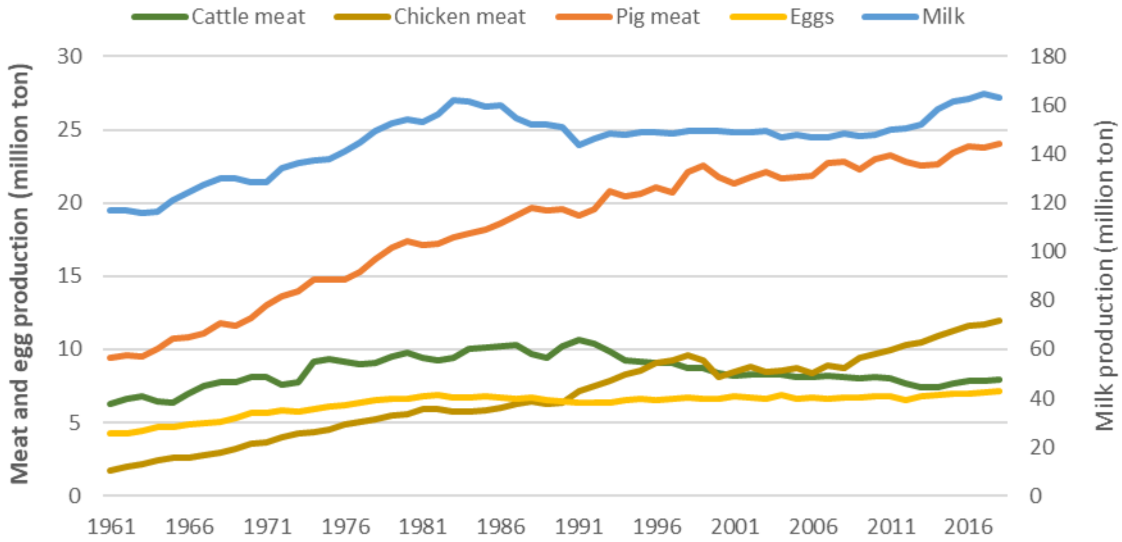

Figure 4.10 Trend in animal production for the EU-28 member states, meat is expressed in carcass weight (source: FAOSTAT)

The increase in milk production is mainly caused by an increase in milk yield. The average milk yield increased from 2700 kg/dairy cow in 1961 to 7000 kg/dairy cow in 2018. The average annual increase of 75 kg milk/dairy cow has been a steady trend, which is likely to continue for the coming decades as well. This increase is the result of continuous improvements in breeding and improved feed conversion ratio. Due to this increase in milk yield, the number of dairy cows has decreased over time. However, the N excretion and CH_4 emissions per animal also increased due to the higher feed intake, nevertheless the increase in milk yield is stronger, which results in a lower GHG intensity (GHG emission per kg milk). Since 1990, total GHG emissions from the agricultural sector decreased by 20% from 549 Mton to 438 Mton of CO_2-eq in 2015 (Duscha et al., 2019). Also in beef production the productivity increased, which means the slaughtered animals have become larger over time.

For pig meat the increase in total production is mainly due to the increase in animal numbers, as the amount of meat per pig has remained constant over the years (around 90 kg/animal). Also for poultry the increase in chicken meat and eggs is mainly due to the increase in animal numbers. However, also these sectors intensified as the feed conversion ratio has improved, which means that less feed is required to produce the same amount of meat and eggs.

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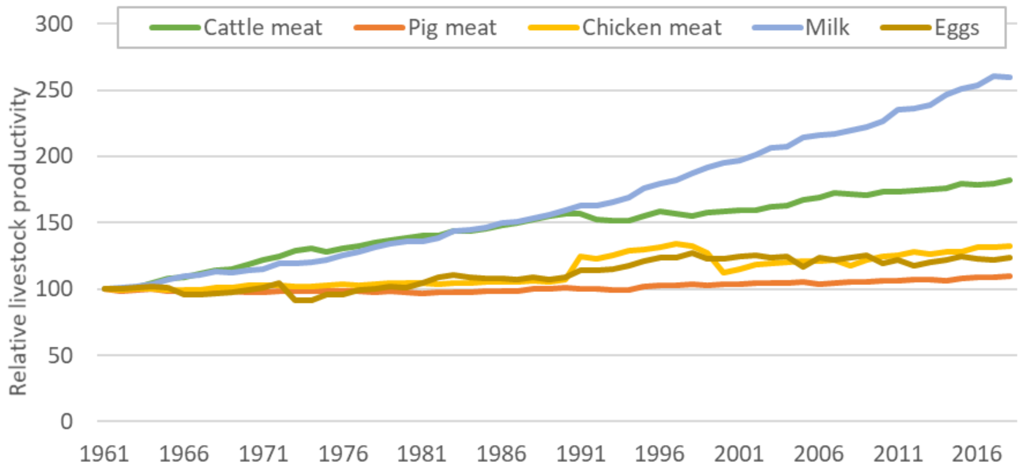

Figure 4.11 Trend in relative animal productivity (yield) for the EU-28 member states (source: FAOSTAT)

4.4.4 Trade of crop and animal products

Trade of animal and crop products is one of the major factors affecting the cycling of nutrient at larger scale. Based on the FAOSTAT food balance sheet statistics, which comprise information about the production, consumption, import and export of animal and crop products, the net trade of the main crop and animal product categories was determined. This net trade was combined with the average N and P content of these categories, as described in Chapter 6, to obtain the net import and export in terms of nutrients, as shown in Figure 4.12. For crop products the EU is a main exporter of cereals and importer of oil crops. During the sixties the EU was still an importer of cereals, but around 1974 this changed into a net exporter. The net imported of oil crops steadily increased, first for the additional demand in feed, and later also for the demand of biofuels.

The EU is a net exporter for most animal products, especially meat and milk. For meat the net export is mainly pig and poultry meat, as for beef the EU is more or less self-sufficient, with no net export or import. Although in absolute numbers the export might seem high, compared to the total production, the export is relatively small. For example the net export of milk outside the EU28 was about 13% of the total milk production in 2017, and for meat it was 9% of the total meat production. Besides these agricultural products, an important import of nutrients is also coming from fish, where the EU is an important net importer, with an net import that is about the same size as the fish production in the EU-28.

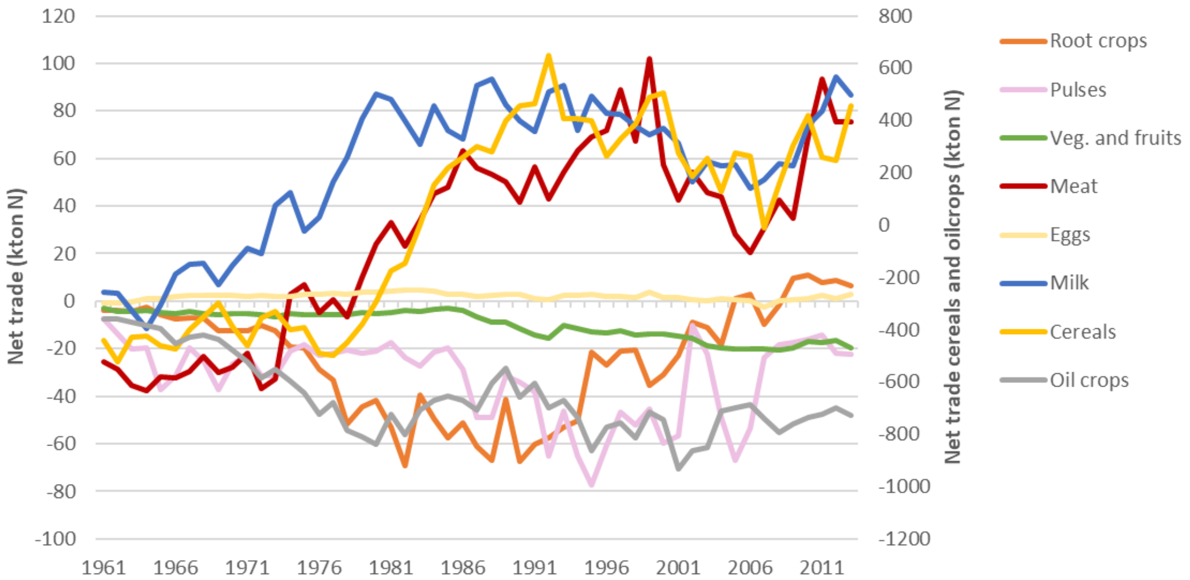

Figure 4.12 Trend in net trade of main crop and animal products for the EU-28. Negative values mean net import and positive values are net export, note that trade of oil crops and cereals is larger and expressed at the right axis (Source: FAOSTAT and own calculations)

Based on the calculations, the EU28 was and is a net importer of nutrients through crop and animal products. However, over time the net import decreased from about 900 kton N and 160 kton P in 1961 to about 250 kton N and 40 kton P in 2013 (Figure 4.13). Nitrogen and phosphorus show the same trend, although over time the N:P ratio of the net import increased from 5.6 to 7.6, which is due to the relatively higher share of oil crops in the net import.

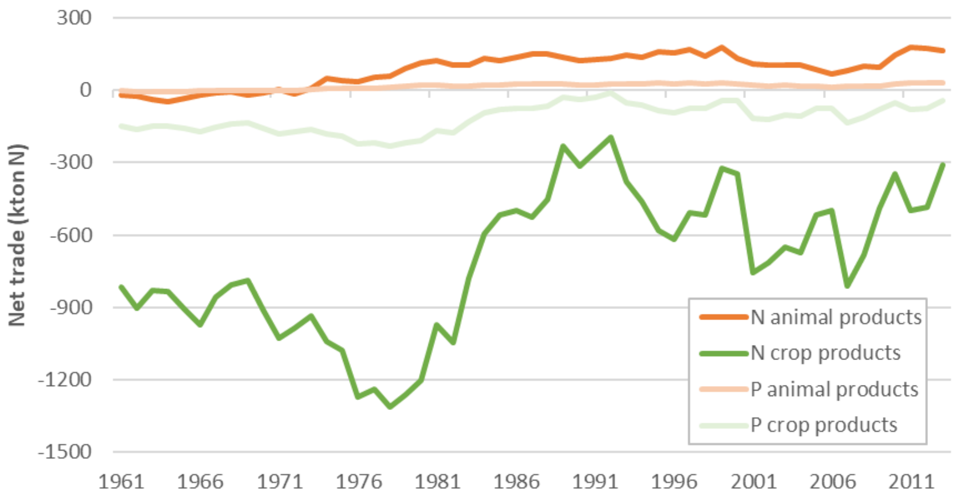

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Figure 4.13 Trend in net trade of N and P in crop and animal products for the EU-28. Negative values mean net import and positive values are net export (Source: FAOSTAT and own calculations)

For oil crops and pulses the EU is a net importer and depending especially on import of soybean from South America. This is nicely illustrated in a paper by Lassaletta et al. (2014) who illustrated the trade flows in agricultural commodities around the globe. Between 1986 and 2009 this trade flow changed a lot, whereas most of the import from the US is now coming from South America (Figure 4.14). To reduce the dependency on import of protein crops, the Commission is working on a plan for the development of increased production of plant proteins in the EU[1].

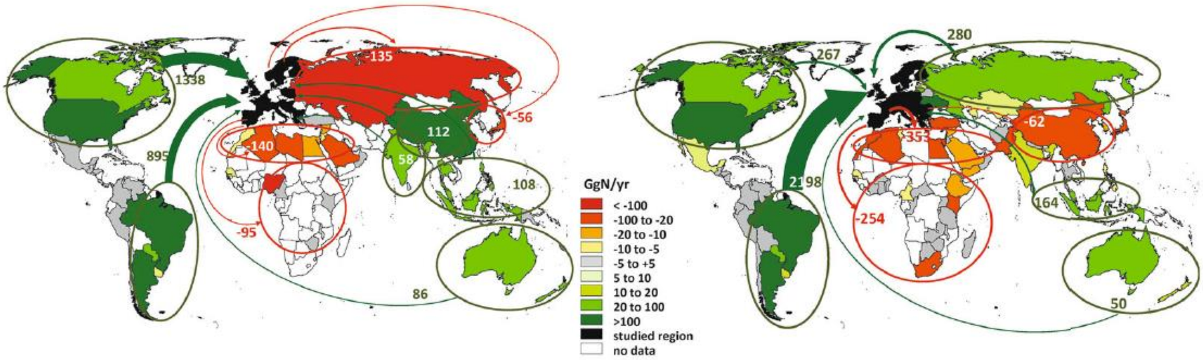

Figure 4.14 Net import of N to and from Europe for the years 1986 (left) and 2009 (right). The arrows show the fluxes between the regions (only fluxes higher than 90 Gg N are represented). (Source: Lassaletta et al. 2014).

4.4.5 Fertilizer consumption

Figure 4.15 shows the trend in fertilizer consumption for the EU-28 since 1961. Mineral nitrogen fertilizer consumption strongly increased in till over 14 million tons in 1989. At that time the fertilizer consumption decreased and remained more or less stable at 11 million tons N per year. Mineral phosphorus fertilizer also increased since 1961, but reached its top around 1979 at 2.7 million ton P, and gradually decreased till 1.2 million ton P in 2017. As the agricultural area also decreased, the decrease of fertilizer use per ha is less, but as crop yields also increased, the nutrient use efficiency increased in most countries.

[1] https://ec.europa.eu/info/sites/info/files/food-farming-fisheries/plants_and_plant_products/documents/report-plant-proteins-com2018-757-final_en.pdf

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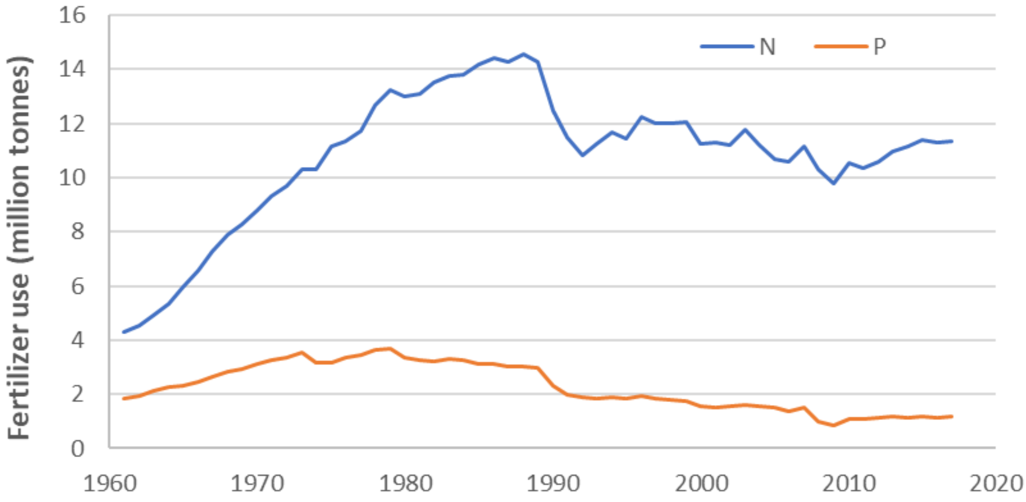

Figure 4.15 Trend in total N and P fertilizer consumption for EU-28 member states (Source: FAOSTAT)

However, within the EU there are large regional differences (Figure 4.16). In Central Europe the N fertilizer increased till 1990 after which a large drop occurred due to the collapse of the Soviet Union, since then the consumption steadily increased again. In northwest Europe a clear drop in N fertilizer occurred after 1990, this mainly has been the effect of the Nitrates Directive, which decreased the very high fertilization rates. In northern and southern Europe the N fertilizer consumption remained more or less stable since 1970. For mineral P fertilizer (not shown) most regions show a decline in P fertilizer use, with the largest decrease for northwest Europe. Only in central Europe the P fertilizer use is slightly increasing after the strong drop in 1990.

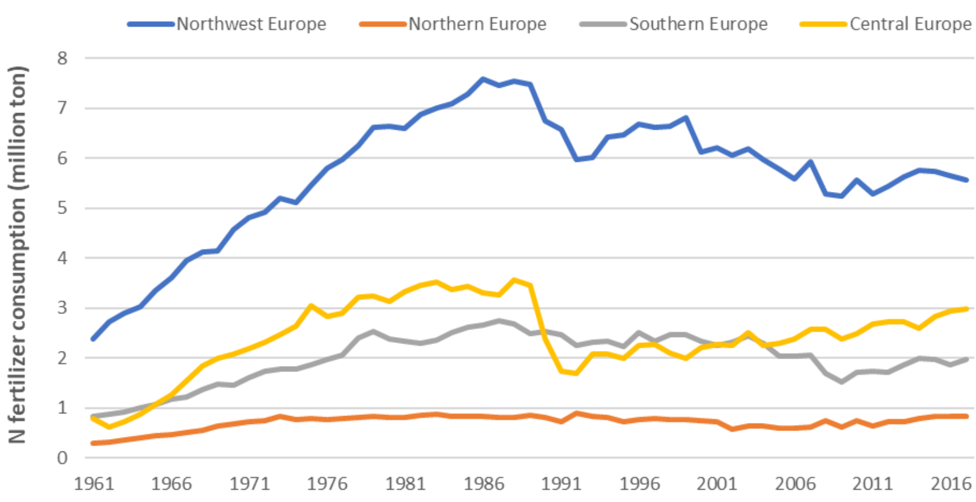

Figure 4.16 Trend in total N fertilizer consumption per region for EU-28 member states (Source: FAOSTAT)

4.4.6 Manure management

FAOSTAT provides also historic data on the amount of N in manure, based on calculations of the Tier 1 approach of the IPCC 2006 guidelines. Although this approach is a simplification and the numbers might differ from the actual N excretion, it still is a good estimate for the historic trend. Figure 4.17 shows the historic trend for the EU28 for applied and grazing manure. The total amount of N in manure first increased till a total of 10.5 million ton N in 1986 and afterwards decreased to 8.4 million ton N in 2017. Grazing manure is about 40% of the total manure N input.

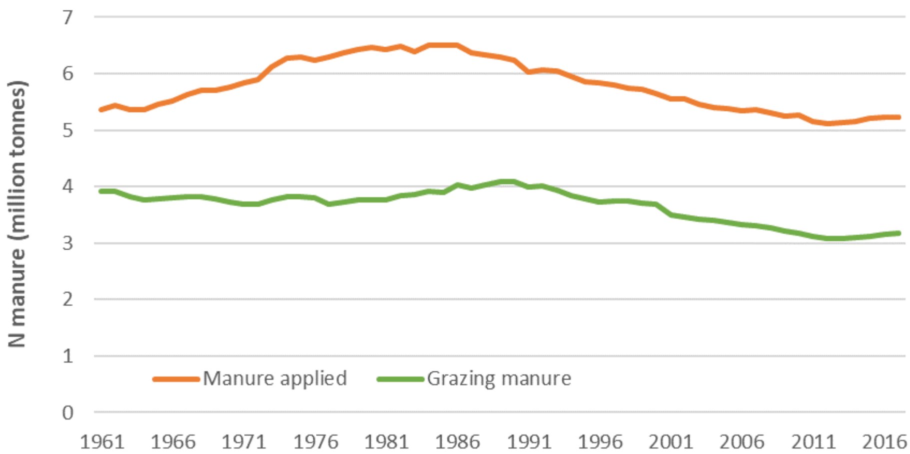

Figure 4.17 Trend in total amount on Nitrogen in applied and grazing manure for the EU28 (source: FAOSTAT, data on N excretion have been derived using IPCC Tier 1 approaches and can differ from the more detailed values that are reported in the National Inventory Reports)

A comparison of the total N excretion by different management systems in 1990 and 2017, based on data from the National GHG Inventory Reports shows an overall decline in N excretion. The main waste was completely eliminated and the role of digesters increased. Within the EU member states, the type of manure management systems that are used differ (Figure 4.18). Most of the EU member states use a liquid system, pasture range, solid storage and dry lot, and pasture range and paddock. Daily spread is most dominantly being used in the United Kingdom (UK), Spain and Romania. Digesters are not yet adopted by all member states. Croatia and Romania are the only two countries that use anaerobic lagoon as a manure management system and Austria is the only EU member state that uses composting.

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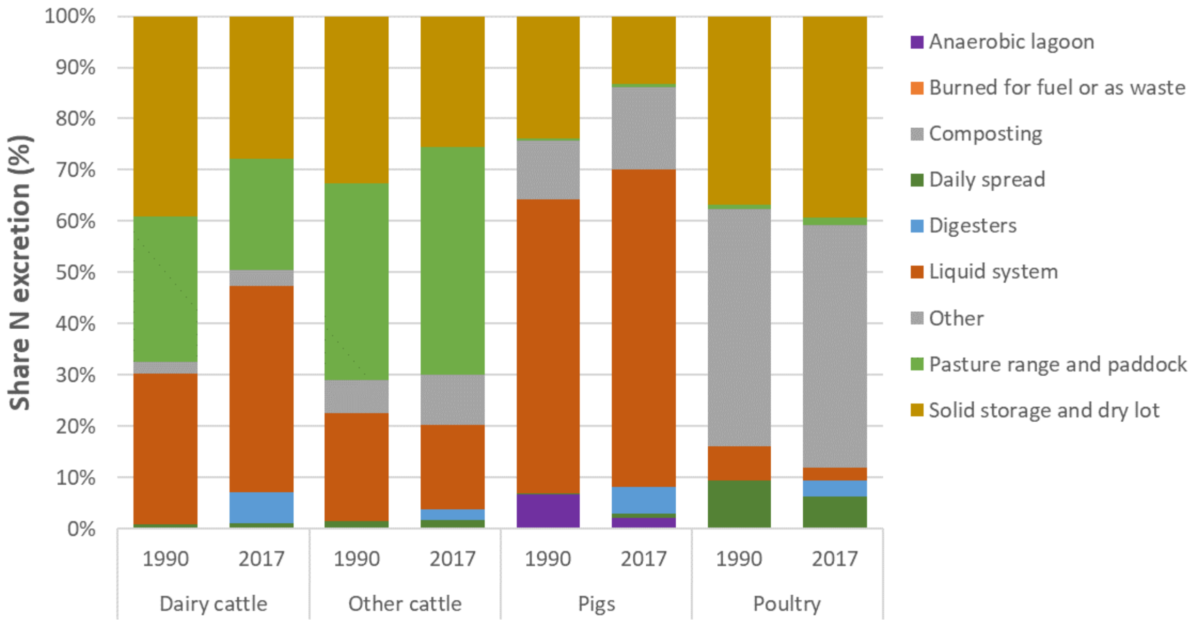

Figure 4.18 Share of total N excretion over different manure management systems for 1990 and 2017, data are based on data from the National GHG Inventories (CRF tables)

4.4.7 Nutrient balances

Data from the previous sections on changes in crop and livestock production systems are combined in this final part of this Chapter to illustrate the effect on nutrient balances and nutrient use efficiency. The OECD is reporting data on N and P balances for its member states since 1990[2]. Their nutrient balance is defined as the difference between the nutrient inputs entering a farming system (mainly livestock manure and fertilisers) and the nutrient outputs leaving the system (the uptake of nutrients for crop and pasture production). A surplus of nutrients in excess of immediate crop and forage needs can lead to nutrient losses, representing not only a possible cause of economic inefficiency in nutrient use by farmers, but also a source of nutrient losses to the environment. In Figure 4.19 the nitrogen surplus is presented for each EU member state for two periods (1990-1995) and (2010-2015) to illustrate the changes. In almost all countries a decrease of the surplus was observed. The decrease was largest in the countries with the high surplus (Belgium and the Netherlands). Only in Czech Republic, Poland and Spain a slight increase in the N surplus was observed. The overall N surplus decreased from 11.5 million ton N/year in 1990-1995 to 8.9 million ton N/year in the period 2010-2015.

[2] https://data.oecd.org/agrland/nutrient-balance.htm

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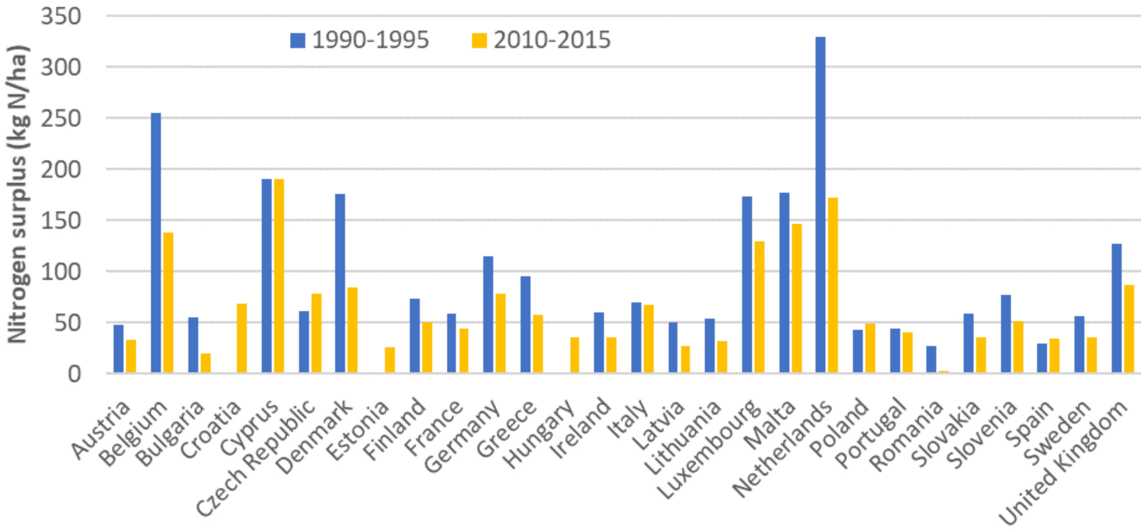

Figure 4.19 Average nitrogen surplus per ha for EU member states for the period 1990-1995 and 2010-2015 (Source: OECD)

For phosphorus a similar figure has been made (Figure 4.20). Most countries show a strong decrease in P surplus, especially countries that had very high surpluses. Belgium and the Netherlands reduced in 20 years the surplus from 30 to 5 kg P/ha. All countries have now surpluses that are below 7 kg P/ha, except for Cyprus and Malta, but these might be overestimated due to uncertain statistical data. Some central European countries (Bulgaria, Estonia, Slovakia) even have negative balances. These countries probably have to increase their P fertilization, as these are not countries that have an historic build-up of P in their soils. For P the overall surplus decreased strongly from 1.44 million ton P/year in 1990-1995 to 0.24 million ton N/year in the period 2010-2015.

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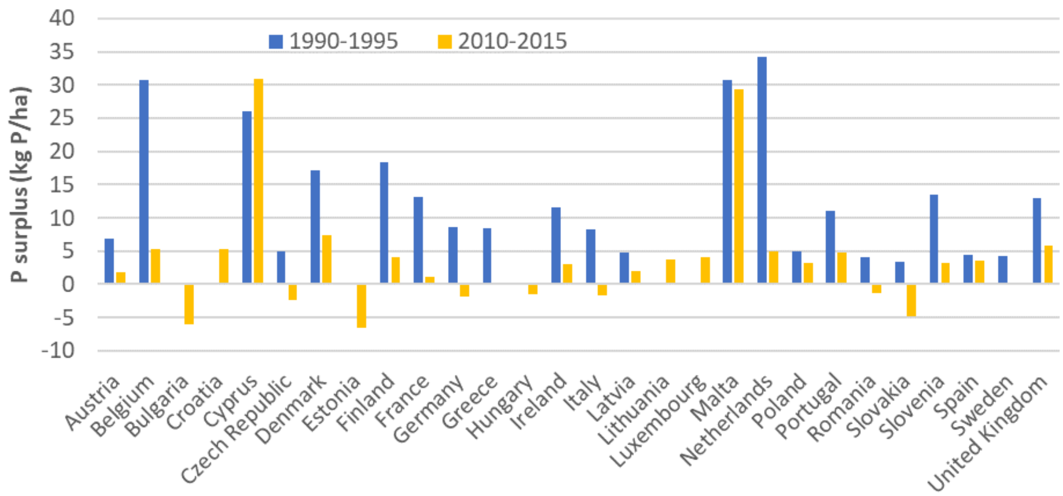

Figure 4.20 Average phosphorus surplus per ha for EU member states for the period 1990-1995 and 2010-2015 (Source: OECD)

In the final graph of this chapter data from the previous chapters are combined to calculate an overall Nitrogen Use Efficiency (NUE) for EU agriculture (Figure 4.21). NUE is defined as the N output divided by the N input, as described in more detail by the Nitrogen Expert Panel (Oenema et al., 2015). A simplified version of the NUE is presented here as not all data, e.g. N fixation, is available for the historic trend. N input is the amount of mineral N fertilizer and N output is the sum of N in animal products and crop products. Crop products do not include grass, fodder crops and cereals that are used as animal feed, as these are considered to be part of the internal flows, just as animal manure.

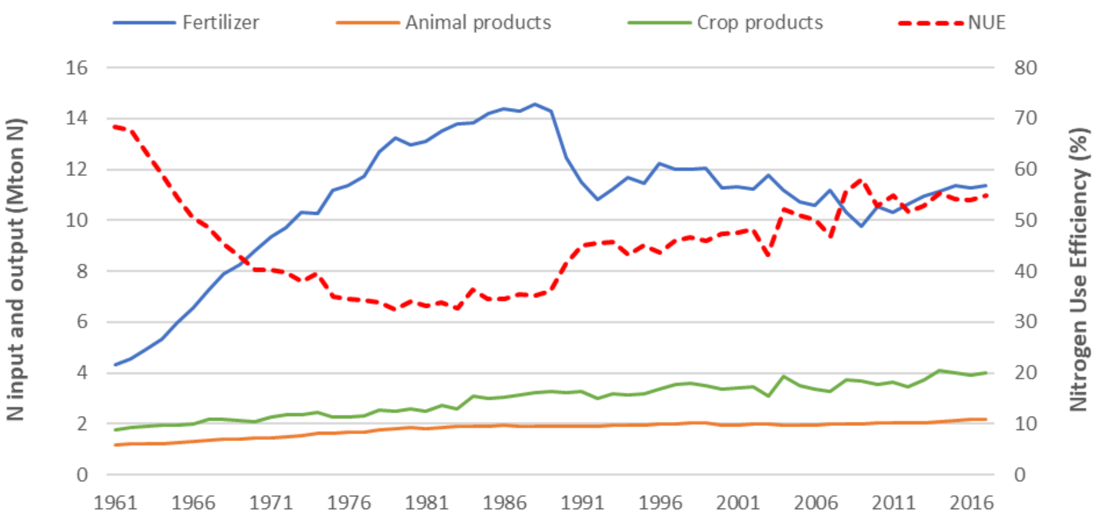

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Figure 4.21 Trend in nitrogen input from mineral fertilizer and manure application and nitrogen output in crop and livestock products, and the resulting Nitrogen Use Efficiency (NUE) for the EU28 member states (derived from FAOSTAT data and own calculations)

The overall NUE for EU agriculture strongly decreased in the period 1961 – 1975, as mineral N fertilizer strongly increased, but the increase of N in crop and livestock products was much lower. Around 1990 the NUE started to increase again from 35% to the current level of 55%. Although some nitrogen losses are inevitable, the NUE can still be improved, as current nitrogen losses to the air and water are still too high. These NUE calculations can also be made for only the crop or livestock production. In that case the NUE will be higher for crop products and lower for animal products as more N losses are involved in livestock production.

5. Ecological stoichiometry – definitions, concept and mechanism

5.1 Introduction

Ecological stoichiometry concerns the way that the elemental compositions of organisms shape the interactions between organisms and in the end all life on earth. It deals with the balance of elemental ratios and how these affect organism growth, nutrient cycling, and the interactions with the biotic and abiotic worlds. All organisms consume nutrients from the environment proportional to their needs. As a consequence, the elemental composition of organisms provide a set of constraints through which the biogeochemical cycles must pass. Variations in food availability have profoundly influenced the evolution of animals, because in many aspects an animal is what it eats.

This chapter provides an introduction to the concept and definitions of ecological stoichiometry. It is largely based on the book 'Ecological Stoichiometry – The Biology of Elements from Molecules to the Biosphere' (Sterner and Elser, 2003), and on papers in the special issue 'Progress in Ecological Stoichiometry', which were published in Frontiers in Microbiology, Frontiers in Ecology and Evolution, Frontiers in Environmental Science, Frontiers in Marine Science, Frontiers in Earth Science and Frontiers in Plant Science (Van der Waal et al., 2018).

5.2 Definitions

Stoichiometry refers to the proportions of elements in reactants and products of reactions and processes; it deals with the application of the law of definite proportions. Strict stoichiometry means that the elements of a compound are in fixed proportions, as in for example glucose ($C_6H_{12}O_6$), sodium chloride (NaCl), diammonium phosphate ((NH_4)2HPO_4), and amino acids. Commonly, the ratios of the elements are expressed as mole:mole ratios[3].

Non-strict stoichiometry refers to compounds that lack fixed proportions of elements. This is the situation for most soil minerals, such as for example illite $(K,H_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}[(OH)_2,(H_2O)]$ and vermiculite ((Mg,Fe2+,Fe3+)3[(Al,Si)4O10](OH)2·4H2O).

Homeostasis refers to the resistance of an organism to change its internal composition to its food, to its external world. It refers to the ability of organisms to keep the chemical composition of their body constant, despite changes in the chemical composition of the environment, including their food.

Strict homeostasis means that consumers stoichiometry does not vary with the food (resource) stoichiometry. No homeostasis means that consumer stoichiometry is similar to resource stoichiometry. In practice, organisms differ in the degree of homeostasis, depending on the resource

[3] Ratios are sometimes presented as mass:mass ratio, which is possible. However, mass:mass ratio and mole:mole ratios should not be mixed.

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stoichiometry. This dependence can be described according to Y =c.x1/H, i.e., consumer stoichiometry = constant * (resource stoichiometry)1/H, where, H is the regulatory coefficient and c is a constant (Figure 5.1). If H=1, there is no homeostasis (called 'conformers'). If H ranges from 1-2, there is weak homeostasis. If H=>5, there is a strong degree of homeostasis (called 'regulators'.

Homeostatic regulation is a function of the type of consumer (species), its life stage, the elements of the study, and most importantly the range of the element concentrations in the resources during the study. Homeostatic regulation is carried out through (i) food choice (selective grazing), (ii) habitat selection, (iii) assimilation (i.e., the process of disregarding and absorbing nutrients during digestion and distributing nutrients in the body for utilization), and (iv) excretion.

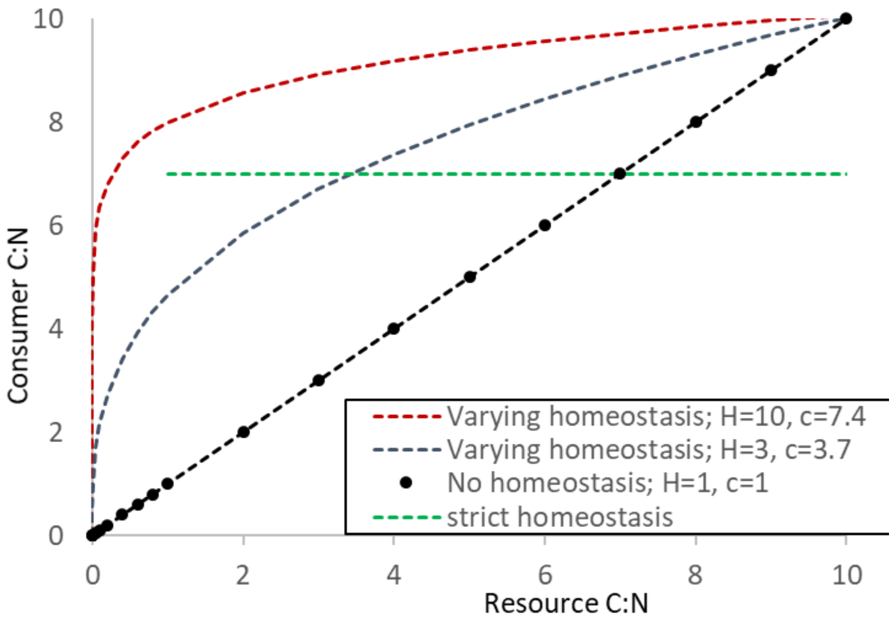

Figure 5.1. Illustration of the concept of homeostasis; consumer stoichiometry in response to variations in resource supply stoichiometry, applied to the case consumer C:N versus resource C:N. The curves follow the equation y =c.x1/H, with various values for H and c. In case of strict homeostasis (green line), consumer C:N ratio is independent from resource C:N ratio (as in most bacteria). Adapted from Sterner and Elser (2002).

In general, macro-elements like C, N and P are much more homeostatic than micro-elements. Heterotrophs (humans, animals) are much more homeostatic than autotrophs (plants, algae). Some algae have a H-value close to 1 (Box 1). The justification for comparing ratios is to compare the balance between elements. Note that ratios do not inform about the absolute amounts and flows.

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Box 1. Homeostatic regulations of oceans.

A special case of homeostatic regulation occurs in oceans. The C:N:P ratio of plankton is similar to the C:N:P ratio of ocean waters. This is the Redfield ratio, after Redfield (1934): C:N:P=106:16:1 (mole/mole). This ratio indicates a balanced form of C, N and P inputs and outputs, the biota determine and reflect the relative concentrations of C:N:P in ocean waters. It suggest that there is a simultaneous and proportional depletion and supply of N and P. It also suggest that both N and P are limiting primary production, although light, and micro-nutrients (Fe, Mn, Zn) also limit production in some areas of the oceans. The Redfield ratio has been observed also in the organic matter of sediment cores. Based on these findings, the following formula for phytoplankton growth has been developed (Stumm and Morgan, 1981):

$106CO_2 + 16NO_3^- + HPO_4^{2-} + 122H_2O + 18H^+$ (+sun + other elements) <--> $C_{106}H_{263}O_{110}N_{16}P + 138O_2$

5.3 C:N:P ratios of components of plants and animals

The human body (dry weight) consists on average of 57% C, 6.4% N and 2.8% P; hence, C:N is 8.9, C:P is 20; N:P is 2.3. Hence, C:N:P = 20:2.3:1 (wt/w) or 53:5:1 (mole/mole). There is slight variation in C:N:P ratios among humans (young versus mature; thin versus thick persons), young and fat persons have relatively less P and more C. The average C:N:P ratio of humans roughly reflects the average C:N:P requirements of the food.

Growing annual plants contain on average slightly less C, N and P than humans and animals, but woody perennials have very high C content but low N and P contents. Much of this variation is related to the relative proportions of main life constituents (components) in humans, animals and plants (Table 5.1 and Table 5.2). The C:N:P ratio in these components and the relative proportion of these components determine in the end the C:N:P ratios in plants, animals and humans.

Table 5.1 Main biological materials in plants and animals; their function and C, N and P contents

Biological materials	Functions	%C	%N	%P
Protein - amino acids	Structure, regulation, metabolism	30-50	17	<0.1
Nucleid acids - C,N,P; RNA, DNA	Storage, transmission, genetic information	30-50	15	8
Lipids; including fatty acids, waxes, sterols, vitamins A, D, E, and K	Cell membranes, energy storage	65-70	<1	<1
Nucleotides - - ATP	High-energy carrier and energy storage	10-30	20	15
Carbohydrates C – glucose, starch, chitin, cellulose, lignin	Structure, energy storage. Lignin are rich in C (>60%)	30-60	<5	<0.1
Chlorophyll a: $C_{55}H_{72}O_5N_4Mg$;	Light absorption	72	6.5	<0.1

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Table 5.2. Cellular compounds in plants and animals; their function and C, N and P contents.

Cellular structures & compounds	Functions	%C	%N	%P
Plant Cell walls - cellulose, hemi-cellulose, lignin	Structure, transport	35-40	<0.5	0
Bacteria cell walls - cellulose, lipids, peptides	Structure, transport	35-40	13	0.5
Cell membranes – phospholipids, protein, carbohydrates	Structure, transport	50-60	13.7	0.86
Cytoplasm – interior of the cell (>50% of volume) except cell nucleus - 80% is water, with dissolved proteins and the materials listed below	Most cellular activities, such as metabolic pathways and cell division	1-10	0-1	0-1
Endoplasmic reticulum (15% of volume)		50-60	12	1.2
Mitochondria	Cellular energetics	40-50	11	0.3
Chloroplasts	Photosynthetic energy capture	40-50	11.3	0.32
Chromosomes	Genetic information	40-50	16.5	3.6
Ribosomes	Catalysis, synthetic activity	40-50	16.3	5.0
Bone (inorganic part), mainly hydroxyapatite ($Ca10(PO_4)6(OH)2$)	Structure, stability	<1	<1	18

5.4 C:N:P ratios of plants

The nutrient content of whole plants depends on the distribution of plant biomass organs and their nutrient contents, i.e., the patterns of allocation or nutrients within plants. This allocation depends also on light intensity and nutrient availability. Allocation is very plastic, i.e., responsive to environmental conditions. Leaves respond much more to changes than stems and roots.

The C:N:P ratios of plants is determined by genotype (variety), environmental conditions and the net difference between uptake and losses (due to respiration, exudation, leaf and root excision). Carbon fixation and nutrient acquisition are not coupled directly, and as a result are not constrained by strict homeostasis. Plants also have the ability to reorganize cellular and nutrient allocation in response to changes in environmental conditions and physiological age. The net result is a relatively large interspecific and intraspecific variations in C:N:P ratios of plants.

Leaves contain more nutrients per unit mass than stems and roots. Thus, wood and roots have (very) low nutrient contents (<0.2% N, C:N >200). Nutrients in leaves may be translocated out of old leaves to prevent nutrient levels in the cytoplasm of young leaves to fall below those necessary for normal growth. Plants may invest also in enhanced nutrient adsorption capacity when the availability of nutrients is low; they may increase the specific root length (increase total root length and thereby the capacity to explore the soil), and they may increase the root : shoot ratios (again invest in roots to be able to scavenge nutrients from soil). Conversely, when the nutrient availability is high, plants may do the opposite; decrease the root : shoot ratio and the specific root length.

All plant cells have a cell wall, a nucleus, some mitochondria, various organelles, ribosomes, chloroplasts, and a large central vacuole. Cell walls contain C but no P and little N. The vacuole functions as a storage of organic compounds and nutrients during growth; it is a major factor in decoupling nutrient uptake from biomass growth in response to immediate environmental conditions. Luxury consumption refers to increases in nutrient contents over what is immediately required for growth during the vegetative growth period; the nutrients (e.g., nitrate, potassium, inorganic P) mainly accumulate in the vacuole (Yang et al., 2017). Seeds and grains function as storage organs during generative grow phase. In many higher plants, P is stored in seeds and grains as phytate ($C_6H_{18}O_{24}P_6$) with a C:P ratio (mole/mole) of 1. Through P storage, autotrophs can have low C:P and low N:P ratios, when they have access to abundant P under conditions of N limited growth.

Luxury consumption and storage of nutrients in the vacuole has a cost, because a large vacuole provides no direct contributions to cellular mechanisms. It also lowers the surface area : volume ratio of the cell and thus decreases the nutrient acquisition ability of the cell. In nature, plants have evolved different strategies (i) low allocation of cellular space to storage; these plants have an elemental composition directly related to growth rate, and have a high growth rate (due to large surface area : volume ratio), but they are sensitive to varying nutrient contents, or (ii) increased allocation of excess nutrients to vacuoles for storage of potentially limiting nutrients, which is advantageous under variable nutrient supply conditions, but at the cost of lower growth rates. As a result, three different plant types have developed over time:

- Competitive strategists: species with high growth rate adapted to fertile areas, and high degree of phenotypic plasticity in response to interactions with adjacent plants (growth strategies)
- Ruderal strategies: adapted to fertile areas with frequent disturbances: high growth rates and low degree of interaction with adjacent plants (affinity strategies)
- Stress tolerators: adapted to inhospitable conditions, and with the ability to extensive accumulation of reserves (storage strategies)

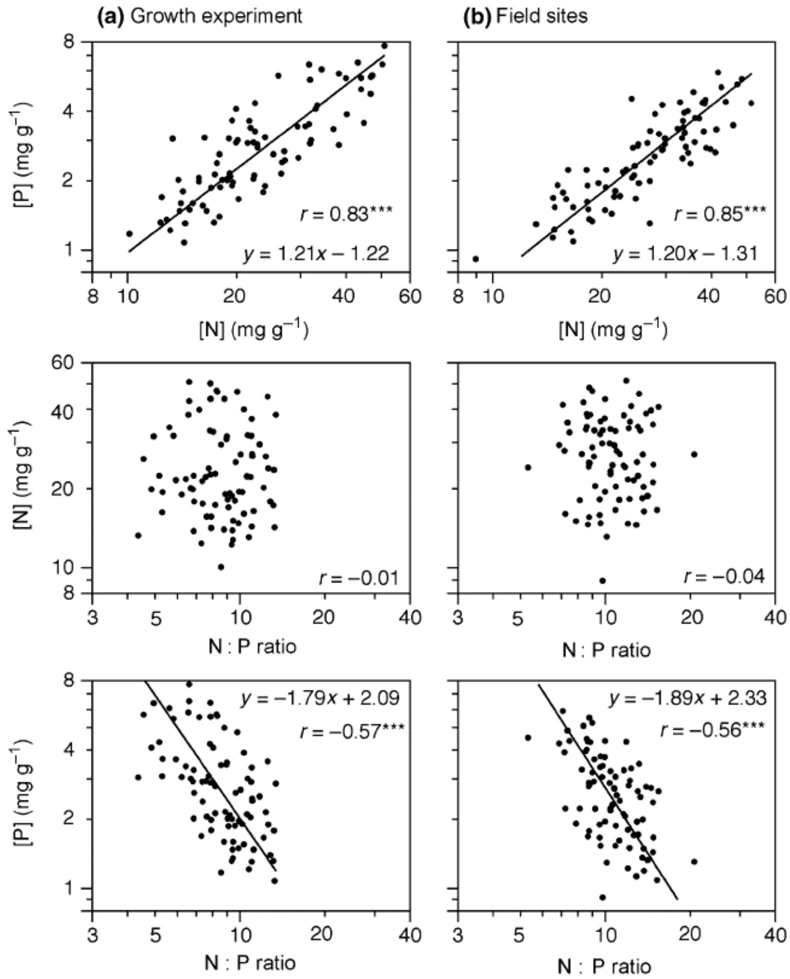

Figure 5.2. Relationships between N contents, P contents, and N:P ratios of plant species; (a) woody species in a growth experiment (Cornelissen et al., 1997); and (b) leaves of plants sampled from natural field sites (Thompson et al., 1997). Each symbol represents one species; all axes are logarithmic. Copied from Güseman (2004).

When many plant species are compared, N and P contents always correlate positively with each other (Figure 5.2). Note that N:P ratios are largely unrelated to N contents, while N:P ratios correlate negatively to P contents. Interspecific variation in N:P ratios is therefore primarily determined by variation in phosphorus contents. These relationships are nearly identical for plants grown under standardized conditions in the glasshouse (Figure 5.2.a) and plants sampled in the field (Figure 5.2.b).

Table 5.3 Differences in N and P contents and N : P mass ratios among plant growth forms in various vegetation types of the world. Copied from Güseman (2004).

	[N] mg g^{-1}	[P] mg g^{-1}	N : P ratio
Worldwide[1]			
Evergreen woody	13.7	1.02	13.4
Deciduous woody	22.2	1.60	13.9
Forbs	22.2	1.86	11.9
Graminoids	16.0	0.95	17.8
Mediterranean (Greece)[2]			
Evergreen woody	10.3	0.62	16.6
Deciduous woody	23.0	1.53	15.1
Herbaceous (mainly forbs)	17.5	1.25	14.0
Mediterranean (Australia)[3]			
Woody	9.5	0.7	13.6
Herbaceous	10.6	0.9	11.8
Temperate (Britain)[4]			
Woody (shrubs)	18.0	1.46	12.5
Forbs	32.3	3.14	10.9
Graminoids	21.6	2.23	10.2
Subarctic (Sweden)[5]			
Evergreen woody	na	na	9.1
Deciduous woody	na	na	10.7
Forbs	na	na	11.1
Graminoids	na	na	13.2
European wetlands[6]			
Evergreen woody (shrubs)	13.6	0.73	18.6
Forbs	14.8	1.46	10.3
Graminoids	11.5	0.89	12.9
In growth experiment			
Forbs	11.1	1.03	10.8
Graminoids	10.8	0.73	14.8

Values in the tables are means of all species with a given growth form included in each study. Sources: [1]Aerts (1996); [2]Margaris *et al.* (1984); [3]Foulds (1993); [4]Thompson *et al.* (1997); [5]Eckstein & Karlsson (1997); [6]Güsewell & Koerselman (2002).

Increasing light intensity and pCO_2 increases C:N:P ratios and relative and specific growth rates. Fast-growing plants have lower N:P ratio than slow-growing species. In general, the N:P ratio is an indicator of both N-limited and P-limited growth. It has been suggested that plants with N:P >33 respond to P fertilization, but there are differences between plant species. A N:P ratio of 33 is higher than the

Redfield ratio (16; see Box 1); this is related to the fact that higher plants allocate tissue and nutrients to structural material (stems, roots) with relatively low N and P contents, while algae do not. Further, C4 grasses produce more biomass per unit of N than C3 grasses; C4 grasses have higher N use efficiency than C3 grasses, and tend to have lower N:P ratios than C3 grasses. However, there is a lot of discussion about critical N/P ratios (Güseman 2004); the lack of a definite answer reflects in part the ambiguity of the concept of nutrient limitation: 'limitation' is defined by differences between process rates and therefore depends on the process, the type of comparison and the time scale over which it is assessed. However, plant N:P ratios do reflect the gradual and dynamic character of nutrient limitation.

A compilation of data sets from several field surveys and reviews shows that N and P contents and N:P ratios do not differ consistently between woody and herbaceous plant species (Table 5.3). Evergreen woody species generally have lower N and P than deciduous ones, but N:P ratios do not differ. Graminoids generally have lower N and P and higher N:P ratios than forbs. The N:P ratio of forest litter does not change much over time (Table 5.4). While the C:N and C:P ratios strongly decrease (by a factor of 3 to 4 in five years), the N:P ratio remains in a rather narrow range of 14 to 19 without systematic changes over time. Note that the C:N and C:P ratios remain relatively high; the changes reflect that C was lost through decomposition but that N and P were largely retained.

Table 5.4 Ratios of nutrient elements to Carbon in the litter of Scots Pine (Pinus sylvestris) at sequential stages of decomposition (copied from Schlesinger and Bernhardt, 2014).

	C/N	C/P	C/K	C/S	C/Ca	C/Mg	C/Mn
Needle litter							
Initial	134	2630	705	1210	79	1350	330
After incubation of:							
1 year	85	1330	735	864	101	1870	576
2 year	66	912	867	ND	107	2360	800
3 year	53	948	1970	ND	132	1710	1110
4 year	46	869	1360	496	104	704	988
5 year	41	656	591	497	231	1600	1120
Fungal biomass							
Scots pine forest	12	64	41	ND	ND	ND	ND

Note: C/N and C/P ratios decline with time, which indicates retention of these nutrients as C is lost, whereas C/Ca and C/K ratios increase, which indicates that these nutrients are lost more rapidly than carbon.

The preferential loss of C following from the litter layers of beech forests was also shown in a German study, where three forest stands differing in fertility were studied in detail (Table 5.5); the C:N and C:P ratios decreased with depth. Two litter layers (Oi and Oe) and the mineral A horizon (top soil) were distinguished. The Oi horizon (3 to 4 cm thick) is the uppermost organic horizon, consisting of undecayed to slightly decayed plant material. The Oe horizon (3 to 9 cm thick) consists of partially decayed plant material with little if any in its original conditions. The low fertility site (LUE) had the thickest Oi (4 cm) and Oe (9 cm) horizon and the highest C:N and C:P ratios. Mineralization rates decreased with soil depth from Oi to A horizons, reflecting increasing stability of the soil organic matter. In the Oi and Oe horizons, net N immobilization occurred.

Table 5.5 Contents of C and ratios of C:N, C:P and N:P in three subsequent soil surface layers (horizons) of three beech forest sites in Germany: Bad Brückenau (BBR), Mitterfels (MIT) and Lüss (LUE). The site BRR has relatively rich parent material and high atmospheric N deposition, and LUE is on poor sandy soil with relatively low atmospheric N deposition (after Brödlin et al., 2019).

Horizon	C content, g/kg			C:N			$C:P_{org}$			$N:P_{org}$		
	BBR	MIT	LUE	BBR	MIT	LUE	BBR	MIT	LUE	BBR	MIT	LUE
O1	472	490	470	32	40	46	445	676	841	14	17	18
Oe	300	438	391	19	19	24	244	461	755	13	24	31
A	117	168	34	15	18	23	222	405	702	18	31	31

In summary, the C:N:P ratios of plants is a function of plant species, with good competitors having high C:N:P ratio.

- Increases with the severity of growth limitation by N and/or P
- Increases with decreased availability of N and/or P compared to other limiting nutrients;
- Increases with increasing light intensity
- Increases with increasing pCO_2

In forest soils, C:N:P ratios strongly decrease with depth, indicating preferential release of C (through decomposition of organic matter) and immobilization of N, depending also on atmospheric N deposition rates. The C:N ratio of top soils is ≥15.

5.5 C:N:P ratios of animals

The primary biomolecules of animal biomass fall into 5 categories (see also Table 5.1):

- Carbohydrates (low N and low P)
- Proteins (high N, little or no P)
- Nucleic acids (high N and high P
- Lipids (little or no N and little or no P)
- Lipids and nucleotides (involve in energy transformations, e.g. ATP)

In addition, there are structural carbohydrate molecules, such as chitin in many invertebrates (animals without a backbone or bony skeleton, including many insects, worms, snakes), which has high C, some N and little or no P, and bone in vertebrates (animals with a backbone or bony skeleton), which has low C, low N and high P contents.
Evolutionary trends towards larger size animals necessitate stiffer structural support, which increases the C:P ratio in invertebrates (animals without a backbone) and decreases the C:P ratio in vertebrates. However, there is a wide interspecies variation in C:P ratios (50-250) and N:P ratios (10-40) in invertebrates. Generally, invertebrate species with relatively low C:P ratios and N:P ratios are fast growers while slow growers have relatively high C:P and N:P ratios. The C:P and N:P ratios in

vertebrates (e.g., humans, ruminants, etc.) are strongly influenced by the bone structure and the large amounts of P in bones. About 85% of P in humans is in bones (N:P=0.8), 14% in muscles and organs (soft tissue, with N:P ~40-50) and 1% in blood (N:P ratio <50). Skin has high N content (16%) and no P. The N:P ratio of vertebrates decreases with body size, due to a decrease in N and an increase in P contents.

There are three ways that animal species can maintain its C:N:P ratios (homeostasis) when confronted with imbalanced resources: (i) selective feeding/grazing and/or supplementation of specific food items, (ii) alter assimilation patters, regulating the passage of feed materials across the gut wall so that they match consumer needs, (iii) homeostatic regulation through its metabolism, such as increased protein degradation and subsequent increased release of N wastes when the diet is high in protein-N, or conserve / recycle nutrients under nutrient scarcity. The reasons why animal species have the C:N:P ratios they have, range from evolutionary pressure on life, to the need to support structure, to the distribution of the availability of energy and materials in ecosystems. Under conditions of feed (and or nutrient) limitation, yield maximization is favoured by selection. The most balanced and efficient C:N:P consumer-resource pair is cannibalism.

Gross growth efficiency (GGE) is defined as 'consumer growth rate per unit of feed intake' (ingestion). GGE is a composite measure of (i) the ratio of assimilation[4] to ingestion (assimilation efficiency S), and (ii) the ratio of growth to assimilation (net growth efficiency NGE). Hence, GGE = S x NGE.

The second law of thermodynamics imposes an upper limit for carbon utilization by animals: 70 to 90% by unicellular organisms (including bacteria, archaea, protozoa and fungi), and 35-50% by metazoans (including vertebrates). However, most consumers fail to achieve these high upper levels.

The assimilation efficiency S increases in the order detrivores (S=10-40%) < herbivores (S=30-80%) < carnivores (S=60-100%). The net growth efficiency NGE increases in the same order as the that for assimilation efficiency: detrivores (NGE=10-40%) <~herbivores (10-60%) <~carnivores (10-80%). Mean GGE is about 30% (25 and 75 percentile values 15-45%). Much of this variation is related to the C:N:P ratios of the resource and the consumer. Animals with low GGE are those that have C:N:P in the feed resources that differs greatly from their own C:N:P ratio.

Further, animals have requirements for some 13 vitamins part of which they either cannot synthesize at all or have such limited abilities to synthesize that they need to be ingested. Humans also have three essential vitamins that are not present in plant-sourced food. Deficiency in one or more vitamins, and deficiency in one or more of the essential amino acids, decreases GGE.

[4] Assimilation is the combination of two processes to supply cells with nutrients. The first process is the process of absorption of vitamins, minerals, and other chemicals from food within the gastrointestinal tract. In humans this is always done with a chemical breakdown (enzymes and acids) and physical breakdown (oral mastication and stomach churning). The second process of bio assimilation is the chemical alteration of substances in the bloodstream by the liver or cellular secretions. Although a few similar compounds can be absorbed in digestion bio assimilation, the bioavailability of many compounds is dictated by this second process since both the liver and cellular secretions can be very specific in their metabolic action. This second process is where the absorbed food reaches the cells via the liver.

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For main domestic animal species Threshold Element contents or Ratios (TER) have been set for nutrient elements, amino acids and vitamins. This is further illustrated in Figure 5.3 for C (energy, glucose), N, and/or P limitations for growth in animals with strict vs variable C:N:P stoichiometry. Mixed limitations often occurs at low growth and low growth efficiency (low GGE and NGE). Commonly, GGE increases with increasing concentration of the element that is in short supply. GGE is maximized in stoichiometrically balanced foods with elemental ratios defined by the body composition. Stoichiometric (Homeostatic) animals tend to retain (recycle) deficient nutrients and dispose of those found in excess.

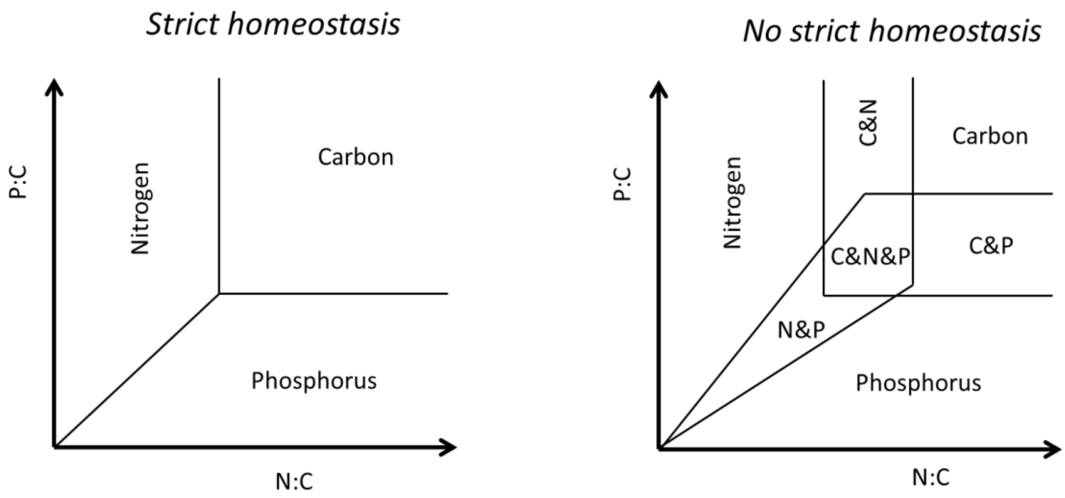

Figure 5.3 Schematic indication of the effects of threshold element ratios (TER) for C, N and P in consumers on growth limitation by Carbon, Nitrogen and/or Phosphorus under conditions of strict homeostasis (left) or no strict homeostasis (right) of the consumers. The x-axis indicates the N:C ratio of the substrate and the y-axis the P:C ratio of the substrate. Under no strict homeostasis of consumers, there are regions with mixed limitations of C&N, C&P, C&N&P and N&P (after Sterner and Elser 2002 and Thingstad (1987).

The major classes of consumers (detritivores, herbivores) have more tightly fixed chemical composition than the resources they usually eat. This has many ecological consequences. Decomposition by saprotrophs/detritivores is the second largest flux in the global cycling of organic matter next to primary production. Fungi have relatively low nutrient contents (2-4% N and 0.1-0.4% P, and C:N 5-17). Bacteria are N and P rich with C:N<7 and C:P<70 and have a strict homeostatic regulation of its C:N and C:P ratios. Fungi have higher C:N and C:P ratios than bacteria. This helps fungi to colonize high C:N substrates first. Bacterivores are bacteria eaters and major regenerators of nutrients.

The importance of the stoichiometric imbalance between soil microbes (with low C:N) compared to plant residues (with high C:N) has been known for long time: on high C:N litter soil microbes immobilize N. A C:N ratio of the litter of about 25 (wt:wt) divides net N mineralization and

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immobilization. Dissolved carbon (DOC) export by rivers is also related to the soil C:N ratio: DOC export is higher when soil C:N is high.

Herbivores differ in size and composition and in foraging strategy and in digestion strategy, and hence in N:P excretion. Small herbivores have short gut passage and lose a large fraction of ingested nutrients in their faeces and have a high TER (are easily N limited) because of low assimilation efficiency. Large herbivores can extract more energy from plant material than small herbivores (due to longer gut passage). Their high C:N TER's allow them to choose a wider range of forages. Two other cases are presented in box 2, showing how animals deal with meeting their nutrient requirements from feed resources that do not match directly.

Summarizing, the N:P ratio of excreted nutrients depend on the N:P ratio of the food, the gross growth efficiency of the nutrients (accumulation efficiency) and on the N:P ratio of the consumer itself (animal retention/production). The relationship between N:P recycled and N:P food is linear when food N:P is > retention N:P, and curvilinear when food N:P < retention N:P. A distinction should be made between assimilated and then metabolized nutrients and excreted, and nutrient not assimilated and hence released in solid form as egesta. Excreted nutrients are usually more soluble and available for mineralization (and losses) than egested nutrients. Decomposition and mineralization rates are inversely related to the C:N and C:P ratio of the excreta and egesta.

Box 2. How do mammals, deer and termites meet their nutrient requirements

Generally, the Ca and P demand increases in body size of the animals, due to skeletal investments. Mammals have high Ca and P requirement during lactation, especially in high-yielding dairy cows, which they mobilize temporarily in part from their own bones. Deer and moose have a large antler, which is rich in Ca and P (about 7 kg Ca (23%) and 3 kg P, equivalent to 10% of antler weight) and replaced each year. This represents a large annual Ca and P demand which is difficult to extract from plants. Thus, there is Ca and P translocation from the animal's skeleton each year.

Termites are famous wood consumers. Termites' N content is 8-13% with C:N ratios of 4-12. In making termites with C:N of 10 out of wood with C:N of 100-1000, requires N supplementation and homeostatic regulation through its metabolism: (i) many termites have symbiotic N fixers in their guts, (ii) under strong N shortage, termites are cannibalistic, and (iii) termites release excess C via CH_4 from the methanogenic bacteria in their guts.

5.6 Stoichiometric interactions at ecosystem level

In ecological stoichiometry, distributions of nutrients within ecosystems (i.e., the amounts and ratios of nutrients within plants, animals, decomposers, soils, etc. at different trophic levels and life stages are being examined to address ecosystem-level questions about e.g. yield, carbon and nutrient use efficiencies, carbon and nutrient losses, and their differences between ecosystems and compartments. A common way to express the result is via x-y scatter plots, with nutrient X1 on one axis and nutrient X2 on the other. In this paragraph, we few general observations and generalization are made.

- The C:N:P ratios of plant and animal species in natural ecosystems are highly variable. This variation is related to differences in trophic level, soil fertility, plant and animal physiological responses, and time (aging). The situation is different for life in oceans (box 3).
- The N content of leaves determines photosynthesis rate more or less linearly; the higher the N content, the higher the rate of photosynthesis. This links the carbon and nitrogen cycles. Nutrient-rich leaves are more efficient at using N to gain C, because at high N relatively more N is located in the leafy photosynthetic machinery, compared to structural proteins and defensive compounds. However, nitrogen use efficiency (NUE) tends to go down when the the light:N ratios goes down significantly. Hence, biomass production per unit N uptake will decrease (hence, NUE will decrease) when available N surpasses some critical level.
- The carbon use efficiency (CUE) is the efficiency of transfer of carbon between trophic levels. CUE tends to be inversely related to NUE, because of the constancy of the C:N:P ratios in consumers, independent of the composition of the resources consumed. Animals utilize the N in feed for animal production very efficiently if the feed C:N ratio is high (hence, NUE is very high), even if the absolute rate of animal production is low. Simultaneously, they use the carbon very inefficiency (hence, CUE is low).
- In fertile soils, productivity and NUE will be high initially due to capture of photosynthetic radiation by green leaves, but productivity and NUE decreases rapidly due to aging, formation of structural biomass (which does not capture photosynthetic radiation effectively), and the resulting effects of self-shading. Hence, at high-fertility, plants with high growth:light ratios are favoured, and the biomass yield per unit of N (or per unit of other nutrients) is reduced at high soil fertility. As a result, fertile soils are inefficient at making plant biomass out of the available nutrients, but they are efficient at making animals out of plant carbon (hence CUE is high).
- In non-fertile soils, plant species with high C:N ratio are superior competitors for N compared to species with low C:N ratio (high N content). Hence, at low-fertility, plants with high growth:N ratios are favoured. Thus non-fertile soils commonly have high NUE (in plants), but low CUE in the food chain (because animals are not able to utilize the C effectively due to shortage of nutrients). Also, the percentage of biomass consumed by animals and the decomposition rate of the biomass decrease in general when the biomass has low N and P contents. This will lead to accumulation of refractory biomass C.
- The nutrient contents of plants decreases in general with the size of the plants. Further, the C:P ratio commonly decrease with trophic level. The C:P ratio is higher in most plants and trees than in their consumers, while the C:P ratio is higher in small consumers than in large consumers.
- Humans alter and accelerate the global cycles of C, N and P greatly and disproportionately. The C:N:P ratio of the annual cycling of CO_2 (from atmosphere through photosynthesis), N (from atmosphere through N_2 fixation) and P (from soil weathering) in the natural terrestrial system (background) is about 50,000:100:1 (Sterner and Elser, 2003).
- The C:N:P ratio of the exhausts of fossil fuel combustion (including N_2 fixation during combustion) was about 24,000:80:1, while the C:N:P ratio of the CO_2, N and P introduced into

the ecosystem through fossil fuel combustion and synthetic fertilizer production during the last decade was about 1,700:25:1. This indicates that, despite the massive emphasis on the massive CO_2 emissions in to the atmosphere, the amounts of P and N introduced into the biosphere/environment have been much larger than the amount of CO_2, when compared to the C, N and P flows and fluxes of the natural (background) system.

Box 3. N:P ratios in oceans

At low N:P in lakes and oceans, N_2 fixation is high, to make up the N debt (N deficiency). Hence, N_2 fixation rate is inversely related to the N:P ratio. N_2 fixation in lakes and oceans seems to be controlled also by the availability of light and metals. At the opposite end of the spectrum, denitrification removes N especially in eutrophic coastal zones and deep waters. This helps to keep the N:P balance close to the Redfield ratio (16:1). Although there is ongoing discussion/debate about the factors limiting ocean primary production, it seems that open ocean are both N and P limited (and Fe, Zn limited), but depending on the locations. In lakes, P seems to be more limiting than N.

Rivers feed into oceans, and they have different degree of pollution. Redfield's hypothesis about P controls on oceanic productivity in geological time leads to the expectation that the N:P ratio in the outflow of major rivers is high. The N:P ratio of potential nutrient sources for lakes and oceans vary widely, from ~250 in the in runoff from unfertilized land to as low as <5 from earth crust and urban runoff.

Oceans contribute about 50% to primary production and hence to O_2 production into the atmosphere. It has been suggested that the efficiency of P burial in oceans is determining ocean productivity and in part the stability of O_2 concentrations in the atmosphere over geological time (500 million years). If O_2 concentration goes up, P in ocean goes down because of oxidation of iron (Fe) oxides and the subsequent binding of P to FeOOH, and subsequently ocean productivity and O_2 production goes down (feedback mechanism).

Summarizing, there are large differences in C:N:P ratios of autotrophic species (plants) and heterotrophic species (animals) on land, oceans and fresh water bodies, but yet are linked through trophic (feeding) interactions. The differences in C:N:P ratios and trophic interactions have developed over time through competition and natural selection, and are complex and not fully understood. Major drivers affecting ecosystem C:N:P ratios include the light-to-nutrient ratio (light-to-soil fertility ratio) in oceans and on land, the spatial variations in fertile and non-fertile habitats, the C:N:P requirements of major autotrophs and heterotrophs, as function of size, and the human alterations of the global and regional C, N, P cycles. The implications of changes in C:N:P ratios are different for different trophic levels. Stoichiometric imbalanced ecosystems through N and P enrichment results in inefficient use of N and P by primary producers (NUE is low), but create a different imbalance for herbivores as they are then efficient at using carbon for their own growth (CUE is high), but NUE is low. Balanced stoichiometry means an ecosystem where major biotic pools are similar. This happens approximately in oceans where C:N:P ratios in biomass and water are close to 106:16:1 (Redfield C:N:P ratios). The

Redfield ratio may provide an absolute point of comparison, because this C:N:P ratio governs ocean plankton and seawater composition, and this ratio is close to that of most animals (Boxes 1 and 3).

6. Review of C:N:P stoichiometry in agriculture

This Chapter will present an review of C:N:P stoichiometry in agriculture with C:N:P ratios in crop and animal products, animal manures and soils. As the variation is large and only few data are available, it is not possible to provide an analysis of how the C:N:P stoichiometry changed over times. Although this certainly might have occurred due to changes in breeding, fertilization, irrigation and climate change.

6.1 C:N:P stoichiometry in crops

The N:P stoichiometry and relation between P content and dry matter content was evaluated for different crop types, including cereals, fruit, legumes, oil crops, potatoes, residues, root crops and other crops. Data from RVO (2019), Velthof et al. (2009), USDA (1992) and feed tables[5] were combined (Table 6.1). For C content few data is available, instead we used dry matter content to derive C content, based on the assumption that C content of dry matter is 45%. For some crop types, including cereals, oil crops and root crops, the data are more clustered for the N:P plots. Legumes, oil crops and root crops have clustered data for P content versus dry matter content. In Table 6.2 information on the stoichiometry for main roughages is provided.

Table 6.1 Summary statistics for N, P and dry matter content per crop type

Crop type	N content (g/kg)		P content (g/kg)		N:P ratio	C content	Number of data	
	Mean	St. dev.	Mean	St. dev.		(g/kg)	N and P	C
Cereals	18.2	4.1	3.4	0.6	5.3	360	42	35
Fruits	0.5	0.5	0.1	0.1	5.9	NA	5	0
Legumes	44.1	10.1	4.9	1.8	6.3	400	15	13
Oil crops	35.4	2.9	6.1	0.6	5.8	410	7	4
Potatoes	2.7	1.1	0.5	0.3	5.4	90	6	3
Other root crops	1.9	0.8	0.5	0.4	3.8	90	9	5
Crop residues	14.7	8.3	4.9	2.9	3.0	340	18	12

Table 6.2 C, N and P (g kg^{-1} dm) in grass and maize silage. The relative standard deviation is indicated between brackets. N is calculated on the basis of crude protein, and C on the basis of ash content *(Source: DairyOneForageLab, 2020)*

Roughages	N content	P content	C content	C:N ratio	N:P ratio	Number of samples
Fresh grass	27 (41%)	3.3 (41%)	447 (3%)	16.6	8.2	346
Grass silage	25 (25%)	3.4 (25%)	451 (3%)	18.0	7.4	1646
Maize silage	13 (12%)	2.5 (12%)	479 (1%)	36.8	5.2	1903

5 https://www.feedtables.com/

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Whereas information is available on nutrient stoichiometry of crops, not much is reported about changes of this stoichiometry over time, due to e.g. plant breeding or differences in fertiliser use. Elevated CO_2 concentrations, however, have been reported to influence nutrient contents of plants. Crops grown at elevated (540-958 ppm) CO_2 concentrations have lower protein concentrations than when grown at ambient (315-400 ppm) CO_2 concentrations (Taub et al., 2008). Taub et al. (2008) found that cereals and potatoes had a much stronger reduction in protein content than soybean. The higher CO_2 concentration leads to increased concentration of carbon in plant tissue, therefore diluting the concentration of other elements. Besides elevated CO_2, warming leads to increased plant C:N and C:P ratios (Sardans & Peñuelas, 2012). Interestingly, plant N:P ratios have been reported to decrease with elevated CO_2, and increase with warming. Most likely, these opposing effects were caused by variations in soil moisture (Dijkstra et al., 2012).

Balboa et al. (2018) analysed historical trends in soybean for the period 1922 to 2015, which showed that seed yield improved from 1.3 Mg ha^{-1} in 1930 to 3.2 Mg ha^{-1} in 2010. The seed nutrient concentration remained stable for N but declined for both P (18%) and K (13%); They also concluded that a focus on plant nutrient ratios and their relations to crop growth rate is likely to provide better tools for nutrient management.

6.2 C:N:P stoichiometry in animal products

For animal products N:P stoichiometry was investigated as well. For this section, various meat sources (animal species), eggs and milk were taken into account. Data was collected from Wageningen Livestock Research, van Dijk et al. (2016), Klop et al. (2014), FAO (2013) and Koning and Sebek (2019)[6]. When no total N content was available, protein content was divided by 6.25 to estimate total N. Summary statistics are given in Table 6.3 and the data are plotted in Figure 6.1. The N and P content of milk as well as eggs are both lower than the N and P content of all types of meat.

[6] https://ec.europa.eu/eurostat/documents/2393397/8259002/LiveDate_2014_Task2.pdf/c940eabf-1736-40af-a6fe-397ccbb1d361
https://www.wur.nl/de/Publicatie-details.htm?publicationId=publication-way-343532333833
http://www.fao.org/3/i3396e/i3396e.pdf
https://edepot.wur.nl/476560

Table 6.3 Summary statistics for N and P content per animal product

Product type	N content (g/kg)		P content (g/kg)		N:P ratio	Number of data points
	Mean	St. dev	Mean	St. dev		
Bovines	24.6	3.0	7.3	0.19	3.4	2
Chicken	30.8	2.3	5.0	0.84	6.2	6
Pig	24.7	4.8	5.0	0.80	4.9	7
Sheep or Goat	24.5	0.7	7.8	0.07	3.1	2
Other birds	30.6	4.5	5.1	0.48	6.0	4
Other animals	29.2	0.7	6.7	0.76	4.4	5
Egg	17.6	0.4	2.1	0.09	8.4	3
Milk	5.4	0.1	1.0	0.05	5.9	7

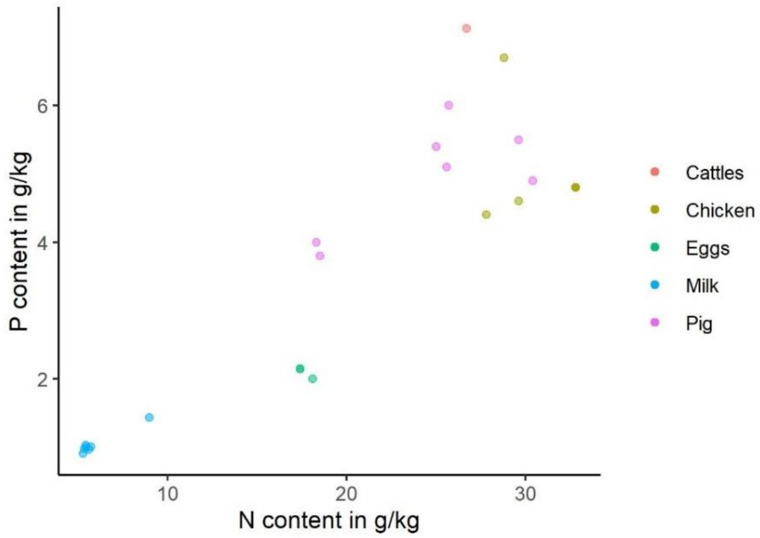

Figure 6.1 N content (g/kg) versus P content (g/kg) for cattle, chicken and pig meat, eggs and milk

6.3 C:N:P stoichiometry in animal manures

The CNP stoichiometry in animal manure can be quite variable and is determined by feed characteristics, retention of nutrients in the animal and type of manure storage. There are quite some sources that provide data or report on manure excretion (e.g., Livedate project of Eurostat (2014), Eurostat-OECD, FAOSTAT, the Intergovernmental Panel on Climate Change (IPCC), Nitrates Directive, Gothenburg protocol, UNFCCC National Inventory Submission, EMEP/EEA), but there are only few sources that report the underlying nutrient and carbon composition in animal manures. Data of Velthof et al. (2015) and the Grassland and Fodder Fertilisation Committee (2019) have been combined and show average CNP values of manure (Table 6.4). Cattle in Europe obtain most of their feed from roughages (grass and maize) and additional feeds resulting animal products and excretion: 77% and 66% of N and P respectively are excreted by cattle (data for the Netherlands; CBS, 2020).

While the N and P content in roughages have a similar variation, the variation of P is much larger than N in animal manure.

Table 6.4 C, N and P (g kg^{-1} fresh weight) in animal manure. Standard deviations within brackets

	N content (g/kg)	P content (g/kg)	C content (g/kg)	C:N-ratio	N:P-ratio
Solid cattle manure	7.3 (6.2)	1.5 (2.3)	95 (44)	13	4.7
Liquid cattle manure	4.6 (1.3)	0.7 (0.5)	37 (19)	8	6.5
Liquid pig manure	5.3 (2.1)	1.1 (0.9)	42 (20)	8	4.8
Solid poultry manure	30.8 (10.2)	11.4 (4.1)	304 (NA)	10	2.7

The availability of manure is unequally distributed over Europe. Therefore, mineral fertilisers are still dominantly being used in areas without manure surpluses. Mineral fertiliser use can be reduced by bio-based fertilisers. Manure digestion plants are able to process manure and other agro-residues into bio-based fertilisers. Some of these manure processing products have similar compositions as the fertilisers for which they act as an alternative (Ehlert et al., 2012; Velthof, 2015). Such products result in less use of mineral fertilisers, but do not change C:N:P stoichiometry of the total amount of fertilisers used. Other manure processing products do differ from mineral fertilisers and can result in a different stoichiometry of the total amount of fertilisers used. These include compost, products from digestate (mix of manure, energy crops, food waste) and products from manure separation (e.g., mineral concentrates), and P containing ashes (e.g., incineration chicken manure). Separation of manure results in lower N:P ratios for the solid fraction, where most of the P remains bound to the organic matter, and higher N:P ratio for the liquid fraction. However, the variation in N:P ratio is much higher for the separated products (Table 6.5).

Table 6.5 N:P ratio of different manure types as derived from a large set of obligatory laboratory analyses for manure transport in the Netherlands. Data are from the period 2013-2015 (CDM, 2017)

Manure type	Median	Average	St. dev	Number of samples
Liquid cattle manure	6.2	6.0	3.7	293524
Solid cattle manure	4.6	4.1	2.5	15789
Solid fraction separated cattle manure	4.6	4.1	3.4	9551
Liquid fraction separated cattle manure	6.6	6.2	6.6	1094
Liquid pig manure	3.9	3.9	2.7	289596
Solid pig manure	2.3	2.3	2.3	4615
Solid fraction separated pig manure	2.1	2.3	4.1	11252
Liquid fraction separated pig manure	6.0	6.4	5.0	22777
Solid broiler manure	4.6	4.6	3.0	33780
Solid chicken manure	2.5	2.5	2.5	42534

Besides manure, also phosphate extracted from incinerated municipal waste water sludge is expected to become more important in the near future (Huygens et al., 2019). Recovered nutrient products from manure with very specific nutrient contents, and manure that is already traded in large amounts from member states with large nutrient surpluses are specifically important to change nutrient stoichiometry (Table 6.6). The recovered nutrient products have the potential to be used as an alternative to mineral fertilisers without changing the nutrient additions in a field. During an inventory, Foged et al. (2011) found that 0.3% of the livestock manure in EU uses air cleaning, producing scrubbing salts such as ammonium sulphate. There are no recent estimated amounts for recovered N from manure. The Intereg project ReNu2farm estimates that it is possible to replace 2% of the mineral fertilisers using products recovered from animal manure (ReNu2farm, 2019). The potential amount of recovered P products have been estimated for 2030 (Table 6.7). This amount is about 18% of the current P fertilizer consumption in the EU.

Table 6.6 Typical nutrient composition of recovered N and P products (% of dry matter)

Products	C	N	P	K	Reference
Scrubbing salts	0.3	19.2	-	0	Huygens *et al.* (2019)
Mineral concentrate	18.1	11.5	0.6	14.6	Huygens et al. (2019a)
Anaerobic digestion-liquid fraction after centrifugation/or enhanced solids removal	29.5	12.9	1.4	7.9	Huygens et al. (2019)
Struvite from food processing industry	0.25-4.8	3-6	9-12	4-13	Huygens et al. (2019b)
Biochar derived from pig manure	42.8	1.8	5.7	2.5	Maggen *et al.* (2017)
Poultry manure ash	39.1	4.2	6.7	14.0	Billen *et al.* (2015)

Table 6.7 Estimated market for recovered P fertilisers in the EU in 2030 (Huygens et al., 2019b)[7]

Strubias material	Pathway	kt P/year in 2030
precipitated phosphate salts (struvite)	liquid fraction of anaerobically digested materials: manure, and food processing industry wastewaters	48
thermal oxidation materials (PK rich ash)	poultry manure	35
thermal oxidation materials (P rich ash)	municipal wastewaters	98
precipitated phosphate salts (struvite)	municipal wastewaters	30
precipitated phosphate salts (struvite)	food processing industry	2
thermal oxidation materials (P rich ash)	slaughterhouse residues	unknown
pyrolysis and gasification materials (P-rich biochar)	slaughterhouse residues	unknown
pyrolysis and gasification materials (P-rich biochar)	solid pig manure fraction	unknown

6.4 C:N:P stoichiometry in topsoils

For the C:N:P stoichiometry in European soils we made use of the LUCAS soil database. LUCAS (Land Use/Cover Area frame statistical Survey) is a harmonised survey across all Member States to gather information on land cover, land use and soils. For the 2009 topsoil survey approximately 20,000 points were selected out of the main LUCAS grid for the collection of soil samples. The samples were sent to an accredited laboratory where a range of chemical and physical soil properties were analysed (Tóth et al., 2013). We selected the soil samples located on arable fields and analysed the average soil

[7] https://op.europa.eu/nl/publication-detail/-/publication/f2109276-d831-11e9-9c4e-01aa75ed71a1/language-en/format-PDF

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properties for CNP (Table 6.8). For P only P-Olsen was measured in the LUCAS data set, which provides an indication of the available P for plant growth. Total P was not available and the relation between total P and P-Olsen is very variable, therefore no N:P ratio is provided.

Table 6.8 Average soil properties related to CNP for arable soils based on the LUCAS 2009 topsoil dataset. Note that P is only available as P-Olsen (indicator for crop available P) and not total P, therefore the N:P ratio is not provided

		Organic C (g/kg)	N (g/kg)	P-Olsen (mg/kg)	C:N ratio
Region					
	Central Europe	15.4	1.5	39	10.0
	Northern Europe	27.5	2.2	37	12.3
	Northwest Europe	19.0	1.8	49	10.2
	Southern Europe	13.8	1.4	24	10.0
Soil texture					
	Loamy soils	17.9	1.7	35	10.2
	Sandy soils	14.4	1.3	47	10.7
Soil pH					
	Acid	19.9	1.7	45	11.1
	Neutral	17.1	1.6	42	10.1
	Alkaline	16.4	1.6	33	10.1

In northern and northwest Europe the organic C content of soils is higher, due to the presence of more organic soils, where decomposition is lower due to the wetter and colder conditions. The distribution of topsoil nitrogen is strongly linked to soil organic carbon, as nitrogen is a main component of soil organic matter. Organic carbon and therefore soil nitrogen is driven mainly by climate and vegetation, where wet conditions result in the build-up of soil organic matter. For arable land the C:N ratio is about 11 (Table 6.8), whereas the C:N ratio is much higher under natural vegetation (Figure 6.2). P-Olsen is lower in loamy and alkaline soils. This is probably more related to the distribution of those soils, which are more located in southern Europe, whereas inputs of P are highest in Northwest Europe, which has therefore also the highest P-Olsen values (Figure 6.3). The P content of soils is mainly driven by land use, where most of the agricultural areas have higher P content. Especially in regions with intensive agriculture and high P inputs to the soils such as NW Europe and the river Po plain in Italy (Ballabio et al., 2019)

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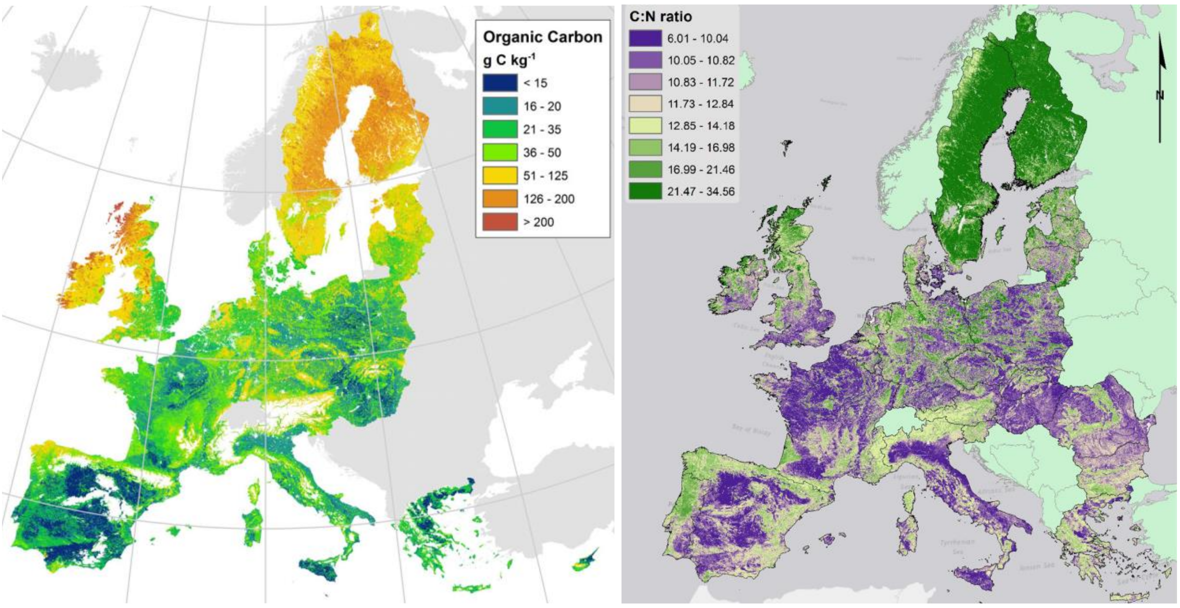

Figure 6.2 Distribution of organic carbon content (left) and C:N ratio (right) of topsoils (0-20 cm) for the EU member states based on the LUCAS soil survey. Source: de Brogniez et al. (2015), and Ballabio et al. (2019).

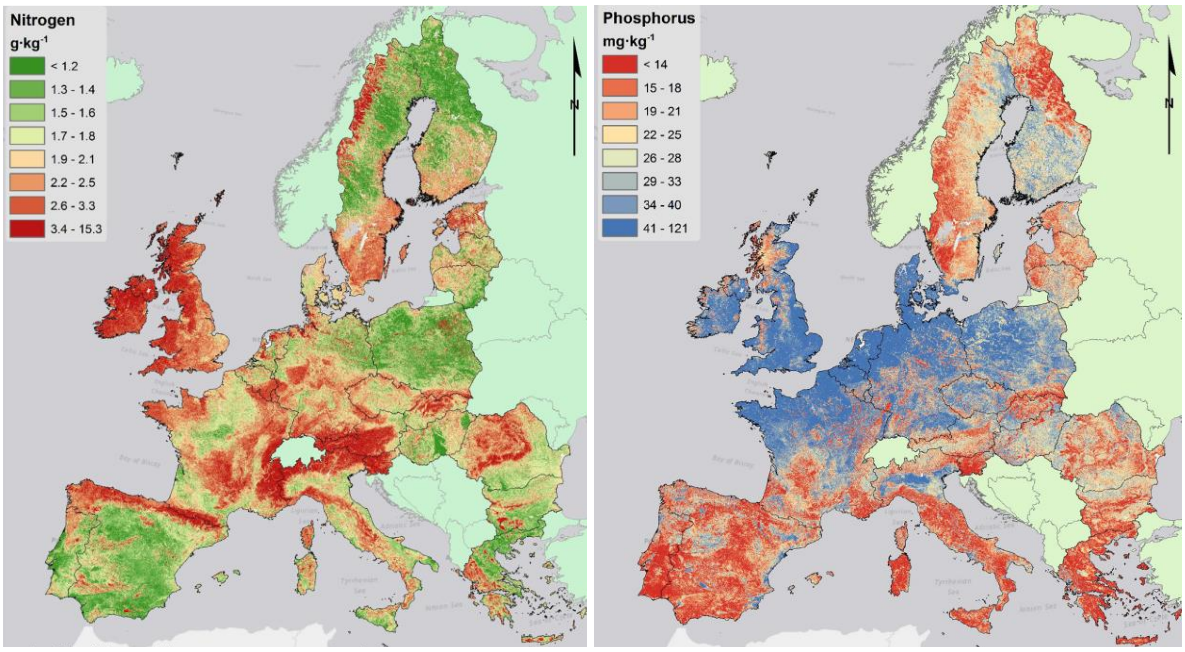

Figure 6.3 Distribution of nitrogen content (left) and phosphorus content (right) of topsoils (0-20 cm) for the EU member states based on the LUCAS soil survey. Source: Ballabio et al. (2019).

Tipping et al. (2016) examined C:N:P ratios of soil organic matter in some 2000 soil samples from across the world (Figure 6.4). The C, N and P contents ranged almost three orders of magnitude. Relationships between % C and % N and between % C and % P were roughly linear when plotted on logarithmic scales. For non-peat soils, positive correlations were found between C:N, and C:P ratios and % organic carbon, indicating that soils with relatively high soil organic matter (SOM) content have relatively high C:N and C:P ratios, and vice versa. They indicated that the variation in C:N:P ratios can be described approximately with a simple mixing model in which nutrient-poor SOM (NPSOM) has C:N and C:P ratios of 25 and 900 respectively, while nutrient-rich SOM (NRSOM) has corresponding ratios of 8 and 62, so that P is especially enriched in NRSOM compared to NPSOM. Tropical soils in have higher C:P ratio in the organic matter than soils from temperate regions. The stoichiometry of NPSOM corresponds to that of average litter. The NRSOM stoichiometry is quite similar to that of microbial biomass. Protein is a likely major source of the nitrogen in NRSOM. The dominant form of organic P is inositol phosphate.

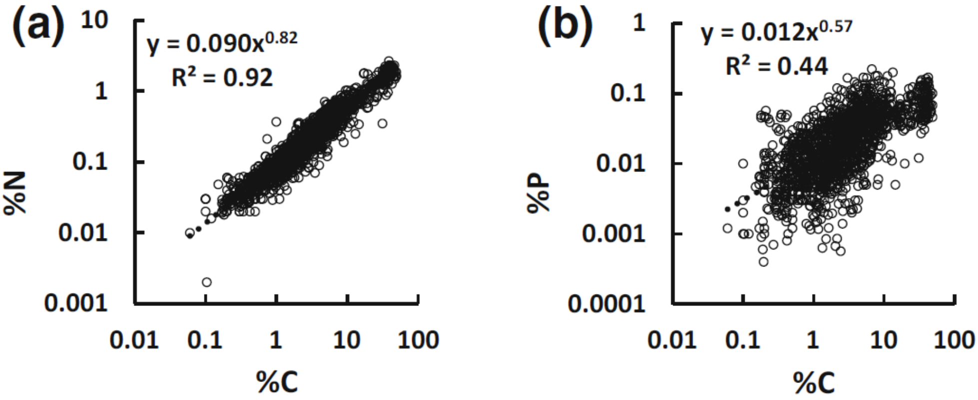

Figure 6.4 Regressions of %N versus %C, and %P versus %C for soils other than ombrotrophic peats. Note the logarithmic scales of the x and y axes (Source: Tipping et al., 2016).

A relative enrichment of P in organic matter occurs in manured soils. Soils receiving heavy applications of poultry, cattle or pig manures for 10 consecutive years had C:P ratios in the range of 70 to 99, while soils that received synthetic fertilizers had C:P ratios in the range of 125 to 135 (Table 6.9). Note that the C:P ratio in the manure soils approached the C:P ratio of the NRSOM end member (62) in the study of Tipping et al. (2016). Most of the P applied accumulated as inorganic P; the total P contents strongly increased, especially in the heavily manured soils. The degree of phosphorus saturation (DPS) was over 100%, suggesting that the capacity of the soil to adsorb inorganic P had been surpassed, and the inorganic P was leaching from the top soil to the subsoil, where the DPS was less than 100% (not shown).

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Table 6.9 Treatments, input-output P balance and characteristic of the top soils (0-5 cm) of a 10 years lasting fertilization experiment on grassland in the Netherlands. Application rates of fertilizers were 200 kg N per ha and 52 kg P per ha per year, and manure application rates were 25 Mg per ha per year. The degree of phosphorus saturation (DPS) represents the fraction of adsorption sites saturated with P (after Koopmans et al., 2003).

Treatment	P balance kg/ha	pH (KCl)	SOM %	Total P mg/kg	Organic P mg/kg	C/P	DPS %
No fertilizer	-158	4.0	5.9	436	269	125	39
N fertilizer	-219	4.0	6.8	349	286	135	35
NPK fertilizer	236	4.1	6.3	742	288	125	66
Poultry manure	2486	6.5	6.5	2400	529	70	194
Cattle slurry	1066	5.7	5.7	1134	328	99	111
Pig slurry	1000	6.7	6.7	1222	441	87	107

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7. Synthesis

7.1 C:N:P ratios as indicators for leakiness

Carbon, nitrogen and phosphorus have numerous functions in plants, animals and humans, and hence in food production, and in the interactions between food production systems and the wider environment. In organic matter C, N and P are intimately linked in a whole range of different organic molecules with different C:N:P ratios. The linking of C, N and P occurs through biosynthesis and chemosynthesis in plants and animals (and also in industry). Delinking or decoupling mainly occurs through decomposition and mineralization of organic matter (also in animals), and partly also through fragmentation, fractionation, fermentation and refinery. High C:N and C:P ratios are indicative for tight N and P cycling, high N and P use efficiencies and low C use efficiency, and low N and P losses. Conversely, low C:N and C:P ratios are indicative for low N and P use efficiencies and high C use efficiency by heterotrophs.

Agriculture has changed (i) the relative proportions of C, N and P in plants, animals, soils and water bodies, and (ii) the coupling-decoupling mechanisms of C, N and P. Natural ecosystems commonly have high C:N and high C:P ratios, with N:P in the range of 10 to 18 (wt:wt). Most agricultural crops have relatively low C:N (10-20, up to 37 for silage maize) and low C:P ratios, with N:P in the range of 3 to 8 (Chapter 6). Hence, agricultural crops are relatively rich in N and P. Further, increased animal production has contributed to increased CNP decoupling mechanism through N rich and C poor urine production (C:N < 5) , and C rich faeces production (C:N > 15). In modern animal production systems, the C use efficiency (CUE) is relatively high and the N use efficiency (NUE) and P use efficiency (PUE) are relatively low when compared to semi-natural and extensive animal production systems. Modern animal production systems produce animal manures with relatively low C:N and C:P ratios and with N:P ranging from 2 to 8 (Chapter 6).

In natural ecosystems, the C:N ratio of the soil is commonly in the range of 15 to 25 (Chapters 5 and 6). Agriculture has decreased the C:N ratio of most soils in Europe to on average 10 to 12 (Chapter 6). Net immobilization of N in soil organic matter occurs when the C:N ratio is >15, while net N mineralization occurs when the C:N ratio is ≤15. Further, soils may accumulate organic N during soil C sequestration; soil C and N sequestration are determined by land use, soil cultivation, soil clay content and climate. Note, mineral N may accumulate temporarily in soils in the form of NH_4+ and NO_3-, but the total amounts of mineral N are very small compared to the amounts of organically bound N. Mineral N in soils with a C:N ratio of ≤15 in the organic matter is either taken up by plant roots or is lost through leaching or denitrification. In contrast, P in soils may accumulate as organically bound P and as mineral P. The C:P ratio of the organic matter in natural soils is commonly >200 and between 60 and 200 in agricultural soils (Chapters 5 and 6). Accumulation of inorganic P in soils occurs in the form of calcium phosphate (apatite) in high-pH soils and as iron and aluminium bound phosphate in acidic soils (pH<6.5). Accumulation rates depend on the availability of calcium (carbonates) in high-pH soils and iron and aluminium (oxy-hydroxides) in acidic soils. Hence, soils store N in organic form and store P in both organic and inorganic forms. The capacity of the soils to store N and P is finite; in

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agricultural soils, much of the capacity has been used already, and this is a main reason why these soils have become leaky for especially N but also P (heavily manured soils).

7.2 Driving forces of farming systems and C:N:P stoichiometry

Agriculture responds to changes in markets, science & technology and governmental policy. Food demand and food diversity have strongly increased during the last centuries, in response to increases in the number of people in the world and in economic wealth of at least a percentage of the people. Developments in science, technology and policy have facilitated agriculture to increase production and to help meeting the increasing food demand and increasing diversity in food demand over time.

The pressures to produce more food and more diversified food have led to changes in farming systems. Production has become more specialized, with only one or a few crops per farm and only one or a few animal species on a farm. Production has also become more intensified, with more output per unit of surface area, animal, labourer and/or capital. Further, production has been upscaled, with more produce per farm and/or entrepreneur. Also, specialized production has become more concentrated in specific areas. As a result, farms have become specialized, more productive, larger, and similar farms tend to concentrate in specific areas.

This specialization, intensification, up-scaling and concentration of farms has influenced the C:N and C:P ratios of agricultural products, and C, N and P cycling. The C:N and C:P ratios of crop products have become lower on average, mainly through selection, breeding and fertilization. This is most apparent in the production of grassland and leafy vegetables, which are harvested in a vegetative growth phase and have the ability to increase the protein content through N fertilization. Moreover, these crops are able to store N (as nitrate) and P (as polyphosphates) in inorganic forms within cells, when well fertilized. It is also apparent in the breeding of wheat varieties and the use of split N application so as to increase the protein content and the baking quality of the wheat flour (Xue et al., 2019).

The C:N and C:P ratios of animal production have also become lower, through selection, breeding and improved animal feeding. The fat content has decreased and the protein content has increased. The protein N and digestible P contents have increased and the quality of the feed protein (amino acid composition) have improved and thereby the growth rate and the feed conversion coefficients, i.e., a greater fraction of the feed is converted into useful animal products. Regulations have now limited the protein and P contents in the feed in many countries and as a result, the N and P use efficiency in animal production have also increased. Yet, animal manures have become richer in N and P compared to a few decades ago, with much of the N and P in mineral forms. As a result, the fertilization values of the manures have increased but at the same time have become more conducive to N losses (Chapter 6).

Processing industries, retail and animal feed companies have further diversified the food and feed through selection, fractionation, refinery, processing, and synthesis. Products have become more uniform in composition and more digestible, with narrow C:N and C:P ratios. Residues and rest products are either processed in the animal feed industries, or are digested/composted and used as soil amendment or are lost during processing via waste streams. Studying the C:N and C:P ratios of processed food and feed products and of the waste products of the processing industries was beyond the scope of this study. Yet, processing industries are modifying food and feed and thereby also the C:N and C:P ratios, but the overall net effect remains unclear.

Manure processing has direct impact on the C:N and C:P ratios of the resulting manure products. Anaerobic digestion results in decoupling of C, N and P in organic matter and results in more mineral N and P in the digestate, while C has accumulated in the biogas as CH_4 and CO_2. Solid liquid separations of animal slurries produces a relatively N rich and C and P poor liquid, and a relatively C and P rich and N poor solid fraction. Composting (of the solid fraction) results in a relatively stable C-rich compost, because most of the easily decomposable C and N compounds have been decomposed and volatilized as CO_2, NH_3, N_2 and N_2O. Reverse osmosis of the liquid fractions results in a concentrated solution with relatively high N content, and a watery solution, with little or no C, N and P. Ammonia stripping of the slurries and liquids results in a relative low-N animal slurry and a N-rich solution. Nitrification-denitrification of animal slurries and liquids results in the mineralization of organic matter and the loss of N via emissions of N_2, NO and N_2O. Evidently, almost all manure processing techniques alter C:N and C:P ratio of the manure products, and not necessarily make the C, N and P cycling less leaky.

Evidently, agriculture has also decreased the C:N and C:P ratios of agricultural soils, through fertilization, soil cultivation and drainage, and selection of specific crops. Specialization of cereal based systems (e.g. wheat, maize and rice), with return of C rich and N and P poor crop residues has likely resulted in soil organic matter with relatively high C:N (>12) and C:P (>120) ratios. Specialization of cropping systems with N-rich crops and crop residues, and with liberal use of N-rich animal manures likely result in a soil organic matter with relatively low C:N (<12) and C:P (<120) ratios. Soils with relatively high C:N and C:P ratios have much greater capacity to respond to and absorb N and P released through sudden changes in environmental conditions (climate variations, changes in farming practices) than soils with relatively low C:N and C:P ratios, depending also on other soil characteristics.

Based on the information collected and presented in this report, a summary figure was made to illustrate the C:N:P ratios and the changes in CNP for the main compartments of agriculture (crop products, livestock products, animal manure and soils (Figure 7.1). The C:N:P ratios were estimated as the average of all crops, livestock products and manures for the EU-28, using weighted averages based on the total amount of nitrogen. For soils the information as derived from the LUCAS survey for arable soils was used. As shown in Chapter 6, the variation in C:N:P ratios can be very large among crops, livestock products, manures and soils, but the overall average is less different, with similar N:P ratios for crops, livestock products and animal manure.

Figure 7.1 also provides an indication of the trend over the last decades in total CNP for each compartment. For crops CNP increased as a result of the increased crop yields, but as described above, the increase in N and P was relatively larger due to fertilization and improved breeding of crops. Also the amount of CNP in livestock products increased, as a result of higher yields and for pork and poultry also the strong increase in animal numbers. The increase in N in livestock products was higher because of the stronger increase in milk and poultry meat production, which have higher protein contents. Animal manures have become richer in N and P over the last decades whereas C decreased, due to the shift from solid to liquid manure management systems. Soils have become richer in P due to high fertilization over the last decades and most of the P surplus has accumulated in the soil. In contrary, N fertilization was also high during last decades, but the N surplus is mainly lost by gaseous emissions or leaching and runoff to groundwater and surface waters. N can be sequestered in soils, but this is mainly in combination with C in the form of organic matter, and as most arable soils have lost organic matter over the last decades/centuries (e.g. Bellamy et al., 2005; Eglin et al., 2010), both C and N have decreased.

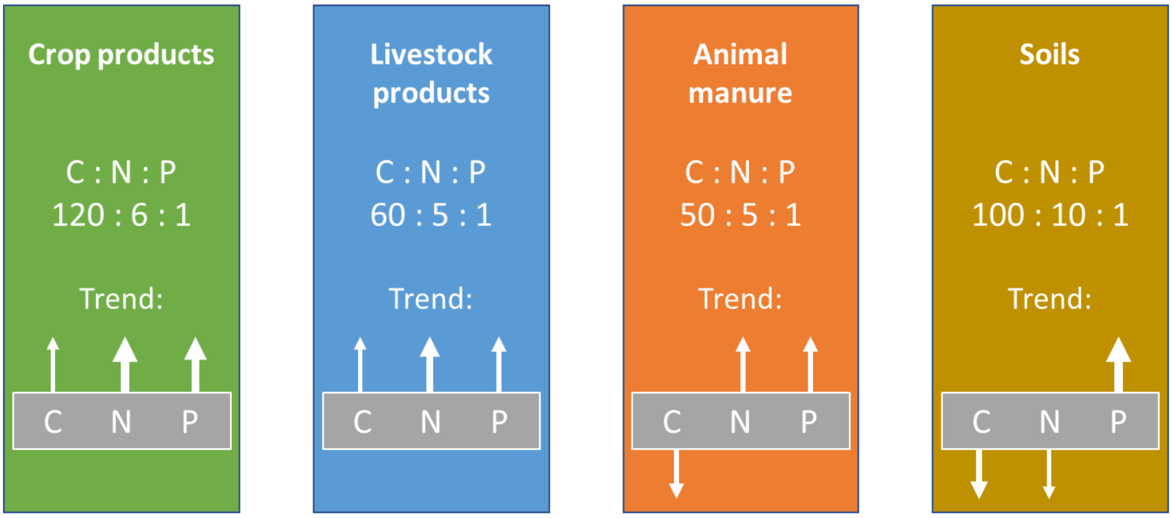

Figure 7.1 Summary of the C:N:P ratios of crop products, livestock products, animal manure and arable soils. The arrows indicate the trend over the last decades in the overall amount of CNP for each compartment. The width of the arrow indicates an estimate of the size of the change relative to the trends for the other elements.

Summarizing, the main driving forces of agriculture (markets, science & technology and policy) have led to more specialized, intensive, and large farming systems, with similar farm types often in concentrated areas. These farming systems are producing relatively N and P rich products, and have decreased the C:N and C:P ratios of soil organic matter. The narrowing of the C:N and C:P ratios have made the systems more leaky and vulnerable to external changes.

7.3 How to manage C:N:P stoichiometry in agriculture?

The main purpose of agriculture is to provide adequate and sustained amounts of nutritious food for consumers and to generate adequate farm income in return. Increasingly, farmers have to comply with additional demands from society, retail, processing industry, governments and society. A main demand is to decrease the losses of N to air and water and of P to water. The N and P use efficiency in global agriculture may have to increase by more than a factor of two, while global food and feed production will have to increase by 50 to 70% between 2010 and 2050 (Godfray et al., 2010; Steffen et al., 2015; Zhang et al., 2015). These targets will be different for different countries. Also, the need for greater food and feed production appears to smaller, relatively, than the need to decrease ammonia and nitrous oxide emissions to air, and nitrogen and phosphorus losses to surface waters, especially in affluent countries (i.e., EU, North America).

What is the role of managing C:N:P stoichiometry in achieving these agronomic and environmental targets? This is a major question but cannot be answered fully at this stage, because of lack of knowledge, tools and clear targets so as what to achieve when and where. Yet, the content of this report provides a number of insights which may be used as basis for further study, as listed here below:

- Farming systems have developed in response to markets, science and technology and governmental policy. These developments have increased over time, and have led to specialized, intensive, and large farms, with specific farms tending to concentrate in specific areas, because of proximity to market, easy access to suppliers, research and technology, and because of specific environmental and climate conditions. Concentration near urban areas is especially the case for intensive vegetable production and animal production. These driving forces have to be understood to be able to understand the changes in farming systems; in general they have been geared toward increasing the productivity and economic profitability of farming systems so as to sustain adequate food supply.
- While the per capita food supplies have expanded in total quantities of food calories, protein, fat, and weight during the last five decades, the crop species contributing to the world's food supplies have narrowed in diversity, with increased proportions sourced from energy-dense foods (Khoury et al., 2014). National food supplies worldwide have become more similar in composition, correlated particularly with an increased supply of a number of globally important cereal and oil crops, and a decline of other cereal, oil, and starchy root species. The interdependence among countries has increased in regard to availability and access to food sources and the genetic resources supporting their production (Khoury et al., 2014). It is likely that the C:N and C:P ratios of the overall mean food sources have decreased, but our data are too limited to confirm this hypothesis for the global scale.
- Animal production has become more globalized and uniform, in the order: poultry production > pork production > dairy production > beef production > sheep and goat production (Liu et al., 2017). The interdependence among countries has also increased in regard to availability and access to animal source food, the genetic resources supporting their production, as well as animal feed. It is very likely that the C:N and C:P ratios of the overall mean animal source food have decreased, but our data are too limited to confirm this hypothesis for the global scale.
- The C:N and C:P ratios of food sources have decreased especially through N and P fertilization of crops and through supplementation of animal feed with protein-rich feed and/or specific amino acids and highly soluble and digestible monocalcium phosphate (MCP). The C:N and C:P ratios of the food intake by humans have also decreased during the last decade; the average

consumption of protein-N and P in food in EU-28 in 2015 was on average a factor of two higher than recommended/needed (Westhoek et al., 2018). The largest use of mined rock phosphates is in P fertilizers (83%), while animal feed–grade phosphates are estimated to account for 6% of total world phosphate consumption. The EU has a share of 10-15 % in the world consumption of feed-grade calcium phosphates. The increased %N and %P in food and feed have also increased the %N and % P in animal manures and human wastes. Fertilization with N and P fertilizers, manures and wastes have also decreased the C:N and C:P ratios of soil organic matter.

- The increases in N and P inputs in farming systems together with all other changes in crop and animal production have increased N and P losses from farming systems. At the same time, N and P losses from food processing industries, retail, restaurants and households have also increased, especially in affluent countries. Total losses of N and P to the environment have created a range of unwanted human health and ecological effects; losses have crossed the safe zones of our planet (Steffen et al., 2015). It is as yet unknown how much of the losses have to be ascribed to just changes in C:N and C:P of food and feed products or to the use of N and P for the production of the food and feed products.
- Several studies have indicated strategies to increase nitrogen and phosphorus use efficiencies and to decrease nitrogen and phosphorus losses (Sutton et al., 2013; Houlton et al 2019). Houlton et al (2019) proposed the following strategies for ensuring sufficient food production and decreasing N losses at the same time:
    - Improving nitrogen-use efficiency for food, feed, and fiber production
    - Getting nitrogen to where it is needed most
    - Removing nitrogen pollution from the environment (emission mitigation)
    - Reducing food waste
    - Encouraging diets with low nitrogen footprints
- Similar strategies can be defined for phosphorus. An additional strategy for utilizing soil phosphorus is needed here, because large amounts of phosphorus can be stored in soil organic matter (mainly as inositol phosphate) and as inorganic phosphorus adsorbed to aluminium and iron hydroxides (in acidic soils) or precipitated as calcium phosphate (apatite). In soil organic matter, the C:N ratio usually ranges threefold, between 8 and 25, but the C:P ratio may range more than tenfold, from 60 to 900, clearly indicating the role of organic phosphorus in soils.
- Ecologists define N and P use efficiencies in natural vegetations commonly by the %N and %P in plants; the lower the %N and %P the higher the N and P use efficiencies. High C:N and C:P ratios in vegetations are associated with high N and P use efficiencies and with low N and P losses. Increasing N and P use efficiencies in plant production does have implications for C, N and P use efficiencies in animal production and in human nutrition; increasing the N and P use efficiencies in animal feed production (decreasing %N and %P in the feed) will decrease the feed conversion efficiency (carbon use efficiency) in animal production, because of suboptimal N and P nutrition. Evidently, a balance has to be found here between increasing N and P use efficiencies in crop production and animal production.

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- As the C:N and C:P ratios of soil organic matter of intensively managed soils likely have decreased, it is likely that their capacity to (temporarily) immobilize inorganic N and P in organic matter has decreased as well. This will make these soils more leaky, especially for N. This should be recognized in developing fertilization recommendations.
- Crop rotations with year-round green cover, in part through cover crops, have the potential of utilizing photosynthetic energy year-round and thereby can increase the input of carbon into the system, while mopping up residual N and P from soil. This will make the system less leaky for N and P and at the same time contribute to the accumulation of soil organic carbon in the soil.
- Animal manures are large sources of C, N and P and other (micro) nutrients, but this is often insufficiently recognized, which leads to under-utilization or manure nutrients. During storage significant amounts of C (through CH_4 and CO_2) and N (through NH_3, NO_X, N_2 and N_2O) may be lost to air, which changes the C:N:P stoichiometry of manures; the C:P ratio decreases.
- Manure treatment and processing has the potential to decrease C and N losses from manure during storage; it may be part of the solution for specific regions. Manure treatment and processing occurs especially in regions with surpluses of manures. Treatment/processing does not decrease the local/regional manure surpluses in an environmentally benign manner, but offers the potential (i) to utilize the energy from the carbon as biogas, (ii) to separate manure in fractions with different C:N:P ratios, which may better match specific C, N and P needs of specific farms/fields, (iii) to lower the transport cost by lowering the moisture content of the manure products, and (iv) to increase the acceptance of the products by clients.

To illustrate this last point an example for the Netherlands is elaborated based on data from NCM (2019). As the Netherlands has a surplus for P due to large amount of animal manure that is used, there is hardly any additional demand for P on top of amount already provided by animal manure. Therefore fertilizer products with no or low P contents are required for the additional nutrient demand. Table 7.1 shows the potential demand for N from mineral fertilizer or recycled organic products on top of the animal manure. This additional crop N demand is currently mostly provided by mineral fertilizer. Using processed animal manure or other recycled organic products can improve nutrient use efficiency and contribute to a more circular agriculture. However, the nutrient contents of these new products should fit with the crop demand. In this case, they should be low in P and high in N, but also other (micro)nutrients should be considered.

Table 7.1. Potential demand for nitrogen from mineral fertilizer or recycled organic products for the main crops in the Netherlands

Crop	**Crop area** (kha)	**N demand** (kg N/ha)	**N from animal manure** (kg N/ha)*	**Additional N demand** (kg N/ha)	**Total potential** (kton N)
Grass	907	350-400	170-250 (60%)	150	136.0
Fodder maize	206	140	170 (60%)	38	7.8
Wheat	113	250	170 (80%)	114	12.9
Potato	166	250	170 (80%)	114	19.0
Sugar beet	85	140	170 (80%)	4	0.3

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Table 7.2 shows that the required N:K ratio of the additional fertilizer products differs among crops, e.g. for grassland a product with an N:K ratio of 1.5 is required while for potato an N:K ratio of 0.5 would fit the demand. Mineral concentrate which is currently produced in the Netherlands has an N:K ratio of about 0.67, which does not fit that well with the additional crop demand. Hence a range of new fertilizer products from recycled organic sources is required to replace the mineral fertilizer products. The total amount of surplus manure in the Netherlands that has to be exported or processed is about 50 kton N. This amount is not sufficient to satisfy the crop demand for nitrogen, which means that even if all surplus manure is processed, still additional mineral N fertilizer is required. In the Interreg ReNu2Farm an inventory was made of the region-specific demand for recycled nutrients. The results show that a potential demand for recycling-derived nutrients exists in all regions of Northwest Europe (Figure 7.2). However, this demand differs for the different nutrients, especially in regions with a lot of manure, the demand for phosphate is low.

Table 7.2 Potential demand for potassium from mineral fertilizer or recycled organic products for the main crops in the Netherlands

Crop	**N demand** (kg N/ha)	**K demand (kg K/ha)**	**K from animal manure** (kg N/ha)*	**Additional K demand** (kg K/ha)	**N:K ratio**
Grass	350-400	350-400	250	100	1.5
Fodder maize	140	300	200	100	0.4
Wheat	250	220	220	0	-
Potato	250	350	220	230	0.5
Sugar beet	140	175	220	35	0.1

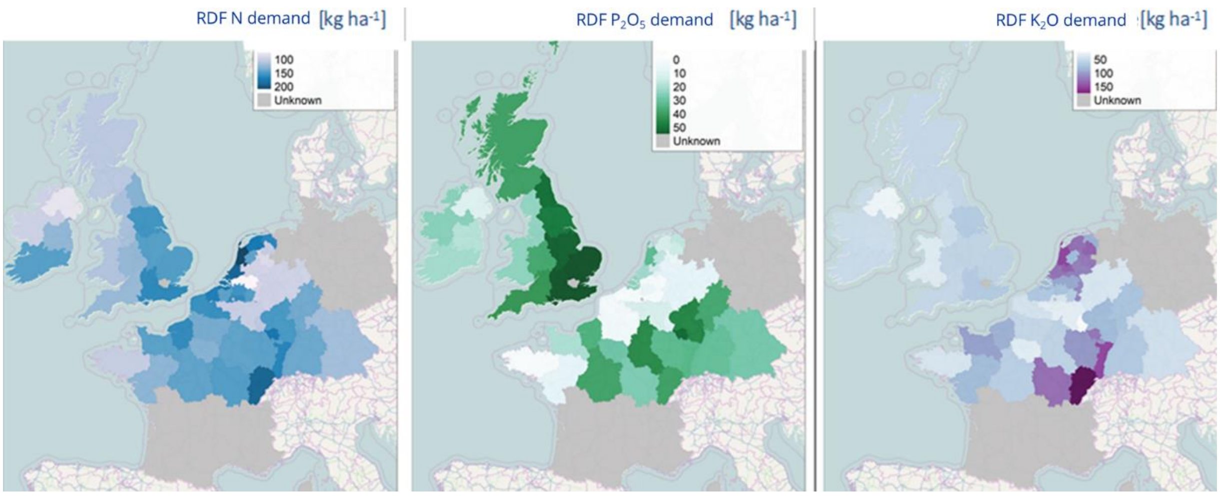

Figure 7.2. Regional demand for nutrients from recycling-derived fertilisers (RDF) in agriculture for North-West Europe

In a circular agricultural system, with no or low use of mineral fertilizers, the crop specific demand for nutrients and the soil specific requirement of C to maintain soil quality (i.e. prevent a negative soil carbon balance) should be derived from manure and recycled organic products. This requires an optimisation of the available manure and other organic inputs over the different crops and soils on a farm or within a region. In the remaining time of the Nutri2Cycle project this kind of optimisation will be further elaborated using the MITERRA model, which can make such a kind of optimisation of the available manure and manure processing products to satisfy the crop and soil demand for CNP and to improve nutrient cycling, reduce nutrient losses and maintain or increase soil carbon levels.

Summarizing, managing C:N:P stoichiometry is not a panacea. It is part of the solution of developing more leak-tight farming systems. It requires in-depth understanding of the linkages and delinking mechanisms of C, N and P in food production – processing – consumption systems. Currently, our notions and studies are too disciplinary, often focused on just one nutrient element while neglecting the interactions with other elements and their functioning. This report must be seen as a first step. The C:N:P stoichiometry is not much studied yet in agriculture. Variations in the contents of C, N and P are in general well understood and known, but how these contents are affected by crop rotations, crop and livestock management, food processing and storage throughout the food chain is less understood. Our knowledge of C:N:P stoichiometry in agriculture is fragmentary, in part because the focus has been mostly on yield (and protein contents), and much less on C:N:P ratios through the food production-consumption chain.

7.4 Recommendations

- More studies have to be conducted on the C:N:P stoichiometry in agriculture. Currently, there is a lack of quantitative data and information about the changes in C:N and C:P ratios of food and feed products and how these changes are related to changes in farming practices. This requires that both C, N and P contents have to be determined in products.

- Relationships should be developed between C:N:P stoichiometry in soils and the leakiness of these soils. Also, relationships should be developed between C:N:P stoichiometry in the inputs and outputs of farming systems and the leakiness of the these farming systems.

- It is imperative that C, N and P contents are determined in products from manure treatment and other organic residues and that hypotheses are developed and tested about where and how these products can be utilized most beneficial from C:N:P stoichiometry and leakiness point of view. Upcoming processing technologies can affect the CNP flows and stoichiometry and should be applied in such a way that the contribute positively to the demand for CNP.

- Recommendations for manure and fertilizer applications have to consider the soil-crop needs for C, N and P. Meeting the P demand first is likely a good strategy, given the fact that P is retained both in manure and soil, and therefore is likely the element with the lowest demand.

Topping up the C and N supply until soil-crop needs are met, will require in many cases specific manure treatments products and/or synthetic fertilizers.

This report provides a foundation for further work in Nutri2Cycle. First, it provides background information about the nature, driving forces and changes in C:N:P stoichiometry in crop and animal production systems. Second, it indicates the importance of considering C, N and P cycling and utilization in agriculture coherently. Third, it shows (indirectly) the relationships between C:N:P stoichiometry and the leakiness of agricultural systems. Fourth, it provides guidance to selecting the types of managerial measures that decrease N and P losses from agricultural systems. In the Nutri2Cycle project we propose to have a workshop in the first half of 2021 to discuss the findings and the usefulness of the framework for application into practice.

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