MSc Thesis

A new global assessment of soil nutrient balances

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Contents

Abstract

Mapping of soil nutrient balances is an essential method for locating future food insecurity and environmental eutrophication problems. This thesis develops this method further by establishing the first global maps of N, P and K full soil nutrient balances on a 30 arcsecond (1km) grid. It makes use of self-developed crop distribution maps, with a relative occurrence of crops. Then building on methods from Stoorvogel and Smaling (1990), five inflows and five outflows of nutrients are calculated.

It is found that the spatial variation found in soil nutrient balances occurs largely between countries, and within countries variation occurs on climatic differences. A number of priorities are given for further improvement of the methodology. About mineral fertilizer, it is well known how it is distributed over the countries but it appears more challenging to distribute it over crops. On organic fertilization, figures on manure quality and application are required. Regarding crop production, there is a need for a comprehensive dataset of crop characteristics.

Altogether, mapping of nutrient balances as a method is promising, now the 1km resolution is attainable with available input data. The required input data is equally available for N, P and K, so it is possible to model all three macronutrients with similar precision.

Acknowledgements

This MSc-thesis gave me a sense of crop production systems around the globe, how to characterize them in terms of nutrient flows. It is a true enrichment to the observations I made in the countries I have visited; particularly Europe, Kenya, the USA and India. This insight would not have been possible without the vast knowledge from my supervisors Jetse Stoorvogel and Eric Smaling, and their useful feedback. Thanks to Jetse for his constructive and flexible attitude, when supporting me in this research.

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My family and dear friends deserve special thanks, for supporting me in the final parts of my studies in Wageningen. I highly appreciate your presence in my life and your sincere interest in my wellbeing and personal development. Thanks to you I could make the step towards the start of my professional career. In the upcoming lifetime, I wish to utilize my knowledge of soils and spatial patterns for the better of the world.

Teun Fiers

1 Introduction

Global food security and sustainability of human activities have been in the sphere of attention in any global development programme. Even though, population growth and further intensification of agriculture are reasons why both food insecurity and nutrient pollution could well increase in the coming decades. In this context, the development of sound methodologies is necessary to gain insight in the extent of the problem. One such methodology is the mapping of soil nutrient balances, which will be concentrated on in this thesis report.

Soil nutrient balances sum the flows of nutrients in and out of the soil, and sum these flows to a net accumulation or a net loss of soil nutrients. This provides insight in the sustainability of farming, and relative importance of the nutrient flows. Knowledge on the spatial distribution of nutrient flows allows for the creation of a map of soil nutrient balances. Such a map thus shows areas with net nutrient accumulation and loss. Macroscale mapping of soil nutrient balances is highly relevant for identifying soils with a high risk for degradation and localizing areas with potentially environmental problems related to an excess of nutrients.

A foundation for the methodology of mapping soil nutrient balances has been laid out in 1990 Stoorvogel and Smaling (1990). Increased data availability created new opportunities to improve the methodology. Increasing data availability has created the opportunity of applying existing methodologies globally, with variability on sub-national scale. This research aims to do exactly that, to provide insight in the potential of soil nutrient balance maps. The existing methodology for mapping nutrient balances is revised to fit the available data on a global level.

1.1 Relevance of nutrient balances on a global scale

On a global scale, soil macronutrients are unevenly distributed. In some parts of the world, a shortage of soil nutrients is one of the root causes of low agricultural production, while in other locations an excess of nutrients is problematic. By mapping soil nutrient balances, one gains insight where excess or depletion is problematic. This research is a very first attempt to create high-resolution (1km grid) maps of N, P and K balances, including all nutrient flows.

Deficiency of nutrients

Net nutrient losses inevitably lead to nutrient deficiencies on the long term. Most often, declining nutrient stocks coincides with other forms of land degradation. Unsustainable farming does not only result in nutrient deficiencies, but also insufficient water availability, soil structure and soil acidity. By diminishing soil functions that are essential for food production, land degradation is considered one of the main drivers of global food insecurity in the future (FSIN 2019, UNCCD 2019, IPBES 2018).

It has been identified by IPBES (2018) that more relevant information is needed to improve long-term sustainability of land resources. More specifically, it appears to be particularly challenging to quantify and assess land degradation, due to a variety in definitions, methodologies and perceptions of what land degradation is (PBL 2018).

In the pursuit for land degradation neutrality, conservation of soil fertility is a key aspect. Moreover, as one of the yield limiting factors, it directly effects food security and rural development. Insight in a net loss or gain of soil fertility can be generated by a soil nutrient balance, a balance of incoming and outgoing nutrient flows. Spatial differences, e.g. between excess and shortage areas, can be shown in a map of soil nutrient balances. In order for adequate solutions and policies to be developed, such maps are essential.

As soil nutrient balances are a quantifiable biophysical aspect of land degradation and a direct indicator for land productivity, it has the potential to overcome part of the methodological challenge on soil degradation. As soil fertility trends quantify changes rather than the current soil fertility status, the estimation of current production capacity is limited but it rather is an indication of the land use sustainability.

Excess of nutrients

A surplus of nutrients can be problematic in multiple forms. First, an excess implies inefficient use of agricultural inputs. Ideally, a farmer applies the exact amount of fertilisation to match the need of his crops. This should be the goal of the individual farmer, as fertilisation is often expensive. Moreover, on a global level an efficient use of fertilizers is important in the context of nutrient shortages elsewhere (as mentioned previously) and the limited availability of nutrients. Particularly for phosphorus this is the case, as geological deposits may be depleted in the coming decades. Thus, in matching global demand for nutrients with the supply, an excess of nutrients in the soil is undesirable.

Secondly, a surplus of nutrients in agricultural systems can be harmful to the natural environment. This is particularly the case for nitrogen and phosphorus. The excess nutrients leave the soil by surface runoff, leaching or gaseous losses. After transportation through groundwater, surface water or air, deposition can elsewhere. Nutrient-poor ecosystems in general can be disturbed. When nutrients accumulate in surface waters, algae blooms can completely disrupt the natural ecosystem and related water quality. Additionally, some gaseous forms of nitrogen (NOx), emitted from the soil nitrogen stock under specific circumstances are greenhouse gasses contributing to climate change.

Few remediation policies are available to solve eutrophication problems. Regarding the efficiency problem of nutrient excess, this is inherently coupled to the management of inputs. Therefore, nutrient balances can provide essential insights in the causes of an excess of nutrients.

1.2 The recent opportunity for a global map of soil nutrient balances

Macroscale mapping of soil nutrient balances is a method developed by Stoorvogel and Smaling (1990) to visualise spatial differences in the sustainability of crop production. The scope of this study was Sub-Saharan Africa. Ever since, the data available for such analysis has been increasing and it has become increasingly easy to compute detailed global maps. Therefore, the challenge has opened up to apply the Stoorvogel and Smaling methods on a global grid. Thus far, the application of soil nutrient balance methods on a global scale has been limited, in terms of including only few nutrient flows using a coarse resolution.

The 1990 methods

The report of Stoorvogel and Smaling (1990) was the first to map nutrient balances. Their calculations, as described by Stoorvogel et al. (1993) were largely based on characteristics of agro-ecological zones and the agricultural systems attributed to those zones. The study was based on five nutrient fluxes of input and five fluxes of output (fig. 1).

The 1990 study sparked a wave of research on nutrient balances, in particular on the regional level. Often, they aimed to improve the 1990 study by a higher resolution (e.g. Lesschen et al., 2007) or added nutrient flows within the farming system (e.g. Beek et al., 2016). A comprehensive analysis of studies in the 1990s and 2000s was carried out by Cobo et al. (2009).

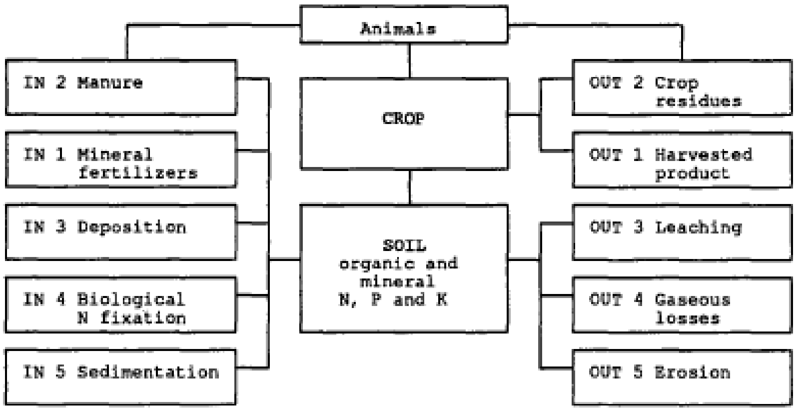


Figure 1: ***Components of the soil nutrient balance*** *(Stoorvogel and Smaling, 1990)*

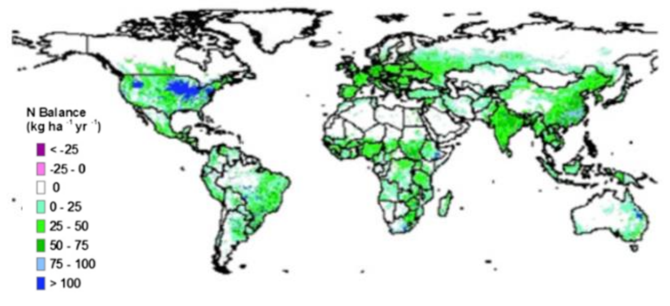
In addition to general acceptance, the 1990 methods have received some critique. In particular, Færge and Magid (2004) argue that the 1990 approach leads to overestimation of losses. According to them, the root of this error lays with the transfer equations predicting OUT3, OUT4 and OUT5 (section 4.2). In particular, they state that there is a lack of evidence for these equations, and more validation is needed. However, in their criticism, Færge and Magid (2004) have ignored updates of De Willigen (2000) and IFA/FAO (2001). Many, if not the vast majority of the studies since 1990, have found the easy way out on the Færge and Magid (2004) critique, by applying a partial balance, also known as the soil surface balance. In a partial balance only the human actions are taken into account, namely fertilization and harvest. The fluxes IN1, IN2, OUT1 and occasionally OUT2 are then considered. Partial balances are generally found to result in significantly higher nutrient balances (Cobo et al., 2009).

Regarding the critique from Færge and Magid (2004), they are unable to present alternatives for the transfer equations, nor do they prove that partial equations are a better approximation of reality. Even though, it is generally perceived that full balances have higher uncertainties than partial balances (Cobo et al., 2009). Alternative modelling approaches are concluded by Cobo et al. (2009) to have similar flaws and challenges, especially on the (supra-)national scale, and requiring even more data.

Recent developments in maps of soil nutrient balances

Macroscale mapping of soil nutrient balances has rarely been done ever since Stoorvogel and Smaling (1990). Folmer et al. (1998) mapped Mozambique by combining maps of land use systems and soil properties. In 2004, in the FAO published Fertilizer and Plant Nutrition Bulletin 15 (FAO, 2004), where the 1990 methods were translated to digital mapping for the first time. As examples of macro-level applications, soil nutrient balances were calculated for the countries of Kenya, Ghana and Mali. Similar methods were used by Lesschen et al. (2007) to map Burkina Faso. Siebert (2005) was the first to model nitrogen soil surface balances around the globe.

The most detailed global analysis so far has been carried out by Liu et al. (2010). This study generated a map of nitrogen flows on a 5 arc-minute resolution (fig. 2). Not much later, MacDonald et al. (2011) created a map of P balances on 0.5° resolution (fig. 3). Both of these studies concern partial balances, only taking into account the nutrient flows IN1, IN2, OUT1 and OUT2. For calculating manure inputs (IN2), both rely on rely on data of livestock, a method elaborately described by Potter et al. (2010). This does not only misrepresent reality as manure is increasingly transported before applied, but also limits the possibilities for downscaling to a finer resolution. On a farm level, application rates of manure depend on the crop and the landuse system. By simply converting livestock densities to manure applications, such management decisions are essentially averaged over a large area.



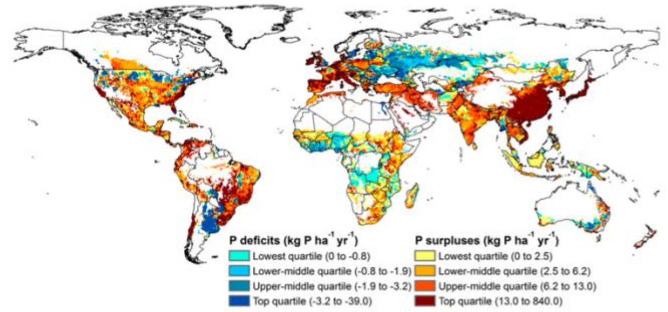


Figure 2: ***Soil surface N-balances (res. 5')***
(Liu et al., 2010)

Figure 3: ***Soil surface P-balances (res. 0.5°)***
(MacDonald et al., 2011)

Most recently, Chen and Grædel (2015) calculated phosphorus flows in the food system, from fertilizer production to human waste, for the same period. Lu and Tian (2017) modelled fertilizer rate applications per country for the period 1961-2013. Xu et al. (2019) compiled several studies with global maps of manure and nitrogen fertilizer inputs, in order to analyse trends between 1860 and 2016.

Increased data availability

In the past decade, more global datasets, directly or indirectly related to the agricultural system, have become available that could be utilized to map soil nutrient balances. This large amount of data creates the opportunity of applying the soil nutrient balance methods on a global grid. Some of these have already been used to generate partial nutrient balances have already been mapped on a coarse resolution (e.g. Liu et al., 2010 and MacDonald et al., 2011).

1.3 Research goal

The goal of this research is to develop the methods from Stoorvogel and Smaling (1990) further by adapting them to the global datasets which are currently available. By doing so, we primarily aim to get more insight in the potential of such maps and the required data to achieve this potential. The potential should be expressed in terms of scale, particularly the scale of spatial variation that is expected to be accurately represented in the map. This scale could differ per nutrient flow or other composites of the soil nutrient balance, like crop-specific nutrient balances. Pursuing this goal leads to the following research question.

In combining the 1990 methods with recent global datasets, several steps have to be taken. The sub-questions (1 to 4) specify these steps. To begin with, a spatial distribution of crops has to be known as a basis for calculating the nutrient flows. Additionally, a global map of land management characteristics, possibly linked to production systems, is required. Once these basic maps are available, the nutrient flows can be calculated. Typically, the partial soil nutrient balance (fertilization vs crop production) poses a larger challenge than the full nutrient balance.

Does the currently available data allow for a global map of soil nutrient balances?

1. Can crop distribution maps be developed?
2. Can land management maps be developed?
3. Can nutrient fluxes be calculated for a partial soil nutrient balance?
4. Can for a full soil nutrient balance be calculated?

The primary goal of this research is to improve the methodology rather than analysing the maps produced. Even though, the resulting maps can provide insight in certain characteristics of the methodology. For instance, the order of magnitude of the nutrient flows could determine which flows are most essential to include in a nutrient balance. Tracing back these results to original data may give insight in which datasets are most essential for securing the accuracy of the maps.

2 Methods

The development of global map of soil nutrient balances are primarily based on the methods of Stoorvogel and Smaling (1990). The 1990 study used polygons of land use systems. Most logically, a substitute for these polygons are raster maps of land management characteristics. As the 1990 study attributed certain crops to each land use system, global maps of crop distribution are required. This study developed such maps by a method of distributing the known production over the available area.

Timespan

Typically, soil nutrient balances are set up for a specific year. For example, the 1990 study created a map for 1983 and a forecast for 2000. In this research, the most recent figures are used, so ideally all data would be available for 2018. However, the overview (appendix 1) reveals that data from different years needs to be combined because of limited availability. The scope of auxiliary data ranges from 2010 to 2018. For the datasets, which were available for multiple years, 2015 is the most reasonable median year.

Resolution

The resolution of most source maps, e.g. S-World (Stoorvogel et al., 2017) and global climate maps, is 30 arc-seconds; approximately 1 km at the equator. Resolution of the ESA GlobCover map (Bontemps et al., 2009) is slightly higher (10 arcseconds). In order to preserve most spatial variation and limit required computing power, the 30 arc-second grid is most suitable. The starting point is that the resolution should reflect the accuracy of the map.

2.1 From polygons to land management maps

In the 1990 study, land-water class (LWC) polygons were defined as the smallest units of calculation. The LWC areas were assumed to be homogeneous entities, with all characteristics being constant throughout the area.

Nowadays, many of the characteristics which were attributed to the LWC polygons are mapped on a global scale. With modern GIS technology, the calculations can also be automatically done for each individual grid cell. Therefore, it is most sensible to use grid cells as the units of calculation, as well as to use maps of the attributes instead of the polygons. Table 1 gives an overview of how the LWC attributes were replaced.

Table 1: *Substitutes for the LWC polygons; for each attribute*

Attribute	Specification (in 1990 study)	Alternative
Rainfall (R)	Average for LWC, in mm/yr	WorldClim (Hijmans et al., 2005)
Soil Fertility (F)	Classes: 1-low; 2-moderate; 3-high	S-World (Stoorvogel et al., 2017)
Management level (L,H)	Differentiated in low and high	Not included
Fertilizer use factor	Weighing factor 0.0-3.0, related to regional distribution of total national consumption	Weights developed based on the IFA fertilizer use per crop figures
Manure application	0, 500, 1000, 1500 kg/ha,yr or 'during grazing'	Approximated by manure production, based on livestock density.
Residue removal	Percentage of crop residues removed from the field or 'crop residues burned'	Figures per crop based on literature
Erosion	Soil loss in ton/ha,yr	Soil erosion map calculated by USLE (see 4.2.10.)
Crops	Certain crops assigned from the FAO database crop list	Crop distribution maps (see 4.1.2.)
Land/water class	Low rainfall; Uncertain rainfall; Good rainfall; Problem area; Naturally flooded; Irrigated area	Replace by irrigated yes/no and by classes of rainfall (e.g. table 7)

2.2 Developing global crop distribution maps

A prerequisite for the mapping of soil nutrient balances is knowledge on the spatial distribution of crops. The crop type is a highly determining factor in the soil nutrient balance, influencing the nutrient flows for fertilization (IN1, IN2), nitrogen fixation (IN4), crop production (OUT1, OUT2) and erosion (OUT5). Leaching and gaseous losses (OUT3, OUT4) are indirectly crop dependent, because these flows depend on several of the previously mentioned flows.

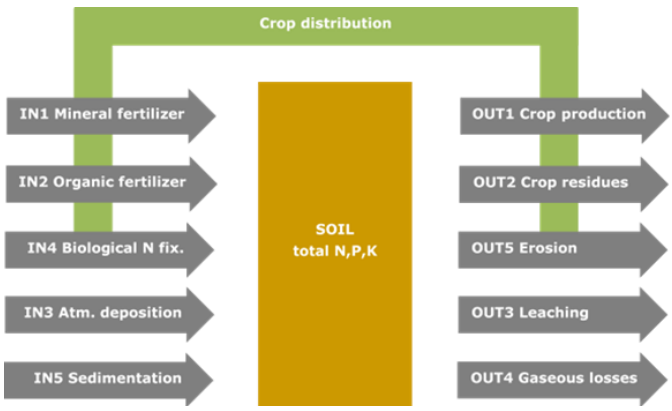


Figure 4: *6 out of the 10 in- and outflows of the soil nutrient balance are dependent on the crop distribution*

Despite global crop distribution maps have been developed in the past, accurate mapping is still found challenging (Anderson et al., 2015). Crop allocation models are still developing (e.g. You et al., 2014), and the existing maps have a lower resolution than other available datasets, like ESA GlobCov land use map. In order to establish suitable crop maps for calculating soil nutrient balances, crop distribution maps are developed from the available high resolution data. Included are the ESA GlobCov land use map, the S-World soil maps, WorldClim climate data (Hijmans et al., 2005) as well as national figures on agricultural production of FAOSTAT (FAO, 1997).

The basic principle of the crop distribution maps is to distribute the known crop production over the available area in every country. Firstly, the area available for crop production is defined based on the ESA GlobCover land use map (Bontemps et al., 2009). Then for every crop, the area is limited to locations with suitable climate and soil properties. Finally, the FAO crop production areas per country were distributed over the available areas in the country by an iterative optimization. The same groups of crops were used as in the 1990 study (Stoorvogel and Smaling, report 28, Winand Staring Centre, 1990). This required grouping some of the crop data of FAOSTAT to be grouped. This is shown below in table 2. It should be noted that one category of crops, namely flowers, are not included in these categories. The FAOSTAT database does also not have any data on flower production.

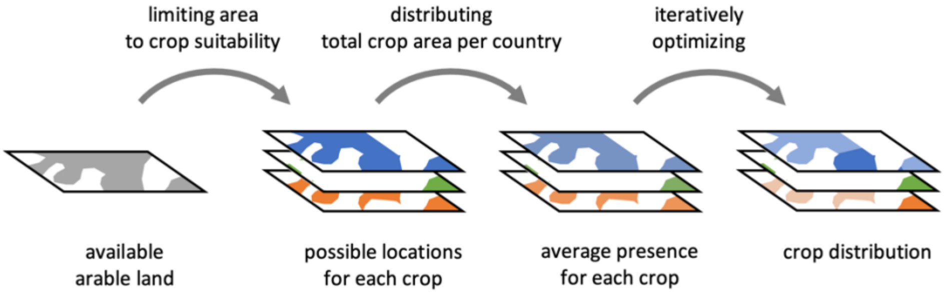


Figure 5: ***General steps in construction of crop distribution maps***

Table 2: ***The crop groups applied, similar to those used by Stoorvogel and Smaling (1990)***

C1	**Wheat**	**Single FAO crop**	**C18**	**Citrus fruit**	**Group of 5**
C2	Rice	Single FAO crop	C19	Other fruit	Group of 35
C3	Maize	Single FAO crop	C20	Other oil crops	Group of 14
C4	Barley	Single FAO crop	C21	Palm oil	Single FAO crop
C5	Millet	Single FAO crop	C22	Soy beans	Single FAO crop
C6	Sorghum	Single FAO crop	C23	Groundnuts	Single FAO crop
C7	Other cereals	Group of 7	C24	Sunflower seed	Single FAO crop
C8	Potatoes	Single FAO crop	C25	Sesame seed	Single FAO crop
C9	Sw potatoes/yams	Group of 2	C26	Coconut	Single FAO crop
C10	Cassava	Single FAO crop	C27	Cocoa beans	Single FAO crop
C11	Other roots	Group of 3	C28	Coffee beans	Group of 2
C12	Plantains	Single FAO crop	C29	Tea	Group of 2
C13	Beet	Single FAO crop	C30	Tobacco	Single FAO crop
C14	Cane	Single FAO crop	C31	Seed cotton	Single FAO crop
C15	Pulses	Group of 12	C32	Jute / fibres	Group of 10
C16	Vegetables	Group of 25	C33	Rubber	Single FAO crop
C17	Bananas	Single FAO crop	C35	Other crops	Group of 24

The process of demining the available crop area starts by selecting the arable land based on the ESA GlobCov landuse map (Bontemps et al., 2009). It is possible to determine specific availability for annual and perennial crops, since some of the land use classes in this map distinguish permanent foliage from seasonal crop growth. On several land use classes, only part of the area is expected to be arable land. For these cases, a percentage of the area is assigned as available. An overview of the availability percentages for the relevant land use classes is shown in table 3. As the original land use map is available on a 10 arc-second grid, the map needed to be aggregated. In this aggregation, the percentage of available area is averaged.

Table 3: ***Percentages of arable land assigned to the different classes in the GlobCover land use map (Bontemps et al., 2009)***

Code	Land use; description	Annual (%)	Perennial (%)	Total arable
10	Cropland, rainfed	100	100	100
11	Cropland, rainfed, herbaceous cover	100	0	100
12	Cropland, rainfed, tree or shrub cover	0	100	100
20	Cropland, irrigated or post-flooding	100	100	100
30	Mosaic cropland (>50%) / natural vegetation (tree, shrub, Mosaic cropland (>50%) / herbaceous cover) (<50%)	70	70	70
40	Mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%) / cropland (<50%)	30	30	30
--	Other landuse	0	0	0

The first limitation is determining the part of the arable land being fallow on average. The fallow fraction is obtained for every country by dividing the fallow area by the total arable area. Both figures are provided in the FAOSTAT database (fao.org/faostat), in the category Inputs > Land use. For a number of the countries, no data on fallow land are available. In order to increase the coverage and reduce any outliers, figures from 2000 to 2018 are averaged if available. Eventually, 87 major countries are covered by the data. Based on these countries, averages for all continents are computed, shown in table 4. Subsequently, these averages were applied on the remaining countries in each continent.

Table 4: ***Average fallow area per continent***

(Sub)continent	Fallow area (% of arable)	Based on # countries
OECD Countries	8 %	25
North Africa	29 %	2
Sub-Sahara Africa	15 %	9
Caribbean	23 %	3
Central America	23 %	5
South America	13 %	6
West Asia (Md East)	19 %	12
South Asia	29 %	2
East Asia	5 %	4
Other	16 %	15

Secondly, the available area is limited by climate and soil properties, based on the FAO Ecocrop database (Ecocrop, 2013). In this database, possible growing conditions are given for a large number of crops. These growth requirements are tested to the climate data of WorldClim and soil data of S-World, as shown in table 5. For the groups of crops (table 2), the least extreme requirements are generalized for the group. An overview of the requirements is given in appendix 2. Reasoning that locations on the globe with a cold climate do grow most crops in summer, the mean temperature of the warmest quarter is used to limit the minimum temperature. For the soil texture, the combination of the sand fraction and clay fraction is used to distinguish the loamy sand and sand from other textures in the texture diagram (see figure 6). It appeared that only a small area limitation had occurred for the maximum temperature, and soil texture. For the maximum rainfall, limitation of available crop area appeared to be none.

Figure 6: The soil texture diagram (ref) with the red part being distinguished by the condition Fsand – Fclay > 0.7. According to the ECOCROP database, this soil texture is not favourable to some crops.

Table 5: ***Crop properties from the ECOCROP database were used to limit the area where a crop can occur. In order to do so, the characteristic was tested to a related map***

Limiting ECOCROP condition	unit	Tested to map
Minimum temperature	°C	WorldClim mean temperature of the warmest quarter
Maximum temperature	°C	WorldClim annual mean temperature
Minimum rainfall	mm	WorldClim annual rainfall
Maximum rainfall	mm	WorldClim annual rainfall
Minimum soil depth	Shallow (>10cm) or Moderate (>50cm)	S-World soil depth
Soil texture (minimum loam/clay)	Fsand – Fclay < 0.70 or no limitation	S-World soil textures

After limiting the available crop area, the FAOSTAT crop area per country is evenly distributed over the available area for this crop in the particular country. For the crop groups (table 2), areas of the individual crops are summed before being distributed. In the resulting map, the most suitable grid cells have more crop area assigned than available, and other less suitable grid cells have less crop area assigned than available. Moreover, the total FAOSTAT crop area is different from the total available arable area. The FAOSTAT crop area appeared to be the smallest, with exception of a few countries. Thus, a large part of the available area would be unfilled when the crop area is evenly distributed. In order to solve for both of these issues, the distributed areas are rescaled according to the available arable land area in the cell. The resulting 'rescaled areas' map would have the crops present in different ratios than the FAOSTAT data on crop production. This is solved by iteratively scaling to the FAOSTAT crop ratios and subsequently to the available area. Experimentation showed that one iteration does already solve for the vast majority of the discrepancies, hence for the sake of computing efficiency, the iteration is done only once (distribution of crop areas is done twice).

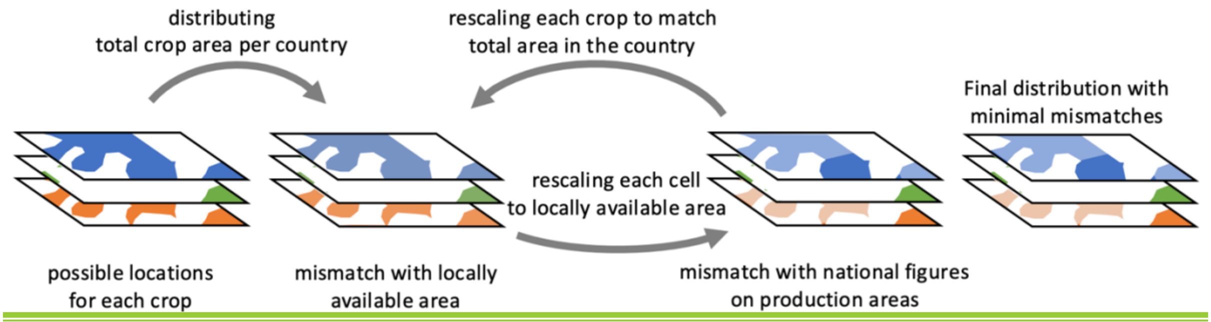


Figure 7: Through iteratively rescaling the crop distribution, discrepancies with the available arable land are diminished while the ratio of the total production of different crops is maintained.

of arable land. If this standardization would not have been carried out, two effects would have distorted the resulting map. First, all nutrient flows and the resulting balance would be scaled to the percentage of arable land within that cell. Therefore, cells with a different presence of arable land would not be comparable. Secondly, the cells at the equator would generally show higher nutrient flows than cells near the poles, relatively to the area in the 30 arc-second cell size. Both distortions are solved by working with a standardized 1 ha of arable land for every grid cell where any arable land is present.

2.3 Nutrient inflows

Mineral fertilizer application (IN1)

Mineral fertilizer application is determined by distributing the total use per country. From the FAOSTAT database, figures are obtained for the total use of mineral fertilizers (in tonne N, P_2O_5 equivalent or K_2O equivalent) per country. In order to distribute the total amount of fertilizers over the crops, a weighing factor is needed. This factor can be obtained from the IFA data 'fertilizer use per crop' (IFA and IPNA, 2017) For the countries which are an IFA member, the organization has published average applications of fertilizer per crop. Regarding the countries in the European Union, these are treated as one single country in the IFA publication. Hence these countries receive the same weights. The countries not being a member of the IFA all received an equal weight, based on the 'rest of the world' figures. With these weights, total fertilizer application per crop per country is calculated.

Subsequently, the fertilizer use per hectare is calculated by dividing the previously calculated total application (per crop per country) over the crop area in the country, which is obtained from the FAOSTAT database. Fertilization of pasture land was subtracted, by the relative weight obtained from the IFA figures. It turned out that for some crops in some countries, this method resulted in unrealistically high fertilizer application. Therefore, the figures are capped to a maximum of 500 kg N/ha, 50 kg P_2O_5/ha and 350 kg K_2O/ha.

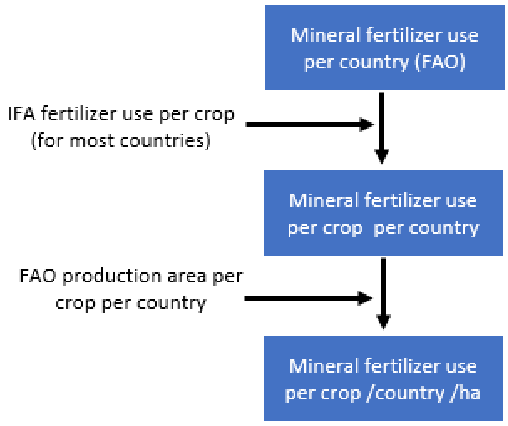


Figure 8: Schematic overview of calculation of mineral fertilizer use per crop per country

In the IFA figures, a different system of crop groups is used, with fewer groups covering several crops. For example, it contains a group 'Roots and Tubers' instead of 'Potatoes', 'Cassave', 'Sweet potatoes', etc. For this reason, some regrouping needed to be done during this process. After all these calculations, the mineral fertilizer use per ha for every crop is summed by using the standardized crop distribution maps, as obtained in section 2.2.

Organic fertilizer application (IN2)

Organic fertilizer application is approximated by determining the available manure based on livestock density maps. Based on the available data, it is the only spatially explicit method possible. The alternative would be to have figures of organic fertilizer application for every country, and ideally for every crop, but such figures are not available.

A similar method has been carried out earlier by Potter et al. (2010) and McDonald et al (2011). As a starting point in this method, the FAO Gridded Livestock of the World (FAO, 2007) are used, as available from the Harvard Dataverse database. The latest version of the GLW shows livestock for 2010. In order to sum the different types of livestock, the livestock numbers are converted to livestock units. In the conversion towards livestock units (table 6), an average cow in North America has been defined as 1 livestock unit.

Table 6: ***conversion of the different livestock to livestock units (source: FAO, 2011)***

Region	Cattle	Buffalo	Sheep	Goat	Pig	Horse	Chicken
North America	1	0	0.15	0.1	0.25	0.8	0
OECD Countries	0.9	0.7	0.1	0.1	0.25	0.65	0.01
North Africa	0.7	0.7	0.1	0.1	0.2	0.4	0.01
Sub-Sahara	0.5	0	0.1	0.1	0.2	0.5	0.01
Central America	0.7	0	0.1	0.1	0.25	0.5	0.01
South America	0.7	0	0.1	0.1	0.25	0.65	0.01
South Africa	0.7	0	0.1	0.1	0.2	0.65	0.01
SE Asia	0.65	0.7	0.1	0.1	0.25	0.65	0.01
South Asia	0.5	0.5	0.1	0.1	0.2	0.65	0.01
Caribbean	0.6	0.6	0.1	0.1	0.2	0.65	0.01
Near East	0.55	0.6	0.1	0.1	0.25	0.56	0.01
Other countries	0.6	0.6	0.1	0.1	0.2	0.65	0.01

From the livestock unit map, manure production is calculated by using N, P and K yearly excretion values for cattle in North America, which are the highest in mass according to FAO (2011). From comparing several sources, representative excretion rates appear to be 20 kg N/yr, 5 kg P_2O_5/yr and 15 kg K_2O/yr. Multiplying the livestock units by the yearly excretion resulted in the map of nutrient production through manure. To account for the loss of manure when cattle are outside the stables and the application of manure on pasture, the assumption is made that just 50% of the manure production is available for organic fertilization.

Generally, manure is not applied on certain crops, especially root crops. This has been common agricultural knowledge for centuries (USDA, 1897). Manure application as applied for the individual crops is shown in appendix 2. After calculating the available area for manure application in every grid cell, the available manure is evenly distributed over this area. A maximum application of 200kg manure is implemented. As several adverse effects can occur when more manure is applied it is very unlikely that farmers' practices would exceed this maximum.

The second part of organic fertilization (IN2), concerns crop residues that have been left on the field. For every crop, these residues are calculated as OUT2, described in section 2.4. By means of a residue removal factor, it is calculated what part of the residues are taken from the field. The nutrients in the other crop residues that remain on the field are added in the organic fertilization. The residue removal factors for each crop (appendix 2) are assessed using literature and expert knowledge about production and harvesting methods. The total organic fertilizer flow is an addition of the manure application and crop residues.

Atmospheric deposition (IN3)

Both atmospheric deposition and biological nitrogen fixation are calculated by methods similar to the study of Stoorvogel and Smaling (1990).

Concerning wet deposition, regression equations (eq. 1) are based on annual rainfall. The principles behind these equations take into account that wet deposition is determined by the annual rainfall and a varying concentration of the nutrient in the rainwater, washing out the nutrients from the air. The average nutrient concentration in the rainwater will thus be lower on average when more rainfall occurs. Dry deposition, like aeolian dust deposition, is not taken into account. Therefore, the total atmospheric deposition is equal to the wet deposition.

Eq. 1

$$\begin{aligned} \text{IN3 (N)} &= 0.14 * \sqrt{R} \\ \text{IN3 } (P_2O_5) &= 0.053 * \sqrt{R} \\ \text{IN3 } (K_2O) &= 0.11 * \sqrt{R} \end{aligned}$$

Where the nutrient fluxes are in kg/yr and R is the annual rainfall in mm/yr.
Source: Stoorvogel and Smaling (1990)

Biological fixation (IN4)

Biological fixation consists of two components; non-symbiotic and symbiotic fixation. For non-symbiotic fixation, Stoorvogel and Smaling established certain base values for their land-water classes. The same base values (table 7) have been used, but due to a lack of data on irrigation practices, the classification is solely based on rainfall.

Symbiotic biological fixation is done by leguminous crops (soybean, groundnuts and pulses), which fix nitrogen by hosting Rhizobia bacteria in their root system. The nitrogen fixation is assumed to be a fixed percentage (30%) of the total nitrogen uptake.

Table 7: The base values for non-symbiotic fixation are adapted from Stoorvogel and Smaling (1990)

LWC (1990)	Classification method 2019	Non-symbiotic fixation
Low rainfall	Rainfall <200 mm/yr	3 kg/ha
Uncertain rainfall	Rainfall 200-500 mm/yr	4 kg/ha
Good rainfall	Rainfall 500-1200 mm/yr	5 kg/ha
Problem area >1200 mm/yr	Rainfall >1200 mm/yr	5 kg/ha
Problem area <1200 mm/yr	Not taken into account	2 kg/ha
Naturally flooded area	Assumed to be negligible	2 kg/ha
Irrigated area	Based on LU map	2 kg/ha

In wetland rice systems, nitrogen is fixed by cyanobacteria, which live in symbiosis with Azolla and other algae. This biological fertilizer has been shown to be highly effective, and therefore it is defined as supplying 60% of the nitrogen demand of the rice, with a maximum of 30 kg/ha per year. Any higher yields should draw more nitrogen from the soil.

Deposition by irrigation (IN5)

Regarding sedimentation processes, nutrient deposition by irrigation is the only process that has been accounted for. Stoorvogel and Smaling defined a fixed inflow of nutrients for irrigated areas. By defining a country-specific irrigation intensity, this method is improved.

In order to construct a global map of irrigation intensity, the Aquastat (Siebert et al., 2013). Global Map of Irrigation Areas version 5. Rheinische Friedrich-Wilhelms-University, Bonn, Germany / Food and Agriculture Organization of the United Nations, Rome, Italy") map of irrigated area is used as a starting point. Then FAOSTAT figures for total amount water used for irrigation (per country) are divided over the irrigated arable area in this country in order to determine a country-specific irrigation intensity. These intensities ranged between 0 and 650 mm/yr. The irrigation intensity is converted to nutrient inflows by assuming a standard nutrient content of the irrigation water, as shown in table 8.

Table 8: Concentrations of nutrients in irrigation water, as deducted from Stoorvogel and Smaling (1990)

Nutrient	Concentration in irrigation water
N	0.0033 kg/m^3
P_2O_5	0.0010 kg/m^3
K_2O	0.0017 kg/m^3

2.4 Nutrient outflows

Crop production (OUT1)

Nutrient removal from the soil by crop production and plant residues are calculated based on FAOSTAT country-specific crop production figures, in combination with known crop characteristics. Then the removal of nutrients by crop growth is mapped by the crop-distribution maps (section 2.1).

FAOSTAT provides figures for the yield of crops in every country. However, for the groups of crops (table 2), the yield needed to be manually calculated by dividing the sum of the production (in a certain group) over the sum of the area. It is checked that average yield is within the range of yields within the group. Then to convert yields into nutrient flows, nutrient contents are obtained from the NutMon (Vlaming et al., 2001) database and additionally from the USDA database (shown in appendix 2). Depending on what practices are common with this specific type of crop, dried or fresh nutrient contents are used similar to the production figures in the FAOSTAT database. For the crop groups (table 2), the nutrient contents are used of the most common crop within that group.

Crop residues (OUT2)

Regarding the calculation of crop residues, a method similar method is used to crop production (OUT1), with nutrient contents specific for the crop residues (appendix 2). The amount of crop residues is calculated based on the yield and the harvest index (also in appendix 2). As the model is estimating soil nutrient flows, the crop residues are considered to be an outflow from the soil completely. Part of the residues, which left on the field, are added again through IN2 (section 2.3).

Leaching (OUT3)

The nutrient losses through leaching and gasification have been calculated by methods similar to Stoorvogel and Smaling.

Loss of nutrients from the soil by leaching is relevant only for nitrogen and potassium, as soil phosphorus is largely immobile. In order account for the nutrient stock in the soil, a soil fertility class ranging from 1 to 3 has been used Stoorvogel and Smaling (1990). Of the available auxiliary data in 2019, the S-World global map of soil organic carbon is the best candidate for approximating nutrient stocks. When using a C:N ratio of 10, an indication SOC value can be attributed to the soil fertility classes as used by Stoorvogel and Smaling (1990). From these SOC levels it is deduced that the soil fertility class can be described best by a square root (figure 9). The maximum soil fertility class is set to 3, as this is the highest class in the Stoorvogel and Smaling (1990) study.

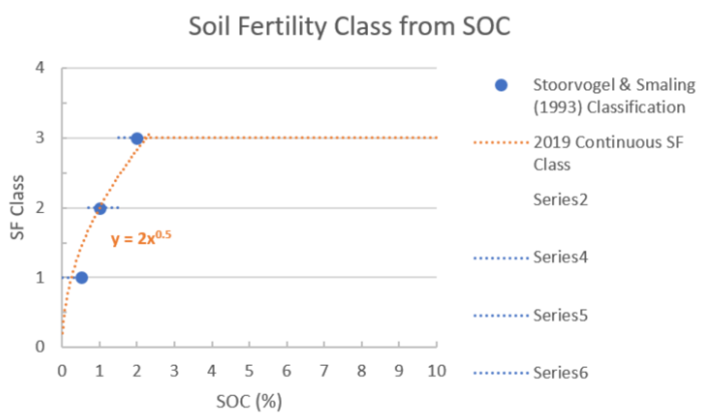


Figure 9: The Soil Fertility Class 1-3 was derived from the SOC in S-World. This relationship was calibrated on three given representative values.

Besides soil fertility, leaching is also dependent on the downward water flux, which is approximated by yearly rainfall. As recently deposited inputs are known to be more mobile, it is assumed that a significant part of the (mineral and organic) fertilizer inputs is lost through leaching. This is assumed to be 30% for nitrogen and 50% for potassium. On the same lines, as crops extract relatively more nutrients from the mobile stock, it is assumed that 10% of the plant uptake is withdrawn from the leaching flow.

Eq. 2 OUT3 (N) = 2.3 + (0.0021 + 0.0007 * F) * R + 0.3 * (IN1 +IN2) - 0.1 * (OUT1 + OUT2)

OUT3 (K_2O) = 0.6 + (0.0011 + 0.002 * F) * R + 0.5 * (*IN1* +*IN2*) - 0.1 * (*OUT1* + *OUT2*)

Where nutrient fluxes are in kg/yr, F is the soil fertility class (0-3) and R is annual rainfall in mm/yr. Source: Stoorvogel and Smaling (1990)

Gaseous losses (OUT4)

This flow was calculated by the same method as Stoorvogel and Smaling (1990). Gaseous losses of nitrogen take place mainly by denitrification and ammonia volatilization. As denitrification is largely dependent on the wetness of the soil a base value for this loss is assigned based on annual rainfall (table XX). Furthermore, a regression equation is used based on the nutrient stock (approximated by the soil fertility class), the fertilizer inputs and the plant uptake, similar to the OUT3 equations.

Eq. 3 OUT4 (N) = *'base'* + 2.5 * F + 0.3 * (*IN1* +*IN2*) - 0.1 * (*OUT1* + *OUT2*)

Where nutrient fluxes are in kg/yr, F is the soil fertility class (0-3), and 'base is the base value (table 9)
Source: Stoorvogel and Smaling (1990)

Table 9: Denitrification 'base'-values were taken from Stoorvogel and Smaling, and applied on areas with a similar annual rainfall (WorldClim, Hijmans et al., 2005)

LWC (1990)	Classification method 2019	Denitrification 'base'
Low rainfall	Rainfall <200 mm/yr	3 kg/ha
Uncertain rainfall	Rainfall 200-500 mm/yr	5 kg/ha
Good rainfall	Rainfall 500-1200 mm/yr	8 kg/ha
Problem area >1200 mm/yr	Rainfall >1200 mm/yr	12 kg/ha
Problem area <1200 mm/yr	Not taken into account	5 kg/ha
Naturally flooded area	Assumed to be negligible	12 kg/ha
Irrigated area	Based on LU map	11 kg/ha

Soil erosion (OUT5)

Nutrient losses due to soil erosion are calculated by using the universal soil loss equation (USLE). The USLE consists of five input factors (table 10), which are estimated with different methods. The R-factor defines the capacity of the local climate to erode the soil. ESDAC (Panagos et al., 2015) modelled erosivity for the globe on a 30 arcseconds resolution, which is a perfect starting point for this study.

Table 10: The components (factors) of the USLE were approximated differently

USLE factor	Approximation
R (Rainfall erosivity)	Available from ESDAC
K (Soil erodibility)	Calculated based on S-World
LS (Slope lenght and steepness)	Related to DEM
C (Cover management)	Based on crop type
P (Support practices)	Average value applied

The second factor, K, describes the erodibility of the soil material. This factor has a value between 0 (not erodible) and 1, and has been approximated in different ways. Although the USLE K-factor is popular and well-accepted, it requires knowledge over several very specific soil properties. Among other variables, the very fine sand fraction, soil structure class and soil permeability class need to be known. Within the wider context of the EPIC model (Sharply and Williams, 1990), a similar K-factor has been developed. The K-factor as proposed by Williams (1995) only requires to know the organic matter content and basic particle size distribution. This equation approaches the K factor from several 0-1 factors (equation 4), which each represent different mechanisms that can make the soil erosion-resistant. The first factor reduces the K-factor for soils with coarse sand, as this particle size requires most energy to erode. In this factor, the fine sand fraction is approached by the product of sand and silt divided by 100. The second factor reduces the K-factor for soils with a high clay to silt ratio, because of the cohesive strength of clay particles. The third factor reduces the K-factor for soils with high organic contents, for similar reasons. The fourth term reduces the K-factor of soils with extremely high sand content.

Eq. 4 $K = f_{sand} * f_{cl\text{-}si} * f_{orc} * f_{hisand}$

The erodibility K [-] consist of multiple dimensionless factors related to sand, clay-silt, organic carbon and high sand contents of the soil. Source: Williams et al. (1995)

$$f_{csand} = \left(0.2 + 0.3 \cdot \exp\left[-0.256 \cdot m_s \cdot \left(1 - \frac{m_{silt}}{100}\right)\right]\right)$$

$$f_{cl-si} = \left(\frac{m_{silt}}{m_c + m_{silt}}\right)^{0.3}$$

$$f_{orgc} = \left(1 - \frac{0.0256 \cdot orgC}{orgC + \exp[3.72 - 2.95 \cdot orgC]}\right)$$

$$f_{hisand} = \left(1 - \frac{0.7 \cdot \left(1 - \frac{m_s}{100}\right)}{\left(1 - \frac{m_s}{100}\right) + \exp\left[-5.51 + 22.9 \cdot \left(1 - \frac{m_s}{100}\right)\right]}\right)$$

Figure 10: ***Equations for the factors which constitute K, by Williams et al. (1995)***

The third factor in the USLE, LS, is a combination of slope length and slope steepness, both enhancing erosion if these lead to the accumulation of overland water flow. In order to make a global estimate of this factor, the EU map by ESDAC (Panagos et al, 2015) is compared with the GMTED2010 (Danielson and Gesch, 2011) digital elevation model and the standard deviation of elevation on the 30 arcseconds grid. By logically reasoning, it is deduced that the local slope steepness is proportional to the standard deviation of the elevation model. Also, it can be assumed that the slope length is related to the elevation. It is assumed that this relation is approached best by a logarithmic relationship, as the difference between 0 and 100m elevation is more relevant than between 2500 and 2600 meters. Then by comparing the digital elevation model to the EU map of LS-factor, scaling parameters were obtained for the following equation.

Eq. 5 LS = 0.15+0.04*Log(10+mean)*SD

The length-slope factor (LS), in relation to the mean and standard deviation of the DEM in meters

The factor C represents the influence of the crop on erosion. The factor is defined as the erosion occurring under this crop compared to the same field in bare condition, without any crop cover. From literature, it is known how the C-factor varies for each growth stage of the crop. Hence, the cropping intensity and the length of the growing season do influence the C-factor. In order to include all those influences, an elaborate dataset with C-factors in all circumstances would be required. The available data on C-factors was found in Wischmeier and Smith (1978). Based on this data, realistic values were assigned to the crops, shown in appendix 2. The most prominent distinction is between annual crops (40 to 80%) and perennial crops (about 20%).

Finally, within the factor P, several land management practices are included, like tillage and anti-erosion measures. ESDAC has generated a map for the EU, but on global scale information is lacking. Based on the EU map, it was concluded that a factor of 0.1 is a common value. This approximation was applied for all USLE calculations.

3 Results

All nutrient flows were calculated on a global scale, on the 30 arcseconds (1 km) grid. As an illustration of the results, average nutrient balance for all three macronutrients is shown for the Netherlands in table 11. Further in this chapter, the influence of the crop distribution maps is presented. In order to gain insight in the contributions of the different nutrient flows, all ten flows are further elaborated on for nitrogen. It was most logical to highlight this nutrient, as all nutrient flows affect its balance.

For all macronutrients, nutrient balances are net negative on average in the Netherlands (table 11). Balances for K are even more negative than N balances. Such negative balances are common around the world for all three nutrients, the Netherlands is no exception in this perspective. As shown in section 3.2, the extent differs mainly from country to country.

Table 11: An overview of average nutrient balances for the Netherlands

	N (kg N/ha)	**P** (P_2O_5 eq/ha)	**K** (K_2O eq/ha)
IN1 Min Fert	229	11	37
IN2 Org Fert	118	29	88
IN3 Atm Dep	5	0.2	0.5
IN4 Bio N fix	5	-	-
IN5 Irr	0.06	0.02	0.03
IN fallow	0.03	0.03	0.01
OUT1 Prod	162	37	146
OUT2 Res	55	13	127
OUT3 Leach	88	-	21
OUT4 Gas	98	-	-
OUT5 Erosion	0.8	0.3	0.8
Net Balance	**-52**	**-10**	**-169**

3.1 Global crop distribution maps

Global crop distribution maps were developed for all 34 crop types. The resulting maps were standardized, containing a number between 0 for absence and 1 for all arable land within that cell. In a lot of countries with a relatively small area, the crop distribution is almost homogenous throughout the country. Larger countries with a variety of environmental conditions, like the USA, China and Brazil, show a certain variety. In figure 11 is shown how wheat, maize and soy are largely separated areas within the USA.

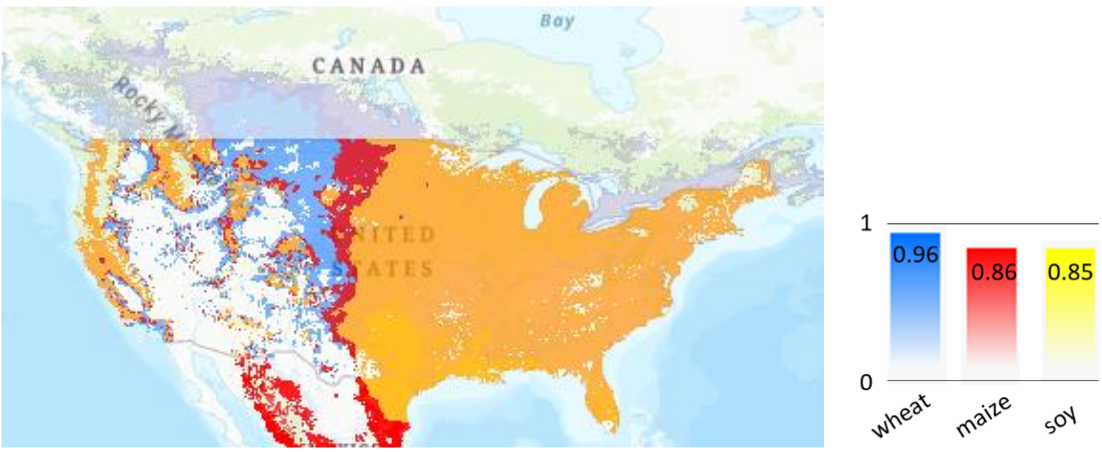


Figure 11: *Crop distribution maps for wheat, maize and soy are largely distinct. Overlapping maize (red) and soy (yellow) are constituting the orange tint.*

The within-country variation was largely related to climatic variables. Particularly, crops were excluded from areas which are too dry or too cold for the crop to grow. Variation on soil parameters was not represented so well. A small fraction of cells got excluded for certain crops because the soil is too shallow, but no soils were excluded on the basis of soil texture.

3.2 A global map of nitrogen balances

Overall, nutrient balances for nitrogen turn out to be negative. The vast majority of cells has a value between -10 and -100 kg N/ha per year, which appears to be significant. Even though, most of the net balances entail not more than 10% of the total yearly turnover. Generally, the agriculturally intensive areas of Europe, North-America and South-America have largest net losses. The main cause for this is probably an underestimation of mineral (OUT1) and organic fertilizer (OUT2), explained further in this chapter. The high yields in these countries require a relatively high fertilizer application rate for the nutrient balance to be net positive.

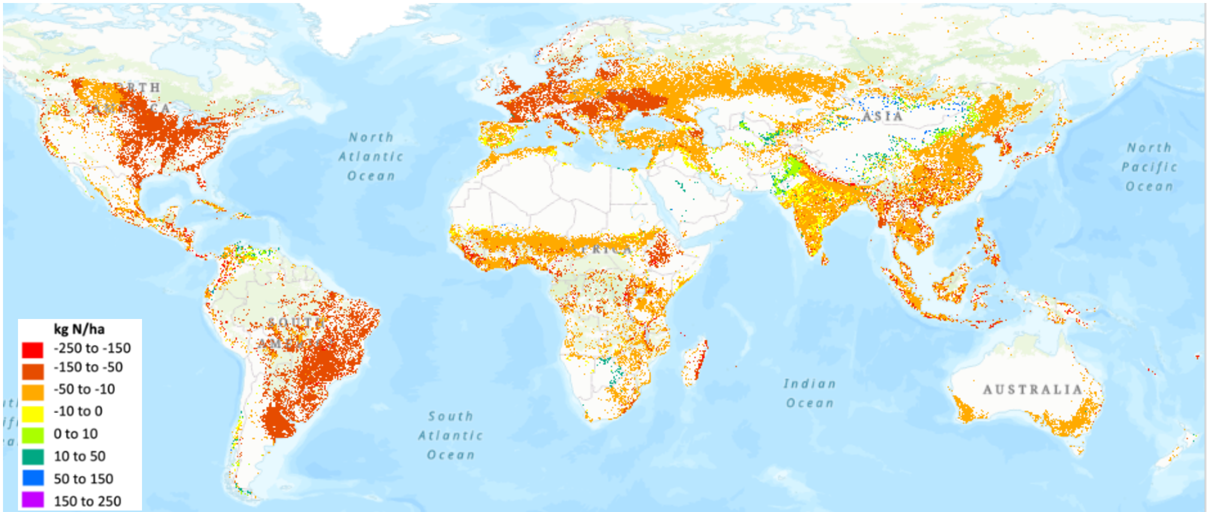


Figure 12: ***The final map of soil nutrient balances for nitrogen, in kg N/ha per year***

Positive nutrient balances can be found in the west of China. The main cause for this effect is the difference in crop distribution. Crops in the East-China, with a negative nutrient balance are wheat and potatoes. Crops with positive balance in the west are fruits and vegetables. Other countries with significant in-country differences caused by the crop distribution are the United States, Canada and Brazil. Pakistan, Zimbabwe, Venezuela Turkmenistan and Uzbekistan generally have positive nutrient balances. These are caused by similar crops that show a high nutrient balance.

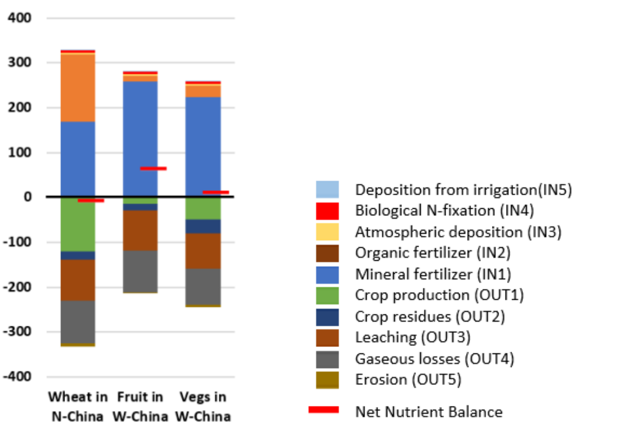


Figure 13: ***Difference in net positive and net negative nutrient balances in China can be traced back to the crop distribution, and crops having a net positive or negative balance.***

3.3 Mapping nutrient inflows

The most dominant inflow is mineral fertilizer (IN1). In some areas, especially Sub-Saharan Africa, organic fertilizer is dominant. Biological N-fixation is the dominant inflow in some areas, mostly where soy is a dominant crop, like parts of Latin America. Occasionally, in countries with dominant rice production this is the case, like parts of Cambodia, Laos and Myanmar. Finally, atmospheric deposition (IN3) is highest in some parts of central Africa, where only very extensive agriculture takes place and yearly rainfall is high thanks to the tropical climate. For IN3 no map is shown below, because of the limited variation between 5 and 12 kg N/yr.

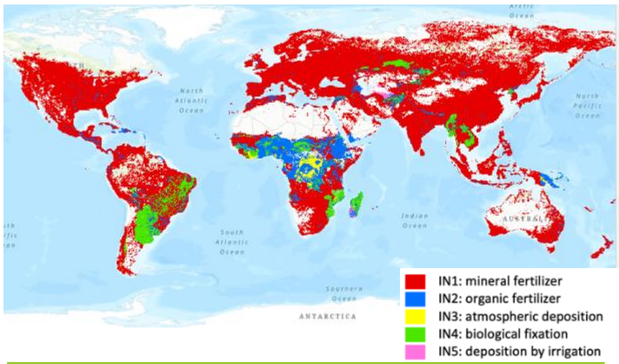


Figure 14: ***The most dominant inflow is mineral fertilizer (IN1), but each of the other inflows is dominant at some location on the world***

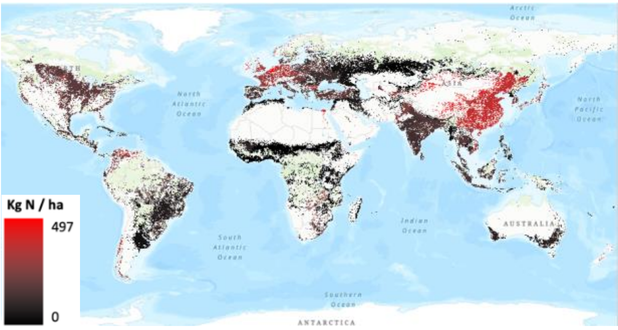


Figure 15: ***Mineral fertilizer application (IN1) in kg N/ha per year***

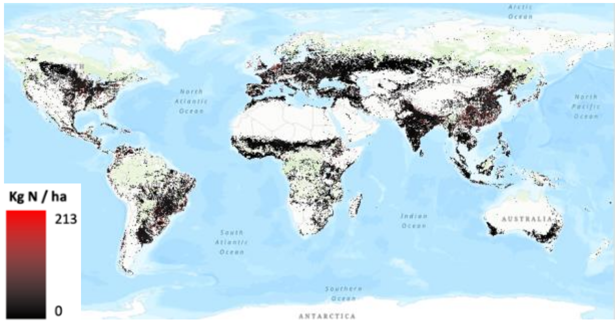


Figure 16: ***Organic fertilizer application (IN2) in kg N/ha per year***

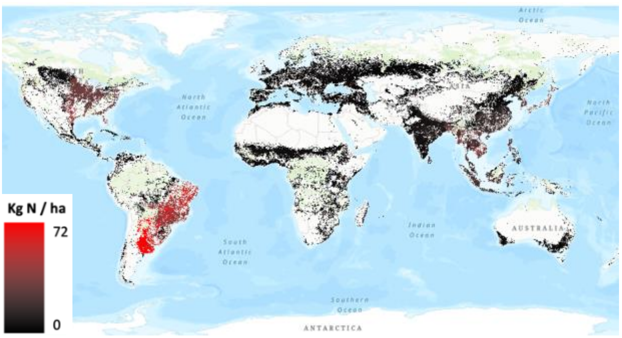


Figure 17: ***Biological nitrogen fixation (IN4) in kg N/ha per year***

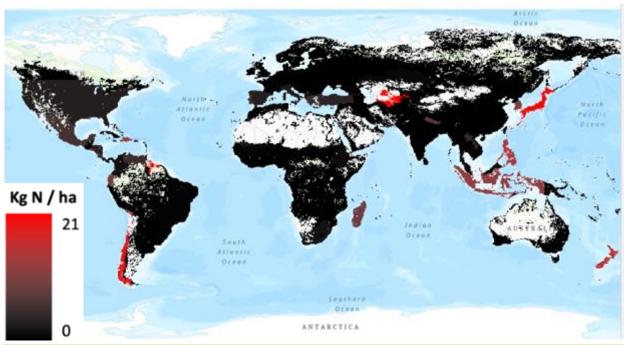


Figure 18: ***Deposition of nitrogen by irrigation (IN5) in kg N/ha per year***

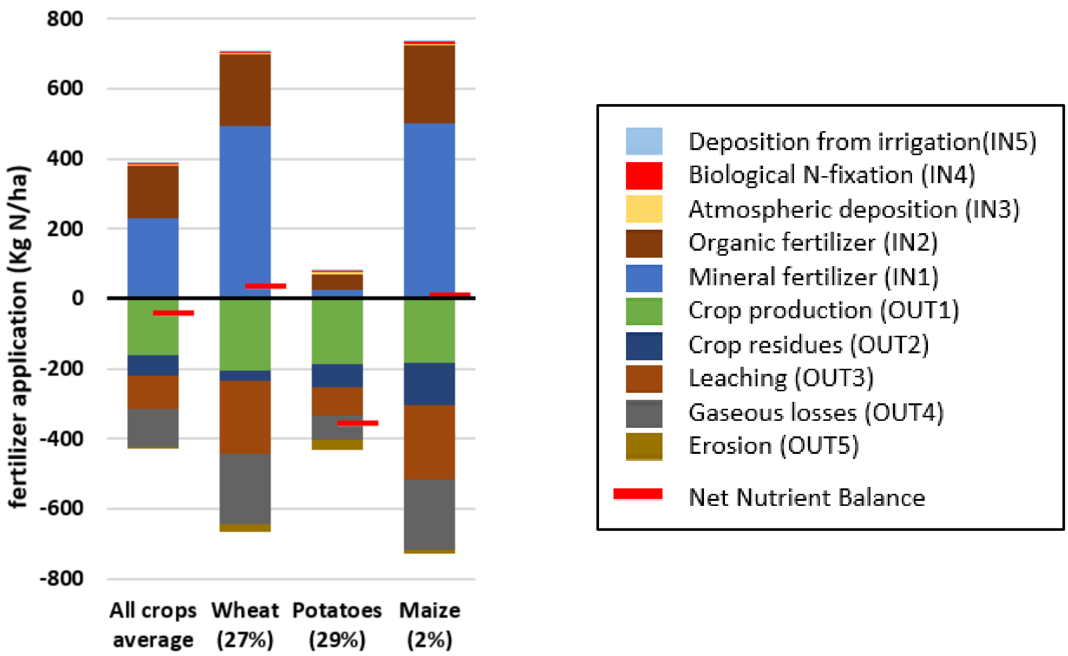


Figure 19: The nitrogen balance for a representative location in the Netherlands (near Amersfoort); averaged for all crops and specifically for wheat, potatoes and maize.

Mineral fertilizer input (IN1) ranges from 0 to 495 kg N per ha. This maximum is the applied maximum of 500 minus the fallow area. When analysing the nutrient balances at a representative location in the Netherlands (figure 19), a large difference between crops is observed. Particularly, for potatoes the nutrient balance is very negative. This seems to originate in the lack of fertilization. The lack of organic fertilizer is understandable, as organic fertilizer is not used for root crops (further explained in section 2.3). Reasonably, you would expect the farmers to compensate for this by using more mineral fertilizer. This has to do with the way mineral fertilizer application was calculated, particularly for the 28 EU countries. These countries all received the same weight for attributing the total fertilizer use to different crops, while the area of the crops in each country differs a lot. In the case of the Netherlands, this means that only 1.7% of the nitrogen fertilizer was attributed to potatoes (the EU average), while potatoes take up 29% of the arable land in this country. On the contrast, for maize 13% of the fertilizer was attributed while (according to the FAO figures) it takes up only 2% of the area. This lead to a fertilizer application calculated to be 2890 kg N/ha. As explained in section XX, such unrealistic fertilizer applications were capped to a maximum of 500 kg N/ha. A lot of fertilizer applied according to the FAO is thus not taken into account. This effect can explain the negative nutrient balances for the EU countries.

Generally, the values for deposition by irrigation (IN5) are really low, but for a few countries significant figures appear. That is because the irrigation intensity was calculated by dividing the total irrigated amount of water (in the country) over the total irrigated area. Apparently for the countries which light up, the irrigated area was relatively small compared to the amount of water.

3.4 Mapping nutrient outflows

Regarding the outflows, removal of nutrients from the soil system by harvest is the highest outflow. Occasionally, nutrient removal by crop residues is higher. As the ratio between harvest and crop residues is only dependent on the nutrient concentration and the harvest index, this is a constant ratio for a particular crop. In the previously mentioned areas, it is mainly the Gaseous losses are highest in areas scattered around the globe, and particularly in Central Asia. These areas generally have a higher fertilization (IN1 and IN2) than crop production (OUT1 and OUT2). Therefore, gaseous losses are calculated to be relatively high.

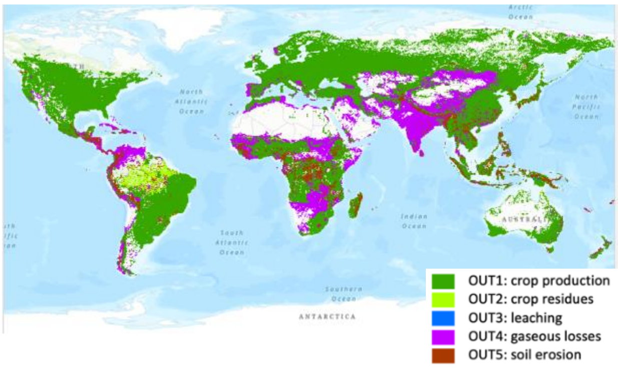


Figure 20: ***The most dominant outflow of nitrogen is by crop products (OUT1). OUT2, OUT4 and OUT5 are also dominant at some place in the world.***

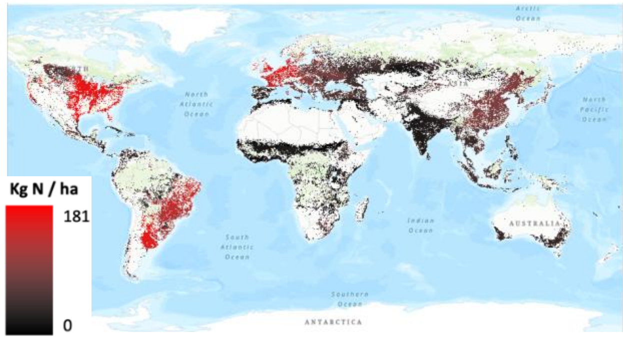


Figure 21: ***Nutrient removal from the soil by crop products (OUT1) in kg N/ha per year***

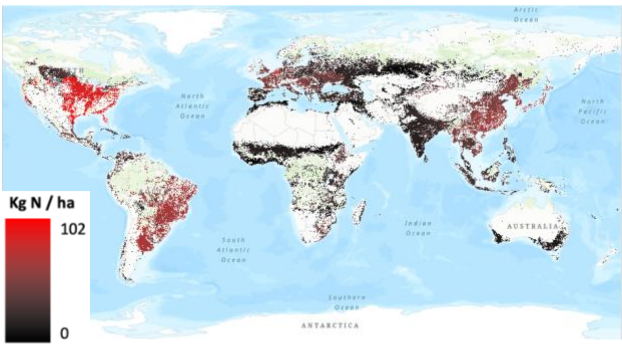


Figure 22: ***Nutrient removal by crop residues (OUT2) in kg N/ha per year***

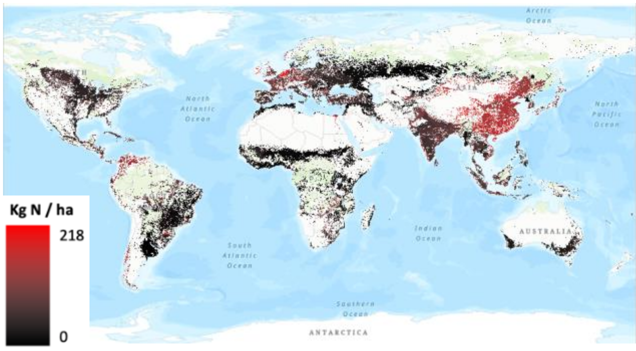


Figure 23: ***Leaching of nitrogen (OUT3) in kg N/ha per year***

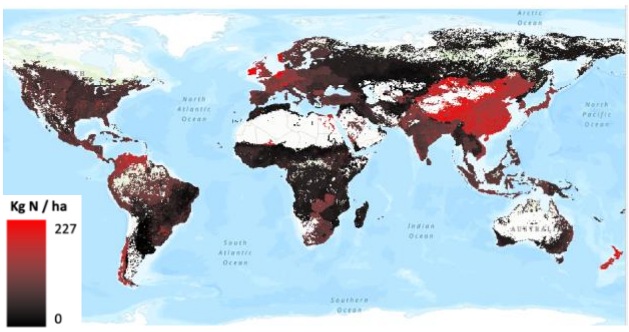


Figure 24: ***Gaseous losses of nitrogen (OUT4) in kg N/ha per year***

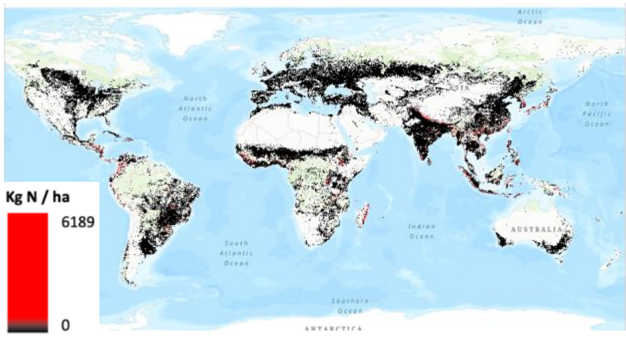


Figure 25: ***Loss of nutrients by erosion (OUT5) in kg N/ha per year***

Nutrient removal by harvest (OUT1) ranges from 0 to 181 kg N per ha. Some individual crops reach a somewhat higher output. Nutrient removal by crop residues (OUT2) ranges from 0 to 102 kg N per ha. Compared to OUT1, some crops reach a higher output. Also, for some crops (shown in table 12) the residue nutrient removal can be higher than the removal through harvest. This is a combination of nutrient contents and harvest index. Thus, the relative size of OUT1 and OUT2 is independent of the location.

Table 12: The crops with OUT2 relatively higher than OUT1

	crop	N_product	N_residue	HI	OUT2/OUT1
C11	Other roots/tubers	0.008	0.04293	0.8	**1.3**
C12	Plantains and others	0.0012	0.0016	0.5	**1.3**
C14	Sugar cane	0.0006	0.0003	0.25	**1.5**
C15	Pulses	0.038	0.01725	0.3	**1.1**
C17	Bananas	0.0012	0.0016	0.5	**1.3**
C25	Sesame seed	0.03	0.015	0.25	**1.5**

Table 13: Taking into account the residue removal factor, Only for sugar cane, the 'effective' OUT2 is larger than OUT1

		NContentOrg	Nresidue	HI	RRR	Ratio OUT2/OUT1
C1	**Wheat**	0,0223	0,0043	0,55	0,9	**0,15**
C14	**Sugar cane**	0,0006	0,0003	0,25	0,9	**1,35**
C15	**Pulses**	0,038	0,01725	0,3	0,9	**0,95**

4 Discussion and methodological findings

The methods described in chapter 2 include a wide range of assumptions, and hence relate to a large number of uncertainties. From the results (chapter 3), it appears some of the uncertainties are tolerable, and others should be addressed. This chapter will describe such methodological findings.

4.1 Improving the methods

On several points, the methods of constructing the crop distribution maps and calculating the nutrient flows can be improved. In the following paragraphs, it is described how such challenges are deducted from the results.

Crop grouping

It is found that the crop groups, as used by Stoorvogel and Smaling, are not contributing to the accuracy of the resulting nutrient balances. Especially on the crop groups vegetables (C16) and other fruits (C19), the characteristics of the group members seems to vary too much. For example, watermelons and apples have very different growth conditions, nutrient contents and harvest index. Even though, these crops are treated with the same properties in this model. This leads to unrealistic nutrient flows on some locations, in particular the nutrient uptake (OUT1 and OUT2) and flows which depend on the uptake (IN2, IN4, OUT3 and OUT4).

Alternative crop groupings could be done better on similar properties, or not at all. Of course, the implications of such an approach are that the properties of all these nutrient balances need to be known, and every crop-specific map needs to be processed a multiple of the 34 crop groups. For reference, for 2015 FAOSTAT provides data of 160 crops. As the crop-specific processing already took a reasonable part of this research, I would propose to try strategic grouping first.

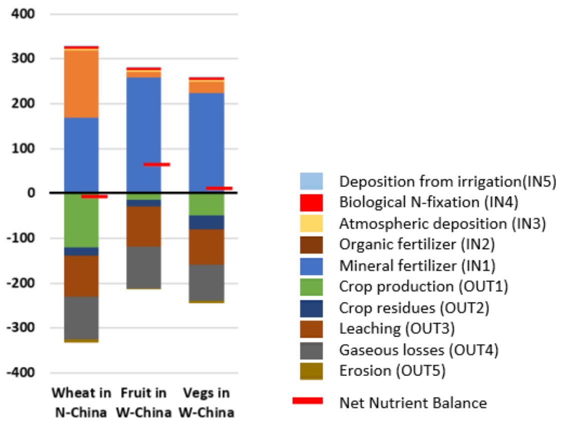


Figure 26: ***Within China, especially for fruits the nutrient removal by crops (OUT1 and OUT2) seems to be unrealistically small.***

Mineral fertilizer: Combining FAO and IFA data

As illustrated in section 3.3, the same weights used in all EU countries, for attributing the national mineral fertilizer use to certain crops, results in over- and underestimations of fertilization. The same counts for all the countries which received the weights of the 'all other countries', as it was classified by IFA.

Manure application: space for improvement

The methods currently used calculated one livestock density map based on 'livestock units', which is defined as an average cow in the USA or Canada. Then average excretion rates of cows were used to approximate how much nutrients is excreted by this livestock density. An error comes into play here, which could be solved. In short, the summing of different livestock types to 'livestock units' has not been developed primarily for excretion rates. In reality, manure from different livestock types contains different amount of nutrients. Therefore, it would be better to calculate the excretion rates for each livestock type and add those.

The manure application rate of 50%, which is used now is very rough. It would be useful to use any scientific results for how many of the manure produced ends up at arable land, and if possible specify this ratio for continents or between developed and developing countries.

In practice, when applying organic fertilizer, legislation and some cultural phenomena can be very influential for the manure applied on the field for specific crops. Ideally, that would be taken into account. Within the methodology based on the livestock density, this could be done by specifying the maximum applied manure for certain countries and crops. In the current methodology, a maximum of 500 kg N/ha is applied everywhere, and this is applied on all crops except for root crops.

Atmospheric deposition

Currently, atmospheric deposition is approximated with regression equations, depending on rainfall. With livestock density maps available, one could make an approximation of the regional production of gaseous nutrients. This could possibly improve the approximation of atmospheric deposition, and show more spatial variability.

Quality of the regression equations

For IN3, IN4, OUT3 and OUT4 flows some form of regression equations are used. These can possibly be updated.
One specific suggestion for improving the regression equations, is less biological fixation when other nutrient availability is limited.

Calculating erosion

Applying the USLE on a global scale has proven to be difficult. Also, the results showed very extreme erosion in some areas. Soil conservation measures are by no means taken into account. Although the methodology works in separating areas with negligible erosion from areas with significant erosion, it is doubted whether the actual nutrients losses are realistic.

The most extreme values calculated for erosion can most probably be traced back to the LS-factor, representing slope. In the deducted relationship (equation 5), the LS-factor is increasingly larger for higher altitudes. This part of the equation results in unrealistically high erosion values for locations on high altitudes.

4.2 Relative size of the nutrient flows

In order to determine what nutrient flow has priority when improving the soil nutrient balance, it is important to know the relative size of the nutrient flows. Moreover, as some of the flows depend on other flows, it is important to know what parameters are most influential on the nutrient balance. In this paragraph, the dependencies will be analysed.

In table 14, it is shown how the ten nutrient flows depend on five main types input data. For the regression equations (OUT3, OUT4), the component of the equation which quantifies the particular dependency is given. In the tables 15 and 16, these dependencies are quantified for two specific locations of nutrient balances.

Table 14, 15, 16: Dependencies of the nutrient flows on prime input data

		Main determining variables					
		Mineral fertilizer	Livestock	Crop production	Rainfall	Soil fertility	Irrigation intensity
Nutrient flows	IN1	Completely dependent					
	IN2		Partly depend. (Excretion)	Partly depend. (Res. removal)			
	IN3				Completely dependent		
	IN4			Largely dep. (0.3 * outputs)	Dependent (non-symb)		
	IN5						Completely dependent
	OUT1			Completely dependent			
	OUT2			Proportional (Harvest ind.)			
	OUT3	Partly depend. (0.3 * inputs)	Partly depend. (0.3 * inputs)	Partly depend. (-0.1 * output)	Partly depend. (a+b*F)*R	Partly depend. (a+b*F)*R	
	OUT4	Partly depend. (0.3 * inputs)	Partly depend. (0.3 * inputs)	Partly depend. (-0.1 * output)	Base value	Partly depend. (2.5 * F)	
	OUT5					Proportional	

Wheat in the Netherlands (in kg N /ha)

	Main determining factors						
	Mineral fertilizer	Livestock	Crop production	Rainfall	Soil fertility	Irrigation intensity	Total
IN1	495						495
IN2		200	3				203
IN3				4			4
IN4			0	5			5
IN5						0	0
OUT1			-204				-204
OUT2			-32				-32
OUT3	-148	-61	21	-20	-20		-208
OUT4	-148	-61	21	-8	-7		-203
OUT5					-2		-2
NutBal	199	78	-191	-19	-29	0	58

Rice in Indonesia (in kg N /ha)

	Main determining factors						
	Mineral fertilizer	Livestock	Crop production	Rainfall	Soil fertility	Irrigation intensity	Total
IN1	80						80
IN2		0	5				5
IN3				6			6
IN4			30	5			35
IN5						11	11
OUT1			-62				-62
OUT2			-48				-48
OUT3	-24	0	11	-34	-34		-47
OUT4	-24	0	11	-12	-5		-30
OUT5					-11		-11
NutBal	32	0	-53	-35	-16	11	-61

From these tables, it is clear that crop production is highly influential factor, because it influences several nutrient flows. Essentially, the balance of fertilization and nutrient removal from the soil system by crop production is largely determining the final nutrient balance. Even though, these flows don't need to equal 1 to 1 for a net zero nutrient balance, as a result of the OUT3 and OUT4 regression equations. This balancing ratio between inputs and outputs can be deducted mathematially as follows.

When equating the sum of all nutrient flows to zero, and some rewriting, this leads to the following expression. The OUT3 and OUT4 regression equations have already been split into their components. The component 'base' is the sum of the base values of OUT3 and OUT4.

$$IN1 + IN2 = OUT1 + OUT2 - 0.2\ (OUT1 + OUT2) + 0.6\ (IN1 + IN2) + rest\ (-IN3 - IN4 - IN5 + base + OUT5)$$

Then by more rewriting of the equation, and grouping a number of flows in 'rest', the following relation between inflows and outflows appears:

$$0.4\ (IN1 + IN2) = 0.8\ (OUT1 + OUT2) + rest$$

Assuming that the nutrient flows in 'rest' are negligible, the ratio of inputs to outputs for a net nitrogen balance is two. In practice, as can be seen in tables 15 and 16, the nutrient flows in 'rest' are not negligible, which in practice leads to the input/output ratio for a net balance to be about 2.5 rather than 2. Because of different, or a lack of, regression equations for P and K, the in-output ratios for these nutrients are roughly 1 and 2 respectively.

Based on this analysis, it is clear how the ratio between inputs and outputs is a logical result of the used regression equations. This makes clear how the full soil nutrient balance methods lead to a different outcome to surface nutrient balance, by definition. In a surface nutrient balance directly compares inputs and outputs, assuming a balance when these flows are equally large.

4.3 Data availability

For making an accurate nutrient balance, a number of parameters from the crop production system has to be known. Arguably, these parameters differ per field, depending on the specific field characteristics, crops and farming practices. When approximating the average nutrient balance over several fields, or in this case over square kilometres of fields, variation between field can never be accurately represented. Even when the average nutrient balance would be calculated accurately, it has limited meaning for the actual crop production systems. For this reason, it is not very useful to improve the accuracy to the fine details.

In this perspective, a lot of parameters could be approximated poorly, but because these parameters do only contribute a little to the final nutrient balance, improving the approximation of these parameters should not be a priority. For example, nutrients concentrations in irrigation water can differ massively, depending on its surface water or groundwater origin. Only the effect of this variation on the flow IN 5, would in the case of nitrogen only mean a difference between 0 and 15 kg N / ha in the most extreme case. This is significantly smaller than the error margins of other flows. Hence, for identifying which data is really lacking, one needs to focus on the larger flows.

As explained in the previous paragraph, crop production is a highly influential parameter. For this reason, it is important to have accurate crop data. Also, it is important that the different characteristics, like yield, harvest index and nutrient contents match well. Together, these should give a representative image of each crop. In this research, crop data was obtained from different sources. For consistency, it would be preferable if all these data were obtained from the same database.

On the fertilization side, particularly on manure application (IN2) a lot of data is required. For instance, a better approximation of the manure application ratio could make a large difference. Likewise, figures on nutrient excretion by the different types of cattle would lead to a more accurate estimation of manure production.

4.4 Spatial differentiation and resolution

In this research, a 30 arcsecond resolution (approximately 1km grid) was used for the calculations. In developing the crop distribution maps, all input data was available at this resolution. In the calculation of nutrient flows, several maps were used with a resolution of 5 arcminute (approximately 10 km grid). In appendix 1, an overview of the resolution in input data is given. Particularly, the livestock density maps and maps of irrigated area had a 5 arcminute resolution.

Most of the nutrient flows are constant for a certain crop in each country. As the crop distribution map does delivers uniform crop distributions for small countries, for these countries it makes little difference to use the country as unit of calculation.

For a certain crop in a particular country, it is also questionable how much variation you would expect. If economic and cultural factors are fairly equal throughout the country, so would then be the yield and the mineral fertilizer application. Arguably, a lot of the variation that can be expected within a country is field-to-field variation, which is not represented in this map. Variation within countries which is expected within countries is largely related to the crop distribution maps (section 3.1), originating in climatic and soil quality spatial differences. As discussed in section 3.1, climatic variation was successfully taken into account, while variation in soil quality was not represented so well in the crop distribution maps.

5 Conclusion

It is shown by a proof of concept that the current available data allow for global mapping of soil nutrient balances. Even though, the results of this research are yet insufficient for further analysis. Methods need to be improved to better represent the dynamics of nutrient flows, and to use the available data to its full potential.

5.1 Nutrient flows

The global distribution of mineral fertilizer is the main challenge to be addressed, in order to produce a map of soil nutrient balances of sufficient quality. The distribution over countries can be accurately taken into account thanks to FAO figures. Within-country differentiation is only relevant for vast countries like the USA, China and Brazil, and is successfully into account by the crop distribution maps (section 3.2). The most challenging is the distribution among different crops. The approach of this research was to use the IFA 'fertilizer per crop'-data to split the national fertilizer figures of the FAO, but these datasets do not match easily for several reasons (section 4.2).

Organic fertilizer application was approximated by calculating the locally available manure. By this method, reasonable manure application can be calculated and regional differentiation can be made (section 3.2). Even though, the method can still be refined and considering that IN2 is a substantial contributor to the final nutrient balance, this is of high priority. As explained in section 4.3, the most apparent improvements can be made by calculating manure production for different livestock types separately, differentiating the manure loss ratio for continents or countries and specifying the maximum manure application per crop.

Atmospheric deposition (IN3), and sedimentation (IN5) together account for an inflow of nutrients varying between 5 and 20 kg for nitrogen. Biological nitrogen-fixation (IN4) can add another 70 kg N/ha, where leguminous crops are grown intensively. Of course, 10 kg N/ha can make the difference between a net negative and a net positive nutrient balance, but relative to flows IN1 and IN2 (fertilization), which can potentially add up to 1000 kg N/ha, these figures are rather marginal. Therefore, it is proposed to include these nutrient inflows in the nutrient balance methods, but improving these nutrient flows does not deserve high priority.

Primarily based on FAO figures on yield and nutrient contents from several sources, the nutrient outflows by harvest (OUT1) and crop residue (OU2) were approximated. As economic, environmental and cultural factors determining crop production can be considered fairly uniform within countries, yield figures per country are sufficiently detailed. Within-country variation in nutrient removal is then expected to be primarily dependent on the type of crop, which is accounted for by the crop distribution maps (section 3.2).

The nutrient outflows by leaching (OUT3) and gaseous losses (OUT4) are highly important for determining the soil nutrient balance for nitrogen and potassium. As shown in discussion section 4.2, the fertilizer-to-harvest ratio is in practice largely determining whether a nutrient balance is positive or negative. With the regression equations used for OUT3 and OUT4, the net nitrogen balance for most crops requires a fertilizer application about 2 times the nutrient removal by harvest. In contrast to surface nutrient balances, where a neutral balance occurs by definition when fertilization equals total nutrient removal, the full nutrient balance method requires more nitrogen fertilization than nutrient removal to ensure long-term production. Given the fact that all types of arable production are to some extent prone to nitrogen losses by leaching and volatilization, the full nutrient balance offers a better representation of reality assuming that the regression equations deliver reasonable estimations of these flows. For phosphorus nutrient balances this discussion is not applicable, as OUT3 and OUT4 are considered to be negligible.

For a number reasons, it is suggested that the nutrient loss by erosion (OUT5) should be considered to be dealt with separately from the global map of soil nutrient balances. Firstly, it proved to be particularly challenging to estimate soil erosion globally (section 4.1). It is doubtful if the auxiliary data used is able to explain the expected variation, and on some aspects like soil conservation measures, data is missing. In general, estimating erosion rates is an advanced field of science at itself. It became clear though, that soil erosion can dramatically disrupt the nutrient balance. Secondly, it should be noted how soil erosion problematic for more reasons than nutrient losses. In illustration of this point one could imagine a field where a lot of soil erosion occurred, and this was compensated by only replenishing the lost nutrients with fertilizers. Arguably, the only real solution to soil erosion are conservation measures. Therefore, it is probably more effective to map soil erosion by itself than to present it as a sub-problem of a negative nutrient balance. Of course, if one chooses to make nutrient balances without OUT5, the footnote should be made that this risk is not considered.

5.2 Resolution

As discussed in section 4.4, the 30 arcsecond resolution (1km grid) was useful for developing the crop distribution maps as all required auxiliary data was available on this resolution. However, for calculating the nutrient flows, a 5 arcminute resolution (10km grid) is more suitable. Several input data are not available on a finer resolution, and a courser resolution does significantly reduce the required computing power. Moreover, on a distance shorter than 10 kilometres, local circumstances and even the individual choices of farmers are playing a significant role in the variability. By a map that is primarily constituted from global data, it is not expected that such local variability can be taken into account.

It is worth noting though that all of the maps used as auxiliary data in this research have a 5 arcminute resolution or finer. For this reason, this map has the potential to be useful at regional scale. As explained in section 4.4, spatial variation on the regional scale is expected to be represented in the map. For determining which crops are most sustainable in a certain area, such a resulting map of nutrient balances could come into use.

6 Bibliography

Beek, C.L. van ,Elias, E., Yihenew, G. S., Heesmans, H., Tsegaye, A., Feyisa, H., Tolla, M., Melmuye, M., Gebremeskel, Y., Mengist, S.(2016) Soil nutrient balances under diverse agro-ecological settings in Ethiopia.Nutr. Cycl. Agroecosyst.106,257–274.

Bontemps, S., Defourny, P., van Bogaert, E. (2010). GLOBCOVER 2009, Products description and validation report. ESA and Université Catholique de Louvain. 53 pp. DOI:10.1594/PANGAEA.787668.

Chen, M., Graedel, T.E., (2016).A half-century of global phosphorusflows, stocks, production, consumption, recycling, and environmental impacts. Glob. Environ. Chang. 36,139–152.

Cobo, J. G., Dercon, G., Cadisch, G. (2010). Nutrient balances in African land use systems across different spatial scales: A review of approaches, challenges and progress. Agriculture Ecosystems and Environment, 136, 1–15.

Danielson, J.J., and Gesch, D.B., (2011), Global multi-resolution terrain elevation data 2010 (GMTED2010): U.S. Geological Survey Open-File Report 2011–1073, 26 p.

De Willigen, P., (2000) An analysis of the calculation of leaching and denitrification losses as practised in the NUTMON approach. Rapport-Plant Research International.

Ecocrop (2013). Ecocrop database. FAO, Rome, Italy

Færge, J., Magid, J. (2004) Evaluating NUTMON nutrient balancing in sub-Saharan Africa. Nutr Cycl Agroecosyst 69(2):101–110. doi:10.1023/B:FRES.0000029680.97610. 51

FAO (1997). FAOSTAT statistical database. Food and Agriculture Organization of the United Nations, Rome.

FAO (2004) Scaling soil nutrient balances—enabling mesoscale approaches for African realities. FAO fertilizer and plant nutrition bulletin 15. FAO, Rome

FAO (2007) Gridded Livestock of the World, 2007, by G.R.W. Wint and T.P. Robinson. Food and Agriculture Organization of the United Nations, Rome. 131 p.

FAO (2011). Guidelines for the preparation of livestock sector reviews. Animal Production and Health Guidelines. No. 5. Rome.

FAO, IFAD, UNICEF, WFP, WHO, (2018) The State of Food Security and Nutrition in the World 2018: Building Climate Resilience For Food Security and Nutrition. Technical report. Food and Agriculture Organization of the United Nations, Rome.

Folmer, E.C.R., Geurts, P.M.H., Francisco, J.R., (1998) Assessment of soil fertility depletion in Mozambique. Agric. Ecosyst. Environ. 71, 159–167.

FSIN, (2019) Global report on food crises. http://www.fsinplatform.org/global-report-food-crises-2019

Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G., Jarvis, A. (2005) Very high resolution interpolated climate surfaces for global land areas. International Journal of Climatology 25: 1965–1978. DOI:10.1002/joc.1276.

IFA/FAO (2001) Global estimates of gaseous emissions of NH3, NO and N2O from agricultural land. FAO, Rome

IPBES (2018): Summary for policymakers of the assessment report on land degradation and restoration of the Intergovernmental Science- Policy Platform on Biodiversity and Ecosystem Services. Bonn, Germany: Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services.

Lesschen, J.P., Stoorvogel, J.J., Smaling, E.M.A., Heuvelink, G.B.M., Veldkamp, A., (2007) A spatially explicit methodology to quantify soil nutrient balances and their uncertainties at the national level. Nutrient Cycling in Agroecosystems 78, 111–131.

Liu, J., You, L., Amini, M., Obersteiner, M., Herrero, M., Zehnder, A. J., and Yang, H. (2010) A high-resolution assessment on global nitrogen flows in cropland, P. Natl. Acad. Sci. USA, 107, 8035–8040, https://doi.org/10.1073/pnas.0913658107

Lu, C. and Tian, H. (2017) Global nitrogen and phosphorus fertilizer use for agriculture production in the past half century: shifted hot spots and nutrient imbalance, Earth Syst. Sci. Data, 9, 181–192, https://doi.org/10.5194/essd-9-181-2017

MacDonald, G.K., Bennett, E.M., Potter, P.A., Ramankutty, N. (2011) Agronomic phosphorus imbalances across the world's croplands. Proc. Natl. Acad. Sci. 108, 3086–3091.

Panagos, P., Borrelli, P., Meusburger, K. (2015) A New European Slope Length and Steepness Factor (LS-Factor) for Modeling Soil Erosion by Water. Geosciences, 5: 117-126.

Panagos, P., Borrelli, P., Meusburger, K., Yu, B., Klik, A., Lim, K.J., Yang, J.E, Ni, J., Miao, C., Chattopadhyay, N., Sadeghi, S.H., Hazbavi, Z., Zabihi, M., Larionov, G.A., Krasnov, S.F., Garobets, A., Levi, Y., Erpul, G., Birkel, C., Hoyos, N., Naipal, V., Oliveira, P.T.S., Bonilla, C.A., Meddi, M., Nel, W., Dashti, H., Boni, M., Diodato, N., Van Oost, K., Nearing, M.A., Ballabio, C. (2017) Global rainfall erosivity assessment based on high-temporal resolution rainfall records. Scientific Reports 7: 4175. DOI: 10.1038/s41598-017-04282-8.

Potter, P., Ramankutty, N., Bennett, E.M., Donner S.D. (2010) Characterizing the spatial patterns of global fertilizer application and manure production. Earth Interact 14: 1–22.

Siebert, S. (2005) Global-scale modeling of nitrogen balances at the soil surface. Frankfurt Hydrology Paper, Institute of Physical Geography, Frankfurt University, 32 pp.

Siebert, S., Henrich, V., Frenken, K., and Burke, J. (2013). Global Map of Irrigation Areas version 5. Rheinische Friedrich-Wilhelms-University, Bonn, Germany / Food and Agriculture Organization of the United Nations, Rome, Italy"

Stoorvogel, J.J., Smaling, E.M.A. (1990) Assessment of Soil Nutrient Depletion in Sub-Saharan Africa, 1983–2000. Winand Staring Centre for Integrated Soil and Water Research (SC-DLO), Wageningen, The Netherlands.

Stoorvogel, J.J., Smaling, E.M.A., Janssen, B.H., (1993) Calculating soil nutrient balances in Africa at different scales: I. Supra-national scale. Fertilizer Research 35, 227–235.

Stoorvogel, J. J., Bakkenes, M., Temme, A. J. A. M., Batjes, N. H., and ten Brink, B. J. E. (2017) S-World: A Global Soil Map for Environmental Modelling. Land Degrad. Develop., 28: 22–33. doi: 10.1002/ldr.2656.

UNCCD; Global Mechanism of the UNCCD and CBD. (2019) Land Degradation Neutrality for Biodiversity Conservation. Bonn, Germany.

United States. Dept. of Agriculture, 1897. Yearbook of the United States Department of Agriculture.

Vlaming, J., H. Van den Bosch, M.S. Van Wijk, A. De Jager, A. Bannink and H. Van Keulen (2001) Monitoring nutrient flows and economic performance in tropical forming systems (NUTMON). Publishers: Alterra, Green World Research and Agricultural Economics Research Institute, LEI, The Netherlands.

Wischmeier, W.H., and Smith, D.D., (1978) predicting rainfall erosion losses. A guide to conservation planning. Agric Handbook No 537. USDA, Washinton DC

Xu, R., Tian, H., Lu, C., Pan, S., Chen, J., Yang, J., & Zhang, B. (2017). Estimation of pre-industrial nitrous oxide emissions from the land biosphere. Climate of the Past Discussions, 13(7), 977–990. https://doi.org/10.5194/cp-13-977-2017

Appendix 1: overview of input data

Dataset	Source	Applied in	Resolution
ESA GlobCover	Bontemps et al., 2009	Crop distribution	10 arcsec
S-World soil maps (SOC, text., depth)	Stoorvogel et al., 2017	Crop distribution, OUT5	30 arcsec
WorldClim (rainfall, temperature)	Hijmans et al., 2005	Crop distribution, IN3	30 arcsec
FAO production figures (total, area, yield)	FAOSTAT (FAO, 1997)	Crop distribution, OUT1, OUT2	Per country
FAO landuse figures (arable, fallow)	FAOSTAT (FAO, 1997)	Crop distribution	Per country
FAO mineral fertilizer application (total)	FAOSTAT (FAO, 1997)	IN1	Per country
IFA mineral fertilizer application per crop	IFA and IPNA, 2017	IN1	Per country
Livestock density maps	GLW (FAO, 2007)	IN2	5 arcminute
Livestock unit factors	FAO, 2011	IN2	Per (sub-)continent
Excretion rates	Several sources	IN2	No spatial differentiation
Organic fertilizer application yes/no	Expert knowledge	IN2	No spatial differentiation
Irrigated area	Siebert et al., 2013	IN5	5 arcminute
Irrigation amount	Aquastat	IN5	Per country
Crop yield	FAOSTAT (FAO, 1997)	OUT1	Per country
Crop nutrient content, harvest index, RRR	NutBal DB, USDA DB, other literature	OUT1, OUT2, IN4	No spatial differentiation
Erosivity	Panagos et al., 2015	OUT5	30 arcsec
GMTED2010 Digital Elevation Model	(Danielson and Gesch, 2011)	OUT5	30 arcsec

Appendix 2: Crop-specific properties

Code	Crop	Type	Min temp	Max temp	Min rain	Max rain	Max texture	Min depth	Manure applic.	Residue Rem. Rate	USLE C-factor
C1	Wheat	Annual	5	27	300	1600	0.7	10	1	0.9	0.35
C2	Rice	Annual	16	38	1000	4000	1	10	1	0.9	0.42
C3	Maize	Annual	10	47	400	1800	1	10	1	0.8	0.2
C4	Barley	Annual	2	40	200	2000	1	50	1	0.9	0.35
C5	Millet	Annual	15	45	200	1000	1	10	1	0.6	0.35
C6	Sorghum	Annual	8	40	300	3000	1	50	1	0.6	0.35
C7	Other cereals	Annual	5	40	250	2000	1	10	1	0.9	0.35
C8	Potatoes	Annual	7	30	250	2000	1	10	0	0.3	0.43
C9	Sweet potatoes and yams	Annual	10	45	500	8000	1	50	0	0	0.43
C10	cassava	Annual	10	35	500	5000	1	50	0	0.4	0.43
C11	Other roots	Annual	10	35	1000	4100	0.7	10	0	0	0.43
C12	Plantains	Perennial	16	38	1000	5000	1	50	1	0.1	0.2
C13	Beet	Annual	4	35	500	1200	0.7	50	0	0	0.43
C14	Cane	Perennial	15	41	1000	5000	1	50	1	0.9	0.2
C15	Pulses	Annual	2	45	250	4300	1	10	1	0.9	0.63
C16	Vegetables	Annual	3	40	200	5000	1	10	1	0.2	0.63
C17	Bananas	Perennial	12	42	650	5000	1	50	1	0.1	0.2
C18	Citrus fruit	Perennial	6	42	300	4000	1	50	1	0.1	0.2
C19	Other fruit	Both	3	52	100	4000	1	10	1	0.2	0.2
C20	Oil crops other than 21-26	Both	3	50	100	4200	1	10	1	0.1	0.3
C21	Palm oil	Annual	12	38	1000	8000	1	50	1	0	0.2
C22	Soybeans	Annual	10	38	450	1800	1	10	1	0.8	0.63
C23	Groudnuts	Annual	10	45	400	4000	1	50	1	0.8	0.5
C24	Sunflower seeds	Annual	5	45	300	1600	1	50	1	0.1	0.3
C25	Sesame seed	Both	10	40	300	1500	1	50	1	0.1	0.3
C26	Coconut	Perennial	14	38	650	4000	1	50	1	0	0.2
C27	Cocoa beans	Perennial	10	38	900	7600	1	50	1	0	0.2
C28	Coffee beans	Perennial	10	36	750	4200	1	10	1	0	0.2
C29	Tea	Perennial	8	35	700	4500	1	50	0	0	0.2
C30	Tobacco	Both	7	35	350	3000	1	50	1	0.1	0.2
C31	Seed cotton	Annual	15	42	450	1500	1	50	1	0.9	0.43
C32	Jute and hard fibres	Both	4	45	350	4400	1	10	1	0.9	0.2
C33	Rubber	Perennial	10	45	1200	6000	1	50	0	0	0.2
C35	Other crops	Both	2	46	250	5500	1	10	1	0.2	0.2