Planetary boundaries of Phosphorus

Towards an integrated assessment of global phosphorus use and depletion
A ressource use and extraction model with LPJmL-MAgPIE

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„ A model is simply an ordered set of assumptions about a complex system… . The model we have constructed is, like every model imperfect, oversimplified, and unfinished.“

MEADOWS et al. (1972, p.20)

Abstract

Phosphorus (P) is one of the elements most necessary for plant nutrition and it is a non-renewable resource. Phosphorus is a major contributor to the erosion of environmental systems by eutrophication of waterbodies, rivers and finally coastal and marine ecosystem, where it can trigger major oceanic anoxic events with severe impacts and unpredictable further implications on global biogeochemical cycles.

Estimates of global phosphorus reserves account for 68 000 Tg phosphate rock (USGS 2014). The depletion of global phosphorus reserves is expected within the next 48 to 400 years (Cordell et al. 2009, Bouwman et al. 2009, White and Cordell 2010, Van Vuren et al. 2010, van Kauwenbergh 2010, Rosemarin et al 2011). However, these projections still have problems to forecast phosphorus consumption because they do not take into account soil phosphorus accumulation.

This thesis provides a modelling approach to calculate stocks and flows within the global phosphorus cycle. I used the MAgPIE-LPJmL model (Sitch et al. 2003, Gerten et al. 2004, Bondeau et al. 2007, Lotze-Campenet.al. 2008, Popp et al. 2010, 2011, 2012, Dietrich 2011, Schmitz 2012, Waha et.al. 2012, Bodirsky et al. 2012) and developed a phosphorus module including a soil phosphorus accumulation model (SPAM) to quantify stocks, flows and losses within the agricultural phosphorus cycle and to estimate the phosphorus fertilizer use and the depletion of global phosphorus reserves.

My model results indicate that fertilizer consumption increases from 13.51 Tg P in 1995 to 23.17 TgP in 2050. The total phosphorus consumption from 2010 to 2050 is 1096.64 TgP. This accounts for at least 8 376 Tg phosphate rock to be necessary for fertilizer production until 2050. Under the estimation of 68 000 Tg global phosphate rock reserves (USGS 2014) 12.3 % of reserves could be depleted in 2050. By an extrapolation of this use global reserves could last for further 336, years until 2386.

By my estimations, total food for human nutrition increased from 1995 to 2050 by 103%, from 5.5 TgP to 11.2 TgP, vegetal products for food use increased by 78%, from 3.7 TgP to 6.6 TgP, crop production for feed use increased by 177%, from 4.9 TgP to 13.6 TgP, total feed use from pasture increased by 82%, from 12.3 TgP to 22.4 TgP, total manure increased by 101%, from 19.75 TgP to 39.72 TgP.

My estimations for total phosphorus input to croplands are 24.7 TgP in 1995 and 54.2 TgP in 2050. My calculated total withdrawals on cropland are 19.6 TgP and 41.4 TgP, respectively. I estimated a phosphorus fixation/accumulation of residual phosphorus to the soils of 19 TgP and 35.1 TgP per year, respectively. The estimated phosphorus pool in cropland soils increases from 438.98 TgP in 1995 up to 985.26 in 2050.

I calculated the total losses to the non-agricultural environment to increase by 83%, from 11.4 TgP in 1995 to 20.85 TgP in 2050.

Model results are still very uncertain due to a lack of data concerning soil phosphorus information and the complexity to rebuild soil phosphorus dynamics. Furthermore my model do not take into account the processes of phosphorus release by soil organic matter loss and the continuance of phosphorus in the context of land conversion and land use change as well as the whole complex of soil erosion by wind and water.

My study indicates that the global "phosphorus problem" switched from a depletion problem to a pollution problem with some severe consequences. Rockström et al (2009) estimate, that the threshold of 11 million tonnes (Tg) of phosphorus inflow to oceans to avoid a major oceanic anoxic event should not be exceeded. Although my estimation of total losses to the non-agricultural environment is a rather rough estimation, it can be considered as a proxy for the phosphorus load ending up in water ways. The calculated increase from 11.4 TgP in 1995 to 20.85 TgP in 2050, underpins the need for an informed global governance of phosphorus and global phosphorus management, in this sense for regulation and guidance to provide a future sustainable phosphorus use.

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List of abbreviations

AFR	Africa (world region)
AM	adapting mosaic (scenario)
BIC	Brazil, India, China
CPA	Central Pacific Asia (world region)
CV	coefficient of variation
DAP	Diammonium phosphate
DM	dry matter
DPPS	dynamic phosphorus pool simulator
e.g.	exempli gratia
eq.	equation
EOS	elasticity of substitution
et al.	et alia
EUR	Europe (world region)
FAO	Food and Agricultural Organization of the United Nations
fig	figure
GAMS	General Algebraic Modeling System
GHG	Global Heating Gases
GO	Global Orchestration (scenario)
i.e.	id est
IA	Integrated Assessment
IAASTD	International Assessment of Agricultural Knowledge, Science and Technology for Development
IFA	International Fertilizer Association
IIASA	International Institute of Applied System Analysis
IMAGE	Integrated Model to Asses the Global Environment
IPCC	Intergovernmental Panel on Climate Change
ISRIC	International soil Reference and Information Center
ISSCAS	Institute of Soil Sciences – Chinese Academy of Sciences
JRC	Joint Research Center of the European Commission
K	potassium
LAC	Latin America and the Caribbean (world region)
LAM	Latin America (world region)
LPJmL	Lund-Potsdam-Jena dynamic global vegetation and hydrology model with managed Land
MAgPIE	Model of Agricultural Production and its Impact on the Environment
MEA	Middle East Asia (world region)
MEA	Millennium Ecosystem Assessment
MFA	material flow analysis
mt	metric ton
mmt	million metric tons
N	nitrogen
n.a.	not available
NAM	North America (world region)

NPP	net primary production
OECD	Organization for Economic Co-Operation and Development
OS	Order of Strength (scenario)
P	phosphorus
p	page
PAO	Pacific OECD (world region)
PAS	Pacific Asia (world region)
pH	potential Hydrogenii
PIK	Potsdam Institute for Climate Impact Research
PO_4^{3-}	phosphoric acid
PR	phosphate rock
PUE	phosphorus use efficiency
P_2O_5	phosphorus pentoxide
ref	referre
SAS	South Asia (world region)
SFA	Substance Flow Analysis
SPAM	Soil Phosphorus Accumulation Model
SRES	special report emission scenario
SSP	shared socio-economic pathways (scenario)
Tg	Terragram
TG	Techno Garden (scenario)
UNESCO	United Nations Educational, Scientific and Cultural Organization
USGS	United States Geological Survey
U.S.	United States
vs.	versus
WISE	World Inventory of Soil Emission Potential
µmol	micromolar

List of physical unit

1 Gigatonne (Gt) = 10^9 t= 1.000.000.000 t = 1 Billionen kg = 1 Petagramm (Pg) = 10^{15} g

1 Megatonne (Mt) = 10^6 t= 1.000.000 t = 1 Milliarde kg = 1 Teragramm (Tg) = 10^{12} g

1 Kilotonne (kt) = 10^3 t= 1000 t = 1 Million kg = 1 Gigagramm (Gg) = 10^9 g

1 Tonne (t) = 1 metric ton (mt) = 1000 Kilogramm = 1 Megagramm (Mg) = 10^6 g

1 Million metric tons (mmt) = 1 Megatonne (Mt) = 1 Terragramm (Tg)

1 Introduction

Phosphorus (P) is one of the elements most relevant for plant nutrition, along with Nitrogen (N) and Potassium (K). Because of its contribution to many physiological processes, it is necessary for plant growth. The use of phosphorus as fertilizer for agricultural soils has significantly increased global food security over the last decades. Continued availability of phosphorus as an input for agricultural systems is necessary to secure the future food production for an expected nine billion human population in 2050.

Phosphorus is a non-renewable resource. Estimates of phosphorus reserves vary between different authors, reflecting the high level of uncertainty about global phosphorus reserves. Depletion of global phosphorus reserves is expected within the next 48 to 400 years depending on scenario and reserves estimation (Cordell et al. 2009, Bouwman et al. 2009, White and Cordell 2010, Van Vuren et al. 2010, van Kauwenbergh 2010, Rosemarin et al 2011).

The quality of the remaining phosphate rock is decreasing with progressive extraction. The point in time when extraction reaches it maximum is economically of high relevance. After this maximum production the availability decreases and technological extraction costs consequently increase. The maximum of global production can be described as Peak Phosphorus and is expected in 2034 (White and Cordell 2010, Cordell et al. 2011), much earlier than the total depletion of phosphorus reserves

Phosphorus is a major contributor to the erosion of environmental systems on a global scale. Anthropogenic manipulation of the global phosphorus cycle by phosphorus use in agriculture leads to phosphorus accumulation in soils, an increase in phosphorus flows via particular and soluble erosion, and eutrophication of surface waterbodies, rivers and finally coastal and marine ecosystem. Eutrophication can trigger major oceanic anoxic events with severe impacts on marine ecosystems and unpredictable further implications on global biogeochemical cycles. This is reflected in the critical discussion on planetary boundaries of the Earth system which describes global physical, ecological and biogeochemical thresholds of the maintenance of the earth system and its different subsystems, thereby defining the safe operating space for humanity. Phosphorus use is considered one of these planetary boundaries (Rockström et. al 2009).

The global natural P cycle is defined by flows between temporary stocks. This includes geological stocks, weathering of parent rock, the soil, the biosphere along the food chain, as well as reflows to the soil and fluxes to the oceans and a rebuilding of geological stocks via sedimentation. The anthropogenic P cycle include additional flows, such as mining of phosphates, fertilization of croplands and pastures, the industrial agricultural production system, food processing, waste management and sewage systems. The P cycle has compartments of very different time and spatial scales. The geophysical, more or less inorganic cycle, including weathering, physical transports via waterways and sedimentation in the oceans runs over some million years and large distances. The biological cycle, including soil-chemical processes has a much shorter time and shorter spatial scale, respectively.

There have been some attempts to quantify stocks and flows within the global phosphorus cycle (Fillipelli 2002, Liu et al 2008, Villalba et al. 2008 Cordell et al. 2009) and estimate future stocks and flows (Bouwman et al. 2009, Bouwman et al. 2013) as well as global future phosphorus demand (Van Vuren et al. 2010) and fertilizer use (Sattari et al. 2009).

However, there remains a lack of knowledge concerning the dimensions of stocks and flows within the future global phosphorus cycle, including potential environmental losses and a lack of global and spatial explicit time series on future expectations of phosphorus fertilizer use.

Potential scenarios of future resource use depend on political decisions and the design of resource use systems. Given its environmental impacts and resource scarcity, sustainable phosphorus use and global phosphorus management is crucial important for coming decades and next generations. An improved understanding and quantification of stocks and flows in the global phosphorus cycle and time-series on future phosphorus fertilizer use under different development scenarios is a necessary requirement for informed political decision making. The representation of phosphorus accumulation in agricultural soils is of crucial importance to estimate future fertilizer demand and future phosphorus resource depletion.

Integrated assessment modelling is an appropriate method to cope with the complex and interdisciplinary dimensions of the issue. Integrated assessment models can simulate the biogeochemical Earth System and the influence of other variables such as; e.g. human land use or energy systems. I used the LPJmL-MAgPIE-Modell (Sitch et al. 2003; Gerten et al. 2004; Bondeau et al. 2007; Lotze-Campenet.al. 2008; Popp et al. 2010, 2011, 2012; Dietrich 2011; Schmitz 2012;Waha et.al. 2012) as a methodological approach to integrate global socio-economic, geophysical and biogeochemical complex interactions and to calculate phosphorus stocks and flows within the global phosphorus cycle, future fertilizer use and phosphorus accumulation in the soils under agricultural use.

For this purpose, I transformed the existing N-module of the MAgPIE model (Bodirsky et al. 2012) which is used for long term estimations in land use dynamics to a phosphorus-module. I then expanded it by a soil phosphorus accumulation model (SPAM) to improve the representation of soil phosphorus accumulation. With this model, the future phosphorus cycle is simulated under a „middle of the road“-scenario. Soil-phosphorus accumulation and fertilizer use are projected on a time-horizon from 1995 to 2050. A sensitivity analysis of the key coefficients of the model is performed to provide a basis for adjustments, improvements and a calibration of the model.

The aims of this thesis are:

(1) to provide a first approach to integrate and represent phosphorus flows within the MAgPIE-LPJmL model, develop a phosphorus module including a soil phosphorus accumulation model (SPAM)

(2) to quantify stocks, flows and losses within the agricultural phosphorus cycle up to 2050,

(3) to provide estimated time series for the agricultural phosphorus fertilizer use,

(4) to estimate the depletion of phosphorus reserves based on agricultural phosphorus demand

The outcomes will be used to:

(a) compare and discuss the amounts of fertilizer use and estimates for reserve depletion with those by other authors,

(b) discuss influencing variables that determine the stocks, flows and losses within the future global phosphorus cycle and to compare results with outcomes of other authors,

(c) discus influencing variables, determining the supply and demand curves concerning its shaping characteristics, elasticity and possible effects on markets, prices as well as on social and environmental costs,

(d) evaluate the soil phosphorus accumulation model (SPAM) based on a sensitivity analysis. Possibilities and recommendations for a calibration and an improvement of the model for further investigations will be given,

(e) conclude with some reflections on integrated and sustainable management of the global phosphorus cycle.

The thesis is structured as follows: Chapter 1 provides the theoretical background on the economics of phosphorus resources, data on phosphorus reserves, the global phosphorus cycle and the state of research regarding the modelling of the phosphorus cycle. Chapter 2 introduces the methodological approach of integrated assessment modelling, the applied MAgPIE-LPJmL model, the phosphorus module with the soil phosphorus accumulation model (SPAM) and the scenario set up. Chapter 3 presents the results concerning the sensitivity analysis, stocks, flows and losses within the global phosphorus cycle, fertilizer use, soil phosphorus accumulation and details of soil phosphorus dynamics. Chapter 4 provides a discussion of the results, with a focus on the phosphorus reserves depletion due to agricultural fertilizer use, and the other results. The model is critically evaluated and recommendations on an improvement and on further research are given.

2 Theory

The aims of this thesis are: (1) to model the future phosphorus cycle under the special representation of soil phosphorus accumulation due to long term use of phosphorus fertilizer, (2) to quantify phosphorus stocks, flows and losses within the cycle, (3) to estimate fertilizer demand under this condition and (4) to estimate the depletion horizon of phosphorus reserves under the applied methodology of an integrated assessment. To provide the theoretical basis for the modeling exercise, the remaining parts of this chapter are organized as follows: Chapter 1.1 provides an overview of phosphorus reserves and economics of resource use. In subchapter 1.1.1 I give an overview of the definitions of reserves, the current state of phosphorus reserves estimations, production and use as well as on prizes. In subchapter 1.1.2 I depict the economics of phosphorus resource use including theoretical reflections on sustainable use and intertemporal optimization, as well as on supply, demand and influencing variables. Chapter 1.2 outlines the global phosphorus cycle within its biological, chemical, physical, ecological, geological and climatic dimensions as well as in its natural state and under anthropogenic manipulation. As a foundation to generate the soil phosphorus accumulation model (SPAM), I will portray some chemical and other aspects of soil phosphorus dynamics. Chapter 1.3 finally depicts current modeling approaches and estimations concerning the global phosphorus cycle and phosphorus budgeting with an overview of different authors´ quantifications of phosphorus stocks and flows.

2.1 Phosphorus reserves and economics of resource use

2.1.1 Phosphorus reserves, production and use

In the following sections I describe the state of global phosphorus reserves and availability, phosphorus production, as well as amounts of phosphorus use and phosphorus markets. Therefore it is necessary to first define the concept of reserves and resources.

2.1.1.1 Reserves definitions

Terms which are used to discuss depletion of non-renewable resources are *resources*, *reserves*, *reserve-base* and *resource potential* or *occurrences*. The idea of fixed mineral resource stocks which are exploited, and at one point in time, depleted is a simplifying assumption. In the longer term, economically relevant stocks are not fixed and will vary with changing economic and technological circumstances (Perman et al. 2011 p. 511). For that reason using the definition of reserves and reserve-base is more appropriate since resource is an unspecified term for the physical issue.

Following Perman et al. (2011) and USGS (2014), *reserves* are quantities of a resource which are economically recoverable at the time of determination and under present costs and prices.

The *reserve base* is the wider and the more vague quantity of a resource which meets specific physical and chemical criteria, and which is estimated to become `reasonably´ economically recoverable in the future under future price and cost constellations and future technological possibilities (Perman et al. 2011, USGS 2014). While Perman et al. (2011) includes reserves that have not yet been discovered, USGS (2014) just includes the measured and indicated quantities. According to USGS (2014) "the reserve base includes those resources that are currently economic, marginally economic, and some of those that are currently subeconomic."

Other *occurrences*, defined by USGS (2014), "are materials that are of too low grade or for other reasons are not considered potentially economic." The boundary between subeconomic and other occurrences is strongly dependent on technological improvements and the potential feasibility of economic production. These circumstances are obviously uncertain.

2.1.1.*2* *Phosphorus production and phosphorus reserves*

Until the mid-19th century, manure and human excrement were the most relevant source of phosphorus reflow to agricultural soils. With the discovery of the guano phosphates a first, but very limited, industrial usable phosphorus fertilizer was found. Calcium phosphates are the most common and useful sources of phosphorus. Phosphate ore is extracted with an average P content of 13%. The beneficiated phosphate rock normally ranges from 15% to 33% P_2O_5 (Villalba et al. 2008). The global phosphorus rock production, as a crude material for phosphorus fertilizers, is depicted in table 1 from Villalba et al. (2008) and figure 1.

	World production of phosphorus (thousand metric tons P)			
Producing country	*1991*[a]	*2001*[b]	*2004*[b]	*2007*[c]
Brazil	284	746	839	810
China	2.840	2.753	3.343	3.951
Morocco	2.490	3.234	3.714	5.715
Russia	4.042[d]	1.704	1.714	2.491
Tunisia	821	1.066	1.048	na
United States	6.336	4.033	4.545	4.682
Rest of the world	3.420	3.900	4.319	3.115
Total	**20.233**	**17.436**	**18.900**	**20.764**

Note: na = not available, to convert to P_2O_5 content multiply by 2.291.
[a]from Rabchevsky (1995), [b]from Jasinski (2005), [c]from Lauriente (2003). [d]USSR

Table 1: World production of phosphorus from phosphate rock, by the main producing countries 1991-2007 from Villaba et al. 2008

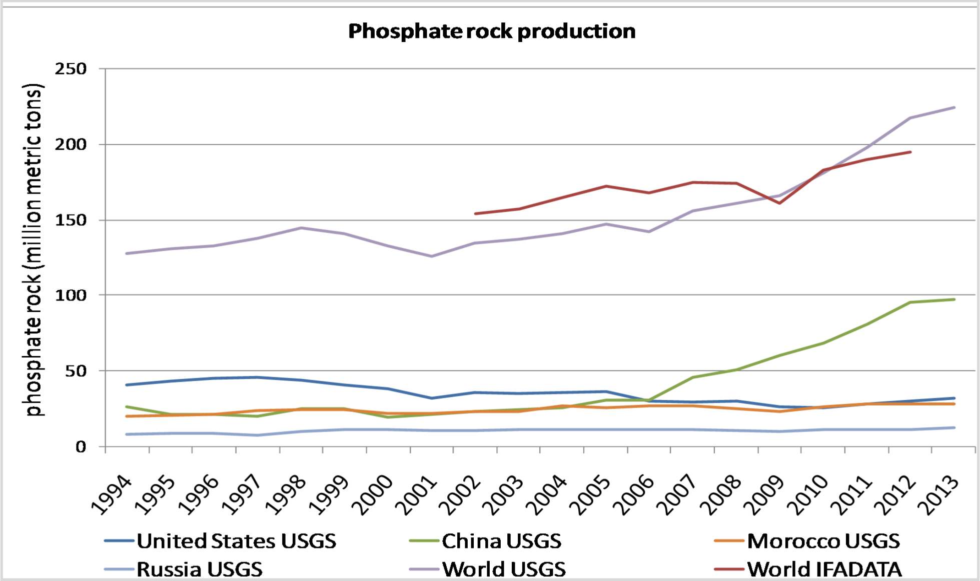

Figure 1: **Global phosphorus rock production with data from USGS (2014) und IFADATA (2014), own elaboration**

There is a shortage of different data sources on phosphorus production and the two available data sources for global phosphorus rock production, USGS (2014) and IFADATA (2014) differ. Most cited data from the USGS (2014) indicate a strong increase in production capacities since 2006 due to heavily increased production in China, from a total of 130 million metric tons phosphate rock in 2001 to up to 220 million metric tons in 2013. While the U.S. stepped down as the top global producer in the 90´s, China quadrupled its production in the last 10 years from 25 mmt phosphate rock to nearly 100 mmt and skyrocketed to the world´s primary producer.

In addition to China, other countries like Morocco have increased phosphorus rock production. Particularly, some Arab countries like Jordan, Egypt and Saudi Arabia increased production by a considerable amount. The picture of phosphorus rock production seems very dynamic and it can be assumed that global phosphorus rock production will increase considerably over time. USGS (2014) estimated a further increase of phosphate rock production up to 260 million metric tons in 2017.

IFADATA (2014) provides data of phosphate rock production from 2002 to 2012, differing from USGS. While production was estimated as higher in the first half of the last decade, the latest estimations lay below the estimation of USGS; leading to a rather linear increase in production up to nearly 200 million metric tons in 2012. Whatever the exact value may be, phosphorus rock production increased in the last decade. A quantity of more than 200 million metric tons seems realistic and a further increase in production capacity seems predictable. With an average amount of 30 % P_2O_5 in phosphate rock, 200 million metric ton (mmt) corresponds to an amount of 60 Terragramm (Tg) phosphorus, containing 26.18 Tg elemental phosphorus.

The state of global phosphorus reserves and reserve base remains uncertain and cloudy due to (1) vague information about reliable amounts of reserves and (2) a change in the declaration of reserves and reserve base within the most reliable and most cited data source, the USGS mineral commodities summaries in 2009 (USGS, 2014; Edixhoven et al., 2013). World reserves and reserve base is depicted in figure 2 with data from USGS (2014).

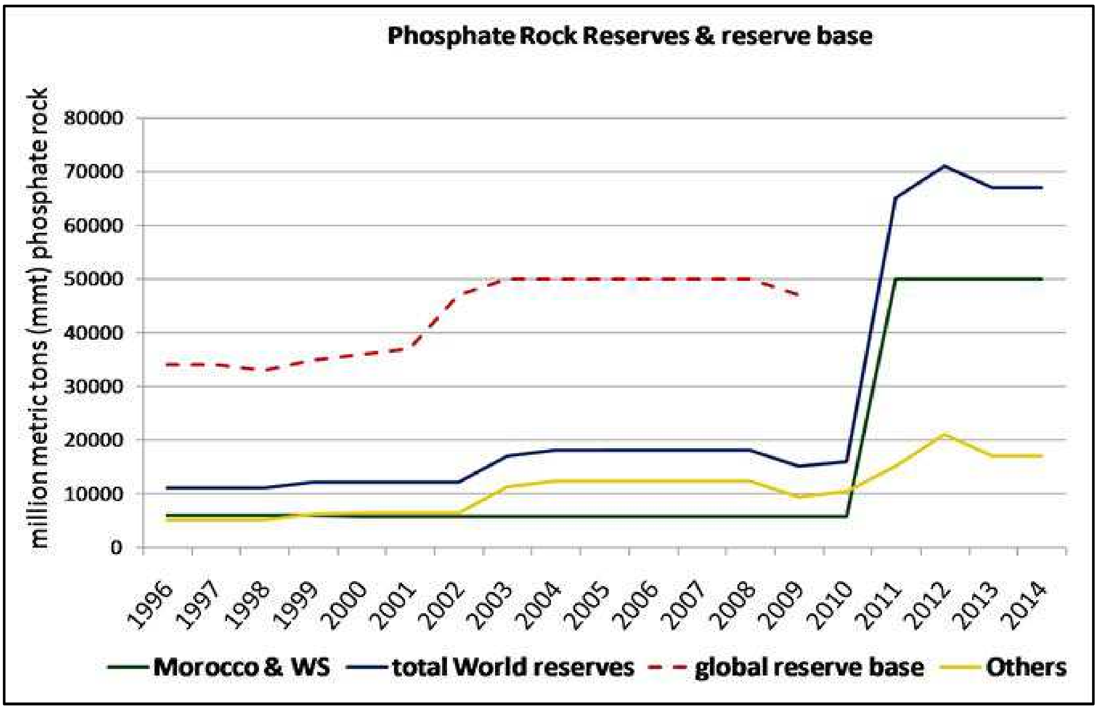

Figure 2: **Global phosphorus reserves and reserve base (until 2009) with data from USGS (2014), own elaboration.**

USGS reported *reserves* and *reserve base* until 2009. Until 2010, global phosphorus reserves had been reported at 18 000 mmt phosphate rock and the *reserve base* until 2009 at around 50 000 mmt phosphate rock. Unfortunately, USGS discontinued the report on the *reserve base* in 2010 (see the dotted red line in the figure 2 with data from USGS, 2014). Coincidently there was a reevaluation and redeclaration of total world reserves in 2011 due to a report of the IFDC in 2010 (Kauwenbergh, 2010). There has been criticism of this reevaluation because of an ambiguity in which *reserves* and *reserve base* are defined and calculated, deviating from former definitions. The main criticism is that the reevaluation is just due to a new definition of *reserves* in the IFDC report, including parts of the former *reserve base* and not denoting new *reserves* (Edixhoven et al. 2013). USGS increased global PR *reserves* to 65 000 mmt phosphorus rock, referring to the IFDC report. *Resources*, which had not been reported by USGS before, were now stated at 300 000 mmt phosphate rock in USGS mineral commodities summaries (USGS, 2014). Formerly, resource classification from USGS defined currently economic deposits as *reserves*, marginally or sub economic deposits as the *reserve base*, uneconomic deposits with a reasonable potential of becoming economic in the future as *resources* and deposits with no reasonable prospect of economic viability in the foreseeable future, as *occurrences* (USGS, 2014; Edixhoven et al. 2013).

The IFDC report (Kauwenbergh, 2010) estimates worldwide reserves at about 60 000 mmt of phosphate rock concentrate. World phosphate rock resources are estimated at about 290,000 mmt, including the unprocessed ore of the reserve estimates. If potential phosphate rock resources are included, the total world resources of phosphate rock may be about 460 000 mmt. Based on these data, and assuming current rates of production, Kauwenbergh (2010) estimates phosphate rock concentrate reserves will be available for the next 300-400 years.

In fact, the IFDC report has profoundly influenced the phosphorus debate, shifting the emphasis from a depletion to a pollution problem (Edixhoven et al. 2013).

For further evaluation and future estimations of global phosphorus depletion I draw on USGS data as the main cited and globally available data only for phosphorus reserves. With respect to the uncertainty of the available data depicted above, it is appropriate to draw a range of reserves estimations. I decide to use 17 000 mmt phosphate rock as an approximated average of the reserves reported between 2003 to 2010 as the lower bound, and 68 000 mmt phosphate rock as an approximated average between 2011 to 2014 as the upper bound. Nevertheless, keeping in mind that estimated resources are higher and potentially economically available in the far future.

2.1.1.*3* ***Phosphorus fertilizer use***

Phosphorus is mainly used as a fertilizer in the agricultural sector. Around 75% (Villalba et al. 2008) to 90 % (Cordell et al. 2009, ref. to Rosmarin 2004, Smil 2002) of global phosphorus production is applied here. The global use of p-fertilizer is depicted in figure 3 with data from IFADATA (2014).

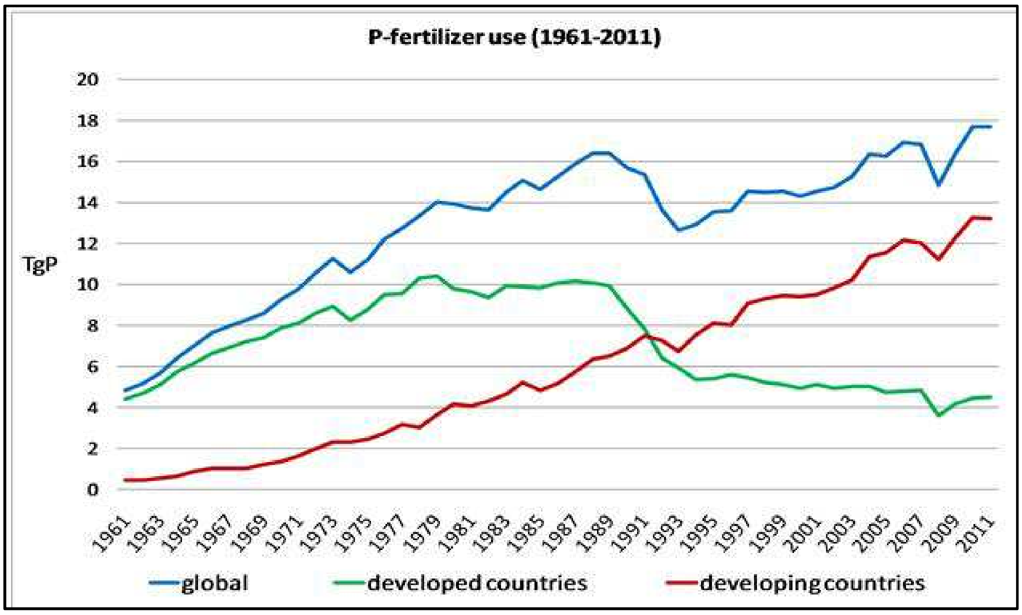

Figure 2: **Global phosphorus fertilizer use with data from IFADATA (2014)**

The blue line depicts the total global p-fertilizer use, the green line the use in developed countries, and the red line the use in developing countries.

Historically, global fertilizer use increased from 1961 to 1989 from almost 5 to 16 TgP per year with a following heavy drop down to less than 13 TgP in 1993. From 1993 onwards, fertilizer use seemed to return to a seemingly near linear increase, up to around 18 TgP in 2011. Phosphorus use as a fertilizer differs between developed and developing countries. Developed countries have exhibited a diminishing growth rate in fertilizer use from the 1960´s to the 1980´s and saturation at 10 TgP per year until 1989, followed by a heavy drop down to less than 6 TgP in 1993, and an ongoing constant or slightly decreasing fertilizer use at something about 5 TgP per year. This feature can be discussed in more detail. The p-fertilizer use in different world regions is depicted in figure 4 with data from IFA-DATA (2014).

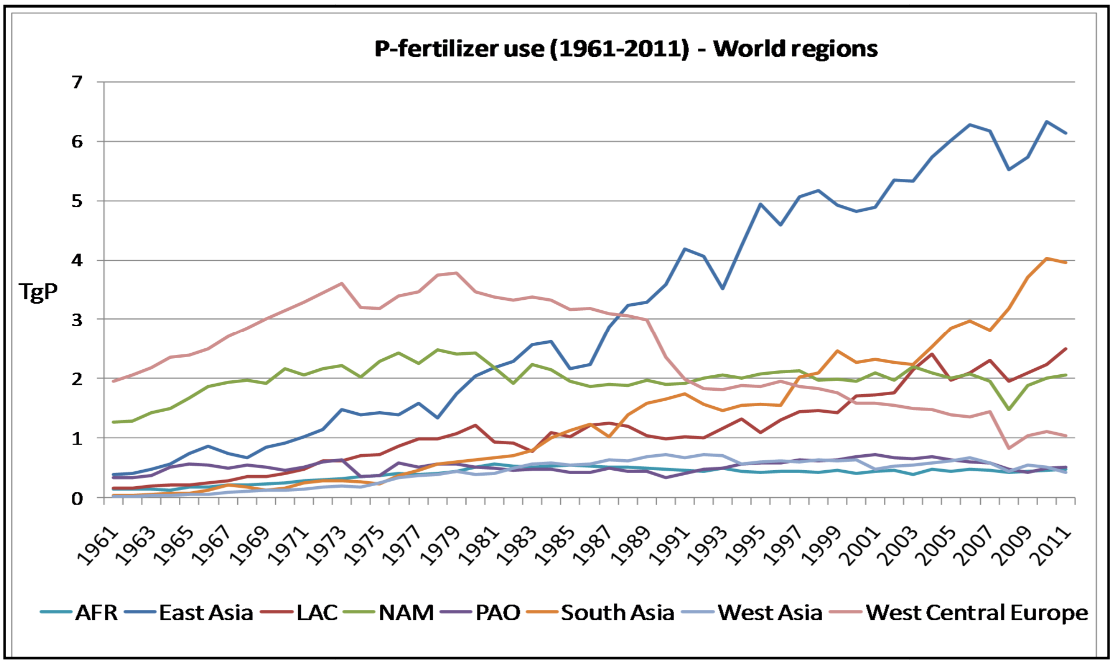

Figure 3: **P-fertilizer use in different world regions with data from IFADATA (2014)**

The heavy drop down in developed countries is caused, to a high percentage, by a strong drop down in fertilizer use in Europe, mainly in central Europe and the former Soviet Union due to the breakdown of economic capacities of the eastern bloc countries after 1989 (figure 4). This includes a potential future increase of phosphorus fertilizer use with the recovery of economic power and the rebuilding of agricultural structures in Eastern European countries. The decrease of fertilizer use can also be observed to a lesser extent in Western European countries, while other developed regions like North America or Australia show a more steady state fertilizer use with a slight tendency to decrease.

In contrast, the fertilizer use in some developing regions strongly increased. In this way developing countries replaced developed countries as the main drivers of the increase in global fertilizer use, becoming the future key drivers for global phosphorus use. The above described tendencies are essential for pathways of global phosphorus fertilizer use in the future.

Within developing regions there are counties and regions which could be referred to as low input regions, like Africa (AFR) and West Asia, with a partly high potential for future agricultural production (AFR)[1]. Other regions can be referred to as medium to high input regions with very different processes of development during the former decades, due to the different historical, socio-

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[1] In this context, it has to be noticed that regions from IFADATA (2014) do not overlay with MAgPIE regions in detail.

economical and political conditions. East Asia, South Asia and LAC particularly, are performing with a strong increase in former years and decades.

Developing countries currently account for 78 % of the worlds phosphorus fertilizer use. Noticeably, just three countries - Brazil, India and China (BIC) - account for 58 % of the world's p-fertilizer use (figure 5).

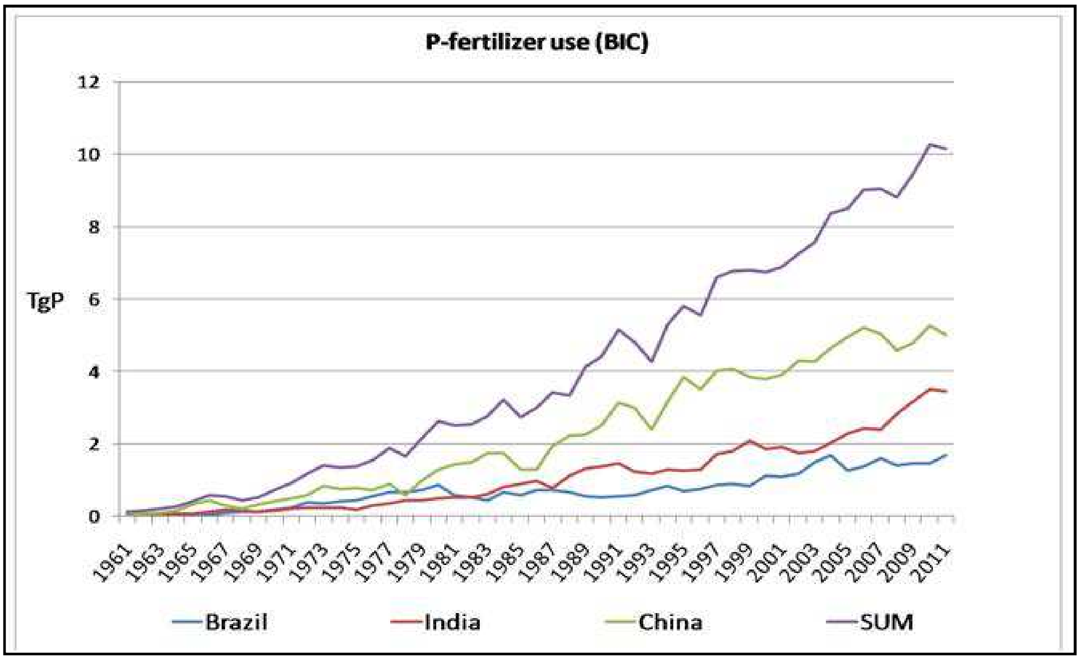

Figure 4: **P-fertilizer use in Brazil, India and China (BIC-Countries) with data from IFADATA (2014)**

With this in mind, future development will strongly depend on the further development of these BIC-Countries, and the geopolitical and socio-economical conditions for development in other developing countries with a high agricultural potential.

2.1.1.*4* *World market prices of phosphorus fertilizer*

As figures 3 and 4 show, in 2008 fertilizer use dropped remarkably in nearly all world regions. This corresponds to world markets prices for phosphorus rock and phosphorus fertilizer (figure 6).

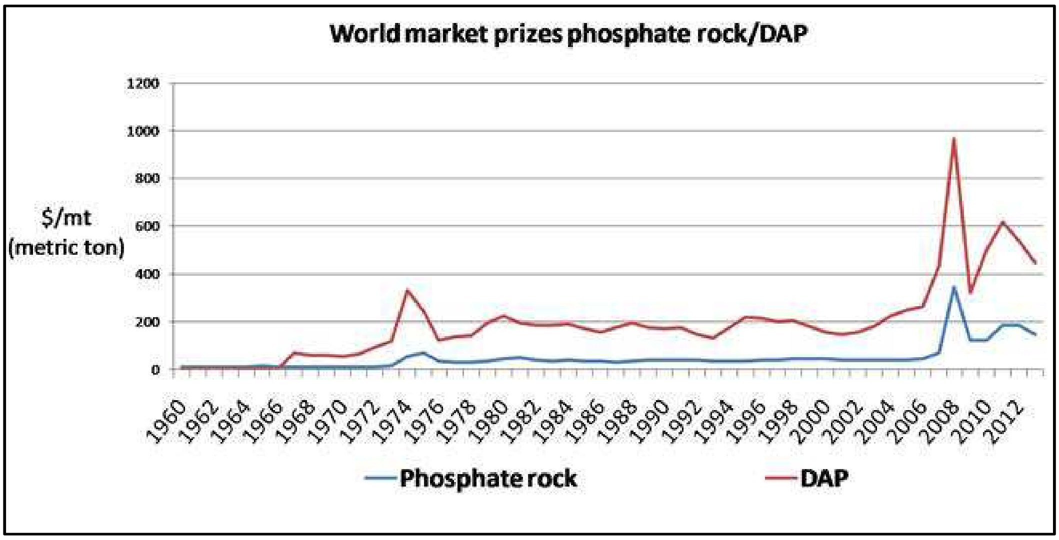

Figure 5: **World market prices for phosphate rock and phosphorus fertilizer (DAP) with data from WORLD BANK (2014)**

As shown in figure 6, there are two price peaks in the timeseries. Both peaks are assumed to reflect impacts of certain economic crises. The first peak is related to the oil crisis in 1974, while the second can be assumed to be caused by the financial crisis in 2008. This can be interpreted as an external shock, resulting from the price peak on fertilizer markets in the global financial crisis with its corresponding financial flows towards "real economy" based investments and "hard facts" like agricultural investments and commodities. Regarding future demand, future prices and the cost of phosphorus production, it can be discussed if the ongoing increase in fertilizer prices over the last ten years could indicate a structural break in global phosphorus prices and a higher relative valuation of phosphorus as agricultural input against the background of future food production in a limited world and growing demands of an increasing global population.

2.1.2 Economics of phosphorus use

2.1.*2.1* *Sustainable use of a non-renewable resource over time*

The use of a non-renewable resource can be optimized by using the total utility from the use it and calculating the total welfare from the resource use by building a social welfare function (Perman et al. 2011, p. 65 ff). To integrate the sustainability criterion an intertemporal utility function has to be built (Perman et al. 2011, p.75), which means to optimize the discounted social welfare over time.

The price of a resource will increase with an ongoing depletion of the resource stocks. The price, relative to other goods especially for capital (as a substitute for all other goods), will normally increase due to resources running out, depending on substitutability. Their resource to capital (other goods) price relation will decrease; while in turn the marginal product of the resource will increase, reducing the marginal product of the capital (Perman et al. 2011, p. 488). The price effect will strongly depend on the elasticity of substitution (EOS) for phosphorus in production processes (here, in agricultural production) but also on the efficiency of phosphorus production due to technology or characteristics of resource stocks. Low substitution possibilities mean that resource depletion pushes up the relative price of the resource (Perman et al. 2011, S.488).

The question is: what can a sustainable use of a non-renewable resource be? Is it possible? To answer this question we need (1) a criterion for sustainability and (2) the description of the material transformation conditions (the production possibilities now and in the future). A customary sustainability criterion is a "non declining per capita consumption, maintained over indefinite time" (Perman et al. 2011, p.488). The future possibilities of production underlie a high insecurity and scenario assumptions for the future world development of socio and environmental system (population, other resources, technology, ecosystems & society). There is a high insecurity about the quantity and quality of resources and reserves. With the exhaustion of high grade reserves, lower grade reserves can be extracted provided that market prices will cover the higher extraction costs. To come to an estimation of future production possibilities and (relative) prices it is necessary to estimate the future economy´s production functions. Sustainability will strongly depend on substitutability between capital and the resource, or high technological progress towards backstop technology, e.g. new extraction technology. Factors that raise extraction costs (depletion of high grade reserves) and factors that lower costs (detection of new reserves and technological progress) dynamically influence future prices.

Perman et al. (2011, p. 491), referring to Dasgypta (1993), list following possibilities of substitution:

1. technological development which increases the productivity of the extraction process;
2. scientific and technical discovery which makes exploration activities cheaper;
3. technological development that increases efficiency in the use of resources;
4. development of techniques which enables the exploitation of low-grade deposits;
5. constant development in recycling techniques, which lower costs and raise effective resource stocks;
6. substitution of low-grade resources for vanishing high-grade deposits;
7. substitution of fixed manufacturing capital for vanishing resources.

Intertemporal optimization of resource use

The intertemporal optimal use of a resource can be calculated by optimization of the social welfare following Hotelling´s rule. Hotelling´s rule defines the intertemporal efficiency condition which must be satisfied by the efficient and welfare-optimizing process of resource extraction: “The discounted unit value of the resource should be the same at all dates.” (Perman et al. 2011, p. 494 ff.)

This is just the general efficiency condition; that the present value of an efficiently managed asset has to remain over time. The rule requires that the growth rate of the price of a resource is equal to the social discount rate, which means that an estimation of the growth rate of the price is a necessary precondition to estimating optimal resource use over time.

The optimization model also supposes a single, known, finite stock of the resource, known prices and extraction costs. These assumptions are usually not given, or often false. In many cases it can be assumed that the total amount of reserves is not known; the stock of resources increases with time due to new discoveries; the share of stock which is economically extractable is unknown and different from the total physical quantity of the stock; research and development as well as technological progress account for a change in extraction costs, the size of the known reserves, economically viable reserves and knowledge about environmental damages and external costs for the resource extraction or use. These details are exceeding the scope of this thesis and are discussed by Perman et al. (2011, p 499ff).

To represent and integrate these extensions within a model, Perman et al. (2011, S. 520 ff.) developed a non-renewable multiperiod model to integrate different assumptions which has not been able to been represented in the mathematical optimization model. The model depicts the demand function depending on price, depicting the price curve within time, the stocks depending on the market demand at a given price and the depletion of stocks within time. With this graphical model some relevant extensions on general assumptions can be depicted, e.g. an increase in interest rate, increase in the size of known stocks, change in resource extraction costs, technical progress, external effects or general market conditions like monopolistic circumstances can be depicted.

For example, an increase in the interest rate will lead to a new price path which starts lower and will grow more quickly, stock extraction will increase in earlier years and total stocks will be exhausted faster. An increase in the size of known stocks will lead to a shift of the price curve downwards and the time until exhaustion is extended. With a sequence of discoveries of new reserves, the size of known reserves increases in a series of single steps and the net price follows a similar path. When demand increases, the demand curve shifts outwards, the price curve shifts upwards and the time until exhaustion is shortened. A change in resource extraction costs requires that the new level of gross price in t=0 must be greater. It will remain above the original gross price level for a while, but will at some time before the resource stock is exhausted fall below the old price path. The time to complete resource exhaustion is lengthened.

2.1.2.2 Global phosphorus supply

The supply of phosphorus for agricultural use is substantially dependent on (a) phosphorus reserves, (b) the extraction costs of phosphorus rock and, if existing, (c) the costs of alternative backstop technology, e.g. recycling of phosphorus from sewage systems.

Currently known and expected reserves and reserve base have been described above in chapter 1.1.1.2. With ongoing extraction and exhaustion of reserves, extraction costs are rising due to substitution of high grade ores by lower grade ores or higher transportation costs associated with minor advantageous mines or deeper lying reserves. Today’s extraction takes place primarily in open pit mining, other reserves lying deeper under earth requiring othercost-intensive technologies.

Van Vuuren et al. (2010) describe the high uncertainty in estimating the availability of underground resources with respect to (i) the likelihood of the discovery of additional resources, (ii) technology development and future production costs, determining the realistically extractable resources at given production costs. On this basis they calculate production costs for different resource categories indicating the increase of extraction costs with ongoing exhaustion of increasingly disadvantaged reserves (table 2).

Production costs for different resource categories. Costs are used as indication of increasing production costs not as exact predictions

	Cum. Prod. 1970-2006	Reserve 1	Reserve 2	Reserve base 1	Reserve base 2	Add. Resource	Add. USA	Ocean USA
Production costs (US$/ton)	25-40	35-70	45-90	85-100	125	150	200	500
Regions with lower costs	Africa, US, Australia (lower side of range above)							

Table 2: Production costs for phosphorus, from Van Vuuren et al. (2010)

Further aspects, they emphasize, are the extraction efficiency and whether phosphorus in different types of resources can be fully extracted. This is dependent on the mine, the characteristics of the ore and the mining technology (Van Vuuren et al. 2010).

In general, supply of a non-renewable resource like phosphorus is dependent on the behavior of extraction costs with respect to technological progress and/or the discovery of new reserves. This can be described as follows (fig.7)

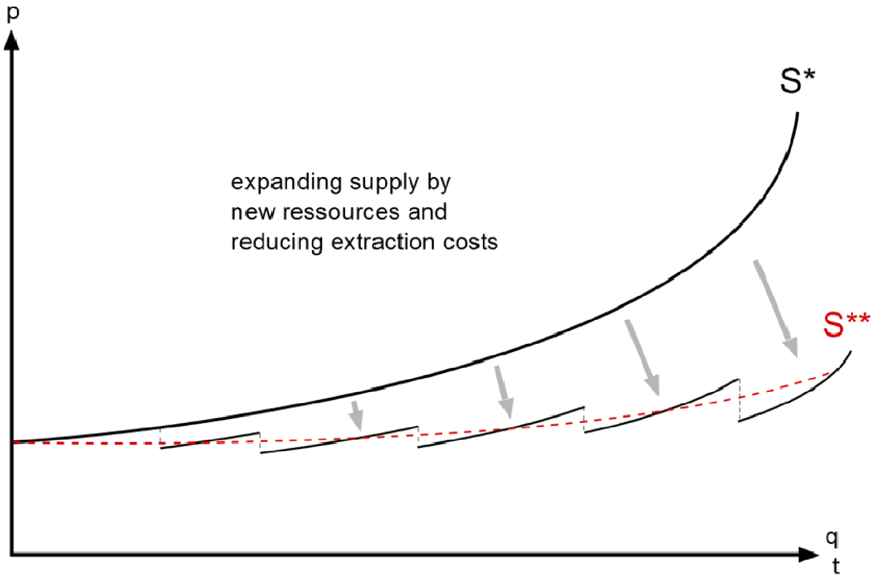

Figure 6: **Expanding supply by new resources, thereby reducing production costs, following Perman (2011)**

Over time, respectively with increasing production, extraction costs are rising due to the circumstances described above. This is depicted in figure 7 by the supply function S*. By technological progress (e.g. new mining technology or extracting power) the supply function can be shifted downwards due to reduced extraction costs. Similarly, the discovery of new resources can push the supply function downwards by reducing production costs due to new, cost-effective exploitable resources or by a higher market supply due to increased extraction activities (supply function S**).

Van Vuuren et al. (2010) calculated time series of future production costs of phosphorus caused by depletion of phosphorus resources under different global future pathways of the Millennium Ecosystem assessment (MEA) and under different assumptions of reserves and reserve base for different world regions (see figure 8).[2]

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[2] Regrettably, the MAgPIE model does not allow for an estimation of phosphorus productions costs on the base of given inputs and arguments. A discussion of future phosphorus prices caused by production costs will be restricted to some further thought models.

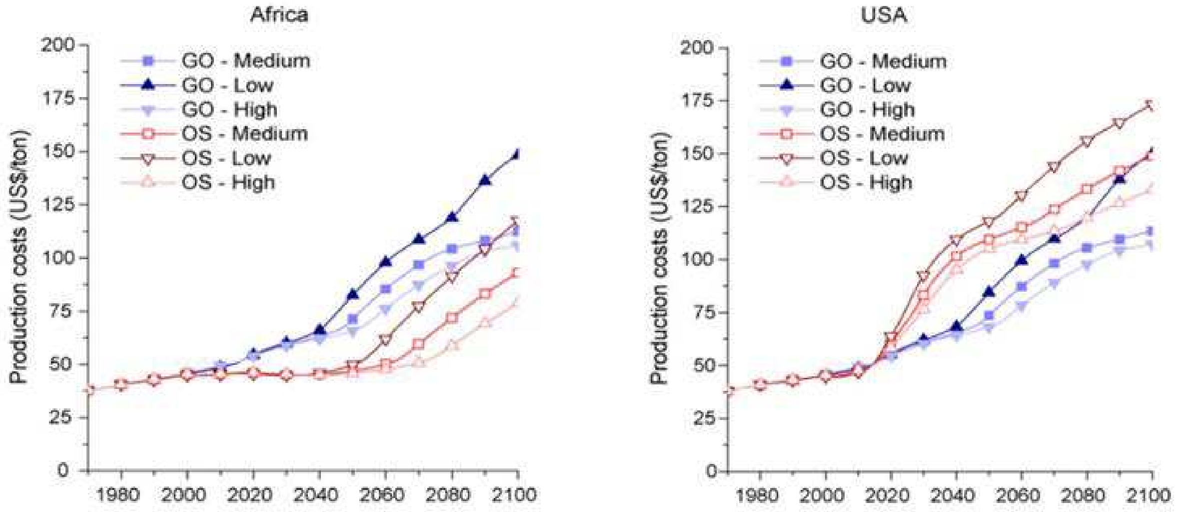

Figure 7: **Phosphorus production costs, depending on reserves estimations and phosphorus use scenario, from Van Vuuren et al. (2010)**

There will remain a great range of influence by external shocks, like the 2008 four hundred percent increase in global phosphorus fertilizer prices by market interferences due to the world financial crisis. Nonetheless, there will be still some consistent factors of influence. One relevant determining factor will be the costs of a backstop technology.

The existence of a backstop technology becomes central to the discussion of possibilities of a global management of phosphorus use because recycling technology in line with global recycling management systems will be essential for global management of phosphorus reuse, due to the limited possibilities of substitution of phosphorus in the global phosphorus cycle. There will be possibilities to work on phosphorus use efficiency on different scales, but the reuse of phosphorus and the limitation of phosphorus losses to environmental systems will be a main matter of concern. The costs and the efficiency of future recycling systems will strongly affect phosphorus availability and total phosphorus prices. The principal model is depicted in figure 9.

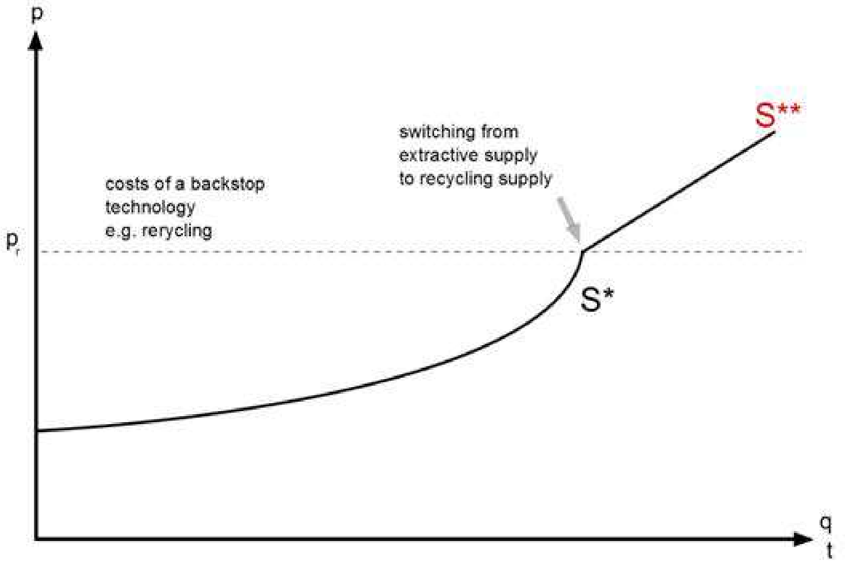

Figure 9: **Introduction of a backstop technology and impacts on the supply curve, Permann et al. (2011).**

S* can be considered as the price curve of supply. Over time, or with an ongoing quantity of production, the price is increasing due to increasing extraction costs and depletion of reserves. P_r is the price of a backstop technology (e.g. recycling technology) or the costs of an advanced and complex global phosphorus management. The increase in the price (and quantity) of phosphorus will follow the depicted S* curve until the price of given extraction technology meets the price of the given backstop technology. Further on, the price curve will follow the indicated S** picture due to a reduction of marginal costs by the alternative technology and a surplus supply by this economical alternative source.

In this context, it can be discussed with respect to a global management of phosphorus if the subsidization of a backstop technology is sensible, regarding the depletion of global reserves (not regarding prevention of serious ecological consequences). It can be argued that the implementation of a subsidized recycling system could reduce production costs and prices of phosphorus provision and thereby increase phosphorus use, and therefore the depletion of reserves. In fact, this is a rather theoretical consideration. It is not realistic that the promotion of recycling technology will influence phosphorus supply in a relevant quantity, unless the level of scarcity is much greater. In another respect, the ecological impact of the provision of recycling technology can be assumed to be much more relevant. With respect to ecological consequences (and `these´ global external costs of phosphorus use), the provision of a global phosphorus management system including recycling technology and improved sewage systems with a much higher efficiency will be necessary to handle an increasing global phosphorus turnover through global nutrition and environmental systems.

2.1.2.3 Global phosphorus demand

For the projection on how the global demand on phosphorus could evolve in future, it is appropriate to discuss special attributes related to the use of phosphorus as a fertilizer in agriculture and global development pathways. Metson et al. (2012) considered the contribution of dietary habits and global population increase on phosphorus demand. They identified principally variables for the increase of phosphorus demand in the past, i.e. (1) the increase in population which require an overall increase in food production, (2) changes in diets to more p-intensive products like meat, and (3) changes in agricultural methods like intensification of fertilizer inputs to increase the yield (Metson et al. 2012).

Economically, phosphorus demand will be determined by the price elasticity of demand (fig. 10).

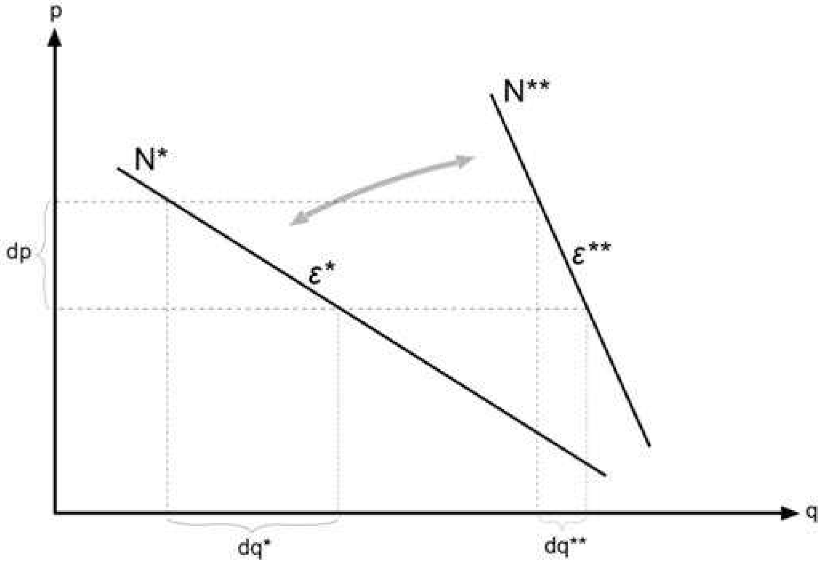

Figure 10: Concept of price elasticity, from Koester (2010)

The price elasticity of demand is defined as the change in demand relative to the change in price. A high elasticity (a flatter curve) means that a change in price has a bigger influence on the change of demand. A steeper curve means that a change in price does not influence the demand to such an extent. This means elasticity is lower. In general, the price elasticity of goods is as smaller, the lower the substitutability of a good is; is higher, the complementarity of a good is; and is smaller, the higher the share of expenditure for the good is (Koester, 2011). This scheme is depicted in figure 10. The figure shows two different demand curves with different price elasticities of demand. Demand curve N* has a high elasticity of demand compared to changes in prices, demand curve N** has a low elasticity of demand regarding changes in prices.

From this general feature, some estimates on the price elasticities of demand can be derived for our particular phosphorus case. On first reflection, it could be sensible to distinguish short-term elasticity versus long-term elasticity. It can be supposed that elasticity in the short-term is higher due to buffering capacity for phosphorus and the low grade of fertilizer which is refound in crop growth. There is limited necessity to bring out phosphorus fertilizer each year on most agricultural soils. So elasticity wilt rather correspond to ε^*. In the long-term, price elasticity is very high due to the non-substitutability of phosphorus for plant nutrition and the necessity to bring in phosphorus fertilizer for an upgraded agricultural production. So it can be guessed that elasticity rather resembles ε^{**}. Secondly, it can be useful to differentiate between longstanding used and fertilized agricultural soils with a high fertility due to the accumulation of phosphorus in agricultural soils and not in upgraded non-fertilized agricultural soils. It can be supposed that for upgraded longstanding used agricultural soils the price elasticity is higher (ε^*), which means the demand curve is flatter than on “fresh” soils not yet fertilized, and with a great need for fertilizer input and a low buffer capacity and, therefore, a lower elasticity (ε^{**}). This reasoning and image can be extended to agricultural management systems. Where agricultural systems are more integrated, regarding, for example, agroecology and sustainable management systems (including sensible application of fertilizer), it can be supposed that elasticities will be higher than in extractive, non-sustainable management systems. Thirdly, a reflection on elasticity of demand concerning global development scenarios is applicable. Population growth and changing dietary habits as well as economic scenarios are the main influencing factors for the global phosphorus cycle and fertilizer use for agricultural production. It can be stated that with increasing population and changing diets towards more animal-based meals, elasticity becomes smaller and the demand curve turns more to N**. This is more relevant to a growing population due to the absolute non-substitutability of phosphorus for plant growth, and less for dietary habits, because in meat consumption there is strong compound of income elasticity in addition to price elasticity; therefore reducing animal-based diets in favor of vegetable-based diets.

The information about elasticities or the reflection and estimation of their general behavior is necessary to size up progression of demand in response to external factors. Which are the particular characteristics in this regard? As a non substitutable element for plant nutrition, agricultural production is essentially dependant on phosphorus as a fertilizer input. Hence, the elasticity of demand plays a major role. Fortunately (or unfortunately, concerning the limited effects of fertilizing regarding potential yields) the production function of phosphorus in agricultural production is a typical curve of diminishing marginal yield with a positive yield with no fertilizer input. This ensures a basic yield when fertilizer input is low. As an elasticity relaxing characteristic, the application of phosphorus fertilizer is (in contrast, for example, to nitrogen) less dependent on time, due to the buffer capacities of soils concerning phosphorus. Firstly, it is not necessary to add phosphorus fertilizer every year. Secondly, the capacity of soils to restore phosphorus over years of non-fertilizing increases with the endurance of fertilizing by building up a buffer capacity.

2.2 The global phosphorus cycle and phosphorus dynamics in the soil

One of the main aims of this thesis is to provide an estimation of phosphorus flows and stocks within the global phosphorus cycle under the special representation of phosphorus accumulation in the soil. Therefore, I will describe the phosphorus cycle within its natural and its anthropogenic influenced dimensions in the following sections. Particular emphasis will be given to the phosphorus dynamics in the soil, since this has to be accurately captured in the soil accumulation model developed in this thesis.

2.2.1 The natural phosphorus cycle

The natural Phosphorus cycle includes phosphorus flows over large global distances (Liu et.al. 2008, Fillipelli 2002) and, due to its geological dimensions, a very long timescale (Bouwman et al. 2009, Fillipelli 2002). It is based on biogeochemical and physical processes and can be divided into inorganic and organic compartments (Fillipelli 2002, Liu et.al. 2008). Within the organic phosphorus cycle from soil to plants to animal and back to soil, land and water-based cycles can be differentiated (Liu et al. 2008).

The biggest compartment of the global P-Cycle is the content of phosphorus in the parent rock of the earth´s crust from which weathering of the soil by natural chemical, physical and biological processes makes the phosphorus plant available (Mackenzie et al. 1998, Mackenzie et al. 2002). Phosphorus is released mainly from apatite minerals (Fillipelli 2002). From the parent rock it enters the organic sphere by weathering of soils, thereby becoming plant available and returning via the food chain to soils (Liu et al. 2008).

Geophysical components run over some million years starting from parent rock via physical, chemical and biological weathering. By leaching, erosion and physical transport, phosphorus is transported to waterways entering the water cycle and forwarded to the sea where it forms insoluble phosphates. These are sedimenting in the oceans incorporated in sediments by geological pressure within large timescales (Liu et al. 2008, Fillipelli 2002)

Erosion and runoff of soil material transfers phosphorus by rivers to the ocean in two different forms; particulate and dissolved (fig. 11).

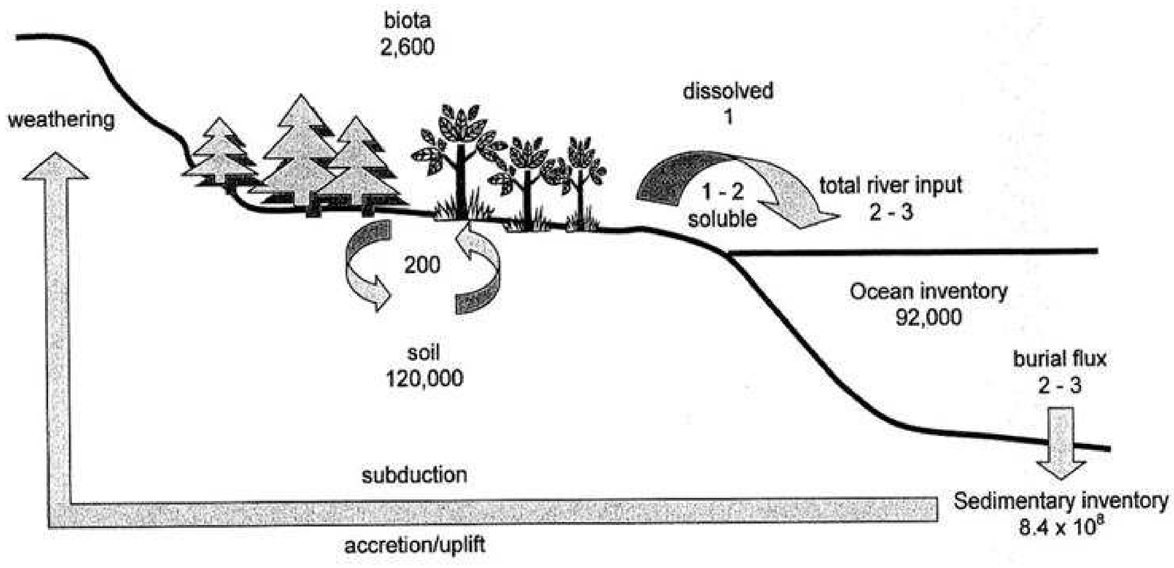

Figure 8: The natural phosphorus from Filipelli (2002)

Much of the P eroded from continents is delivered relatively unaltered to the oceans, where it is sedimented on continental margins and in the deep sea, and re-enters the geological cycle (Mackenzie et al 1998, Mackenzie et al 2002, Fillipelli 2002). In the marine system P acts as a limiting nutrient to biological productivity because of very low P-concentrations in surface waters (Fillipelli 2002).

Considering the low solubility, leaching of soluble phosphorus plays a minor role in phosphorus losses from the soil, but surface losses by runoff and erosion (wind and water) plays a major role by the geologically long distance transportation of phosphorus. The cycling of organic phosphorus between soil and biosphere plays an important role for plant growth because of a rapid turnover and availability (Bouwman et al. 2009).

In biological processes - by birds catching fish - there has been a concentration process of phosphorus which has built historical reserves of guano, which played a role in the historical use of phosphorus in the beginning of industrialization for fertilizing (Liu et.al. 2008)

In contrast to the global C and N – cycle, and as a unique characteristic among biogeochemical cycles of elements, the phosphorus cycle has no gaseous compounds, a very small atmospheric component and there is nearly no atmospheric link from ocean to land. (Mackenzie et al. 1998, Mackenzie et al. 2002, Smil 2000, Liu et al. 2008).

Table 3 summarizes quantifications of stocks and flows within the global natural phosphorus cycle as calculated and estimated by different authors. These data will be discussed with my estimations of the model in chapter 5.

Issue	Quantity or range (TgP/year)	Source
Sea dust	4.6	Liu et al. (2008)
Weathering of calcium phosphate minerals to soils	13	Liu et al. (2008)
Global phosphorus losses from lithosphere into freshwater	18.7 - 31.4	Liu et al. (2008)
Eroding phosphorus carried into the atmosphere	3.0	Liu et al. (2008)
… there from 25% redeposited on cropland and other areas	0,75	Liu et al. (2008)
Phosphorus transported to the ocean by water	12 to 22	Liu et al. (2008), Emsley (1980), Meybeck (1982), Richey (1983), Sposito (1989) and Howarth et.al (1995)
Pre-human flux to the oceans	2-3	Fillipelli (2002)
… there from dissolved	1	Fillipelli (2002)
… there from potentially soluble	1-2	Fillipelli (2002)
Phosphorus pool in the ocean and sediments	27 000 000 – 840 000 000	Liu et al. 2008 ref. on Emsley 1980, Richey 1983, Grove 1992, Filipelli 2002; Smil
from which sea water contains	80 000 to 120 000	Liu et al. 2008
Amount of phosphorus in the world's soils	90 000 - 200 000	Liu et al. 2008 ref. to Emsley 1980, Meybeck 1982, Richey 1983, Filipelli 2002
Available in soil to biota	1 805 to 3 000	Liu et al. 2008 ref. on Grove 1992, Emsley 1980 and Richey 1983
Soil/biota systems on continents	122 600	Fillipelli (2002)
… there from in soils in different forms/continent	120 148	Fillipelli (2002)
… there from in biota systems/continent	2 452	Fillipelli (2002)

Table 3: Quantifications of stocks and flows within the global natural phosphorus cycle

2.2.2 The anthropogenic phosphorus cycle

Within the modern anthropogenic phosphorus cycle, processed mineral phosphorus becomes a routinely used fertilizer for agricultural soils and acts as an important plant nutrient applied on cropland and pastures. The global food production system is nowadays most dependant on non-renewable mineral phosphorus reserves. The primary source of phosphorus for fertilizers comes from rock phosphate, generally phosphate-rich sedimentary rocks (Fillipelli 2002, Liu et al. 2008, Cordell et al. 2009). The anthropogenic use of phosphorus from sedimentary rock implies that biogeophysical processes of geological timescales and associated physical mass flows are heavily altered. This is related to strong increases in mass flows and the depletion of reserves.

Liu et al. (2008) and Cordell et al. (2009) trace phosphorus flows through the global food production and consumption system in a Substance Flow Analysis (SFA). Cordell et al. (2009), from the mine to consumption; whereby they identify losses throughout the system. Liu et al. (2008) examine the global natural and anthropogenic phosphorus cycle with special attention to phosphorus movement in the soil system (which will we illustrated in depth in section 1.2.3).

According to Cordell et al. (2009) relevant industries and processes within the anthropogenic phosphorus cycle are mining, fertilizer production, application in agriculture, crop harvesting, food and feed processing, food and feed consumption, excretion and the respective leakages from the system to environmental systems. Liu et al. (2008) report that, within the anthropogenic phosphorus cycle, phosphate rock is initially milled and converted into phosphoric acid (P_2O_5) to be processed to phosphorus fertilizers and applied to croplands (and, in minor part, to grasslands). Minor industrial applications represent just about 3% of the total consumption.

Next to the natural phosphorus cycle, the relevant stocks and flows within the anthropogenic phosphorus cycle are phosphate mining from phosphate rocks, fertilizer production and use, stocks and flows within the industrial food and sewage systems including land use systems and animal production as well as waste dumping, losses to the environment and sanitation management. The human intensified global phosphorus cycle is depicted in figure 12 (Liu et al. 2008).

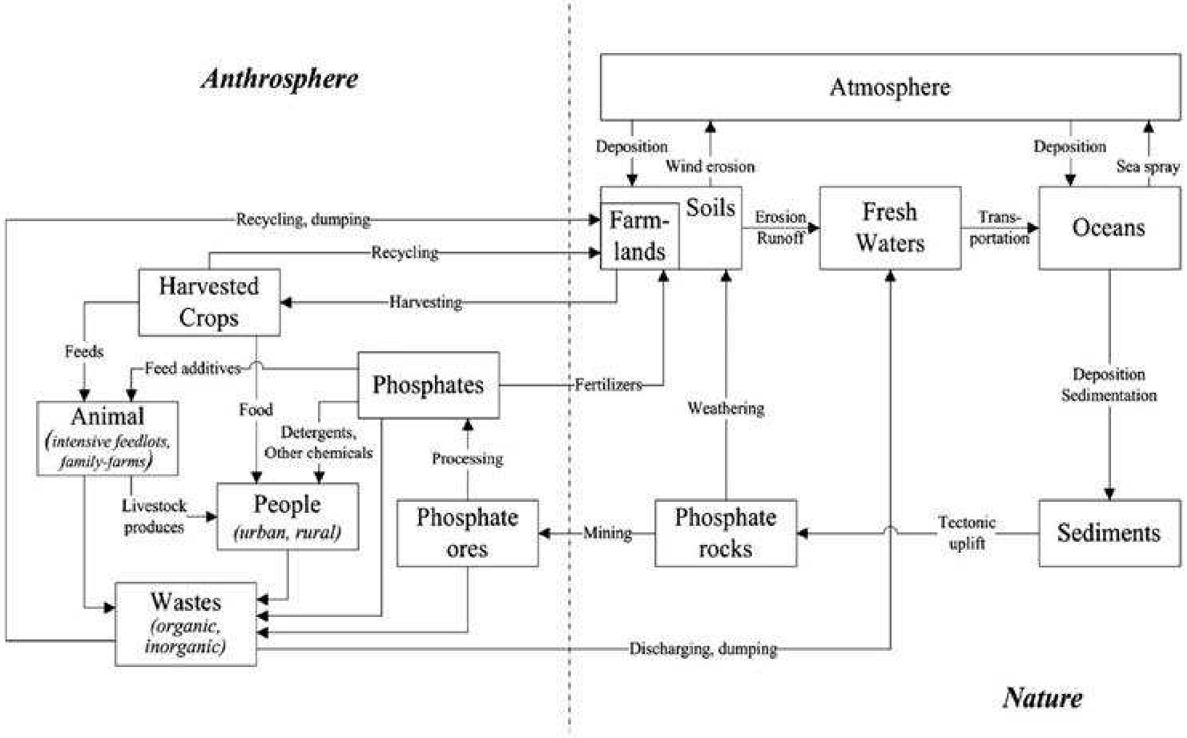

Figure 9: The human intensified global phosphorus cycle from Liu et al. (2008)

A quantification of ranges of stocks and flows within the anthropogenic influenced phosphorus cycle by different authors is given in table 4:

Issue	Quantity and range (TgP/year)	Source
Phosphorus reserve base	6 500	Villalba et al. (2008) ref. to USGS (2006)
Phosphorus reserves	2 400	Villalba et al. (2008) ref. to USGS (2006)
Phosphate mining	17.5-22.4	Cordell et al.(2009), Villalba et al. (2008)
Use for fertilizer production	14.1-14.7	Cordell et al.(2009), Villalba et al. (2008)
Other industrial use and losses	1.8-4.75	Cordell et al.(2009), Villalba et al. (2008)
Livestock feed additives	0.9-1	Cordell et al.(2009), Liu et.al. (2008)
Fertilizer use on arable soils	14	Cordell et al.(2009)
Total animal manure	15-20	Liu et.al. (2008), Smil (2000), Cordell et al.(2009)
Manure to arable soils	2.5- 8	Liu et.al. (2008), Cordell et al.(2009)
Crop uptake	12-12.7	Cordell et al.(2009), Liu et.al. (2008)
Crop residues to soil	2-2.2	Cordell et al.(2009), Liu et.al. (2008)
Crop residues for feed	1.1	Liu et al. (2008)
Industrial byproducts and kitchen waste to animals	1	Liu et al. (2008)
Erosion losses from arable soils	8-19.3	Cordell et al.(2009), Liu et al. (2008)
Crops harvested for food, feed, fiber	7	Cordell et al.(2009)
Losses from crops to environment	3	Cordell et al.(2009)
Crops feed to animals	2.6-2.9	Cordell et al.(2009), Liu et al. (2008)
Post harvest losses	0.9	Cordell et al.(2009)
Total feed to animals (non grazing)	6	Liu et al. (2008)
Crops for food	3.5	Cordell et al.(2009)
Food use to human nutrition	3	Cordell et al.(2009)
Organic waste from food	1.2	Cordell et al.(2009)
Organic waste reflow to arable soils	0.2	Cordell et al.(2009)
Organic waste to environment	1	Cordell et al.(2009)
Pasture grazing to animals	12.1	Cordell et al.(2009)
Animals to food	0.6	Cordell et al.(2009)
Total human biomass	3	Liu et al. (2008)
Human excreta	3-3.3	Cordell et al.(2009), Liu et al. (2008)
Human excreta to environment	2.7	Cordell et al.(2009)
Animal manure to environment	7	Cordell et al.(2009)
Total organic fertilizer on croplands	6.2	Liu et al. (2008)
Total input to croplands	20	Liu et al. (2008)
Total input to soil (all)	18.5	Villalba et al. (2008)
Net accumulation	7.3	Liu et al. (2008)
Total flow to inland/coastal waters	4-22	Cordell et al.(2009), Cordell et al. (2008), Liu et al. (2008), Fillipelli (2002)

Table 4: Quantification of ranges of stocks and flows within the anthropogenic influenced phosphorus cycle

Besides the depletion dimension of the global phosphorus problem (which is elaborated intensely in chapter 1.1.1), the environmental dimension of the problem is of crucial importance.

Phosphate rock contains cadmium, uranium and other heavy-metals, so the basic raw material has to be processed by leaching techniques to separate P from the toxic heavy metals (Fillipelli 2002). Thereby phosphorus fertilizer production is linked with harmful carbon emissions, radioactive by-products and heavy-metal pollutants (Cordell 2009).

Phosphorus is brought to agricultural croplands and pastures. The agricultural use of phosphorus fertilizers is related to the non-productive, environment-harming loss of phosphorus from agricultural soils and the influx of phosphorus to above-ground waterbodies; mostly by runoff, wind and water erosion (Fillipelli 2002, Cordell et al. 2009, Liu et al. 2008). Also, phosphorus from food consumption, animal waste and manure systems ends up in waterbodies by excretion via sewage systems and wastewater. From waterbodies, phosphorus is transported via rivers downstream to the oceans. In above-ground waterbodies and marine ecosystems, phosphorus leads to eutrophication. (Fillipelli 2002, Cordell et al. 2009)

A second human contribution to phosphorus release is deforestation and loss of soil and soil organic matter. Particularly, the burning of vegetation converts P plant matter into ash from which P is rapidly leached from the ash and transported as dissolved loads in rivers (Fillipelli 2002).

Human activity contributes to higher loads of phosphorus bearing particles and dissolved P from land to the ocean within the range of 4-6 Tg P per year, where phosphorus is influencing coastal zone and marine ecosystems via eutrophication (Fillipelli 2002).

According to Liu et al. (2008) the different socioeconomic complexes of environmental impacts can be summarized as follows: (1) mineral reserve conservation and environmental pollution impacts of phosphorus mining, (2) soil erosion losses of phosphorus and impacts on soil fertility degradation, (3) animal waste management and agricultural phosphorus recovery management, (4) human excreta and sanitation management for phosphorus recovery, (5) eutrophication of waterbodies in different ways.

This goes in line with an intense discussion on global physical, biological and other limitations of the maintenance of the earth system as a whole and its different subsystems, as well as on future sustainable ways to meet global challenges like climate and environmental change. Rockström et al. (2009) describe planetary boundaries of the Earth system which define the safe operating space for humanity. The planetary boundaries concept is trying to identify control variables and critical values. The global phosphorus cycle is one of these relevant biophysical subsystems, closely bound to the nitrogen cycle ranging on position four of the global challenges in keeping resilience within the whole global earth system.

Rockström et al. (2009) define the phosphorus inflow to oceans as the control variable to avoid a major oceanic anoxic event, with impact on marine ecosystems and unpredictable further implications on global biogeochemical systems, and potential mass extinctions of marine life. Presently, from nearly 20 million tonnes of phosphorus mined, around 8.5 to 9.5 million tonnes are running down rivers to the oceans – approximately eight times higher than the natural background rate of influx. Rockström et al. (2009) estimate that by a greater than ten times higher than natural phosphorus influx rate a major anoxic event becomes likely. That leads to threshold of some 11 million tonnes of phosphorus as a boundary that should not be exceeded (Rockström et al. 2009).

2.2.3 Phosphorus dynamics in the soil

From my modeling approach to represent phosphorus accumulation in the soils under agricultural use, it is necessary to rebuild phosphorus dynamics in the soil within the soil phosphorus accumulation model (SPAM) and to fix the model to qualitative data as much as possible.

The distribution, dynamic and availability of phosphorus in soil is controlled by a combination of biological, chemical, and physical processes (Liu et al. 2008). P is released from the mineral bedrock by biological, chemical and physical weathering. P in the soil exists in mineral forms like apatite - a calcium phosphate - depending on the pH (Liu et al. 2008). Soil phosphorus is not as mobile as nitrogen and has a slow diffusion rate. Phosphorus released by weathering is usually rapidly immobilized into insoluble forms or absorbed by soil matter (Brady 1990, Scheffer & Schachtschabel 1992). Regarding this, a bigger part of the phosphorus content of soil is unavailable to plants.

A minor fraction is directly available as dissolved phosphate (PO_4^{3-}). The different available forms change with time and soil development (Liu et al. 2008). When phosphorus is applied as fertilizer a considerable proportion of this applied phosphorus is transformed into insoluble calcium, iron or aluminum phosphates (Liu et al. 2008). Plants can contribute in making soil phosphorus available by reducing the pH through the excretion of phosphates and organic acids. Also, soil microbes and symbiotic fungi play an important role in making phosphorus plant available (Fillipelli 2002). An overview of chemical processes and biological interactions are described in Bouwman et al. (2009).

We can roughly group the different forms of soil phosphorus into readily bio-available and not readily bio-available forms. The first group includes P in apatite minerals and P absorbed onto iron and manganese oxhydroxides (“occluded” P). The second group includes dissolved phosphate ions in the soil solution and phosphate ions absorbed onto soil particles (“non-occluded” P), as well as P incorporated in organic soil matter. It is necessary to know that both fractions are in a state of equilibrium (Fillipelli 2002, Fillipelli 2008, Liu et al. 2008). The equilibrium concentration of phosphate in the soil solution is low - below 5 µMol (Condron and Tiessen 2005; 2008) - but can be replenished from the inorganic, organic and microbial phosphorus pool in the soil (Liu et al. 2008).

Bouwman et al. (2009) described the different compartments of phosphorus in the soil as in the figure below (figure 13).

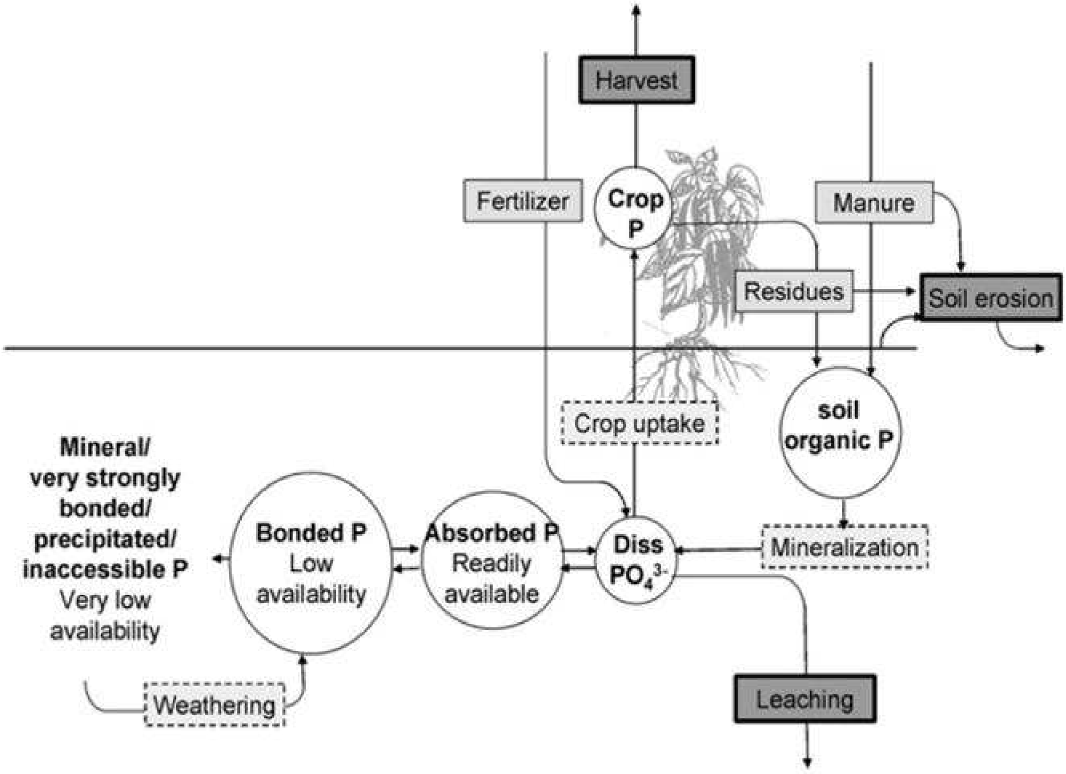

Figure 13: Phosphorus cycle between soil and plant from Bouwman (2009)

The two main determinants, that control the availability of soil phosphorus to plants are the concentration of phosphate ions in the soil solution and the soil P-buffer capacity; the ability of the soil to replenish these ions in the soil solution when plants remove them. The P-buffer capacity of soils differs (Sattari et al. 2012).

Due to the high absorption capacity of phosphorus, added fertilizer-P is first filling up a soil stock before becoming plant available in the full range. Most agricultural soils in North America and Europe have exceeded this level of P-content. Phosphorus accumulated in agricultural soils because the advised phosphorus fertilizer amounts lay a long way above the extracted amounts by harvests. To replenish soil-stocks of phosphorus it is necessary to replace withdrawals by harvest. The situation in most developing countries and emerging economies is contrasting. To reach a highly productive status of soil-fertility it is necessary to fill up soil phosphorus stocks. It is relevant to reproduce this demand in future phosphorus supplies when modeling interactions in the global phosphorus cycle (Liu et al. 2008, Bouwman et al. 2009).

The fertilizer recovery of phosphorus in crops is often only around 10-20% in the short term, when soil accumulation is low. A substantial part of applied phosphorus accumulates in the soil as residual phosphorus, building up the soil phosphorus status (Sattari et al. 2012). This increases the more or less plant available compartments of phosphorus in the soil, thus increasing the phosphorus use efficiency (PUE) of fertilizers. In this way, P recovery can slowly increase up to values of around 90% (Bouwman et al. 2009).

2.3 State of research in modelling the global phosphorus cycle

2.3.1 Spatially explicit soil phosphorus data and other soil information for modelling

As described in the previous sections, the total content of phosphorus in the soil, as well as the phosphorus availability to plants is dependent on a large number of variables interrelated in a complex manner (i.e. parent rock, soil formation, chemical and physical conditions, management practices).

Due to this, there is a lack of spatially explicit soil phosphorus data like phosphorus content, different pools or extractability, or on potential limits to plant growth and agricultural activities. Nevertheless, there have been different efforts to compile global spatial explicit data for soil phosphorus for modeling approaches and geographical information. Omuto et al. (2013) provide the latest overview of recent soil information resources, soil data and digital soil mapping. At a global scale there are different promising approaches to providing soil information in general and for soil phosphorus data specifically. Even though none of them is yet able to provide spatial explicit data that could be used for providing an initial phosphorus content and soil phosphorus extraction by agricultural activities. The merging of different soil information data can promote future useful data for modeling the global phosphorus cycle. This would be of great interest. Therefore, the current state of soil information regarding soil phosphorus is outlined here.

The International Soil Reference and Information Center (ISRIC) provides a global dataset of derived soil properties on a 0.5 by 0.5 degree grid containing twenty-two derived soil parameters but no explicit data on soil phosphorus content or availability (Batjes, 2005). The ISRIC – World Inventory of Soil Emission Potential (WISE) – also provides a database containing a homogenized set of soil data which can be used for a broad range of environmental research (Batjes, 2008). Recently there has been combined efforts by the Food and Agricultural Organization of the United Nations (FAO), the International Institute of Applied System Analysis (IIASA), the ISRIC-World Soil Information, the Institute of Soil Sciences – Chinese Academy of Sciences (ISSCAS) and the Joint Research Center of the

European Commission (JRC) to update the FAO-UNESCO soil map of the World (FAO 1988). They jointly provided the harmonized soil database (Nachtergaele et al. 2012).

Batjes (2011b) provides an overview of soil phosphorus data from a large international soil database to prove the feasibility of extracting soil-p data for major soil types for possible use in model-based assessments of resource scarcity. He provides an inventory of extractable soil phosphorus (p-Bray, p-Olsen, p-Mehlich, p-Water) and p-retention with the aim to assign representative p-values to broad soil groups and link derived data to global soil geographic databases. Batjes (2011b) compiles median and mean p-values for each FAO soil group depth layer but with high Coefficients of Variation (CV) in excess of 100% (up to 224%) between most soil characterizing variables and soil-p contents. He observed smaller CVs for p-retention in major soil groups from 20% to 72%.

Considering that limited p-availability to crops may be due to p-deficiency or a strong phosphorus retention in soils, Batjes (2011a) derived p-retention potentials on a global scale for finding alternative solutions for studying crop responses to p-fertilizer application on a global scale. He derived values for controlling factors for soil p-retention like pH, soil mineralogy and clay content. Subsequently p-retention classes (low, moderate, high, very high) were assigned to a likely p-fertilizer recovery fraction. By this he derived an approximation of the world soil phosphorus retention potential for spatially explicit integrated model-based studies and provides a global map on soil-p retention potential in qualitative classes (Batjes 2011a).

The given data provide the possibility to display a first approximation of p-retention for the construction of a phosphorus use efficiency (PUE) in fertilizer use. A main disadvantage is that there is no possibility for a derived buffer capacity and therefore a display of residual phosphorus and the reissuing of phosphorus in the long term for plant growth is not possible. For further work, there have to be efforts to build a model which represents the different p-retention potentials in the short term and integrates the theoretical buffer-capacity for residual soil phosphorus in the long term.

2.3.2 Modelling the global phosphorus cycle and estimating future demand

Recently there have been different attempts to partly model dynamics and sections of the global phosphorus cycle to improve the quantification of future resource use and exhaustion of reserves, or for global integrated assessment. Scheldrick et al. (2002) developed a model for nutrient auditing and soil balances on national, regional and global scales. Van Vuren et al. (2010) calculated the phosphorus demand and resource depletion for a time-period from 1970 to 2100. Bouwman et al. (2009) simulated global phosphorus soil balances and Bouwman et al. (2013) changes in the global phosphorus cycle in agriculture by livestock production from 1900 to 2050. A substantial work regarding the soil phosphorus dynamic is Sattari et al. (2012)´s model of residual soil phosphorus.

Sheldrick et al. (2002) are quantifying global, regional and national P-balances of soils on the basis of a 197 country nutrient audit. They are developing a mathematical input-output model that uses relevant crop groups, fertilizer input, recycling of residues and others as well as different losses from the system at the national level to gain nutrient balances. The main handicap of the nutrient balances approach of Sheldrick et al. (2002) is that phosphorus losses by soil erosion, as well as phosphorus fixation in the soil, manifest as phosphorus losses in general. By this there is no explicit accounting for residual soil phosphorus.

Bouwman et al. (2009) are calculating soil phosphorus balances for agriculture and natural ecosystems on the basis of p-inputs and outputs in a 0.5 by 0.5 degree grid cell resolution for the period from 1970 to 2050, also on the basis of the four Millennium Ecosystem Assessment (MEA) (Carpenter 2005). They used the Integrated Model to Asses the Global Environment (IMAGE) for calculating spatially explicit soil nutrient balances within the MEA scenarios for each grid cell as the sum of p-inputs and outputs described in the figure 14 (Bouwman et al. 2006), by this quantifying p-accumulation or depletion in soils on a grid cell level. Control factors have been land cover/land use spatial distribution of manure, human excreta, fertilizer use and crop uptake. 14 natural land cover types were simulated with the BIOME model (Prentice et al. 1992), agricultural use is simulated by crop groups and agricultural land use groups (Bouwman et al. 2009).

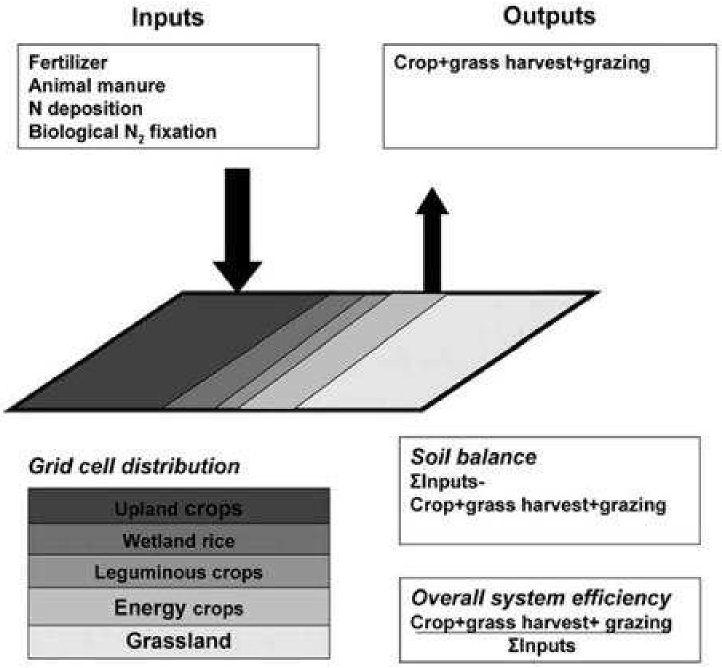

Figure 10: Construction of soil phosphorus balances from Bouwman et al. (2009).

In their soil nutrient budgets, on a 0.5 x 0.5 degree grid resolution scenarios, Bouwman et al. (2013) are identifying livestock production as a main driver regarding the global p cycle and soil budgets surpluses. They are contributing estimations for future scenarios for 2050 based on the International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD) (McIntyre 2009). A main shortcoming of Bouwman et al. (2013) is that the soil nutrient budget does not represent p-accumulation in soil, organic matter buildup and decomposition and mineralization. The budgetary surplus does not represent the difference between a loss to the environment and p-accumulation in the soil, which could potentially be used in future.

Sattari et al. (2012) applied a two-pool soil P model to simulate historical and future plant uptake of soil phosphorus based on target crop production from the global orchestration (GO) scenario of the Millennium Ecosystem Assessment (Carpenter 2005) to estimate global and regional P application rates (fertilizer and manure), and by this the phosphorus requirements for future crop production between 2008 and 2050 (figure 15).

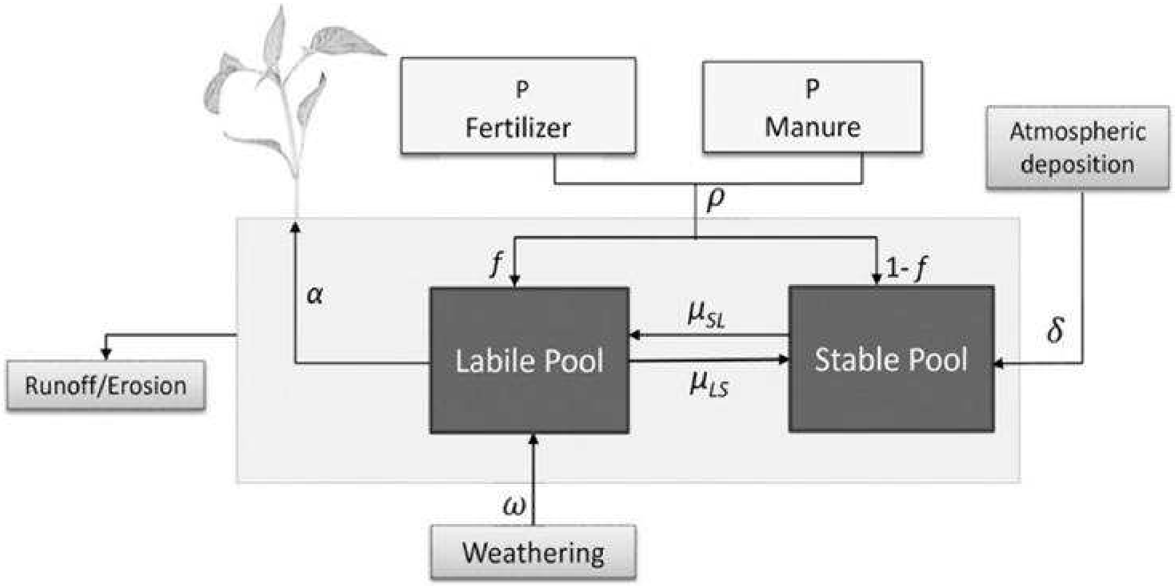

Figure 11: DPPS model, from Sattari et al. (2012).

The model includes two dynamic pools of P: the labile (P_L) and the stable (P_S) pools, comprising organic and inorganic P. P-inputs to the system are: fertilizer, manure, weathering and deposition. The coefficient ρ refers to total P-input (mineral fertilizer and manure) after subtracting runoff loss. The coefficients *f* and *1-f* refer to the fraction of ρ that transfers to the P_L and P_S respectively. Coefficient α represents the crop uptake fraction from P_L. Parameters ω and δ are weathering and deposition inputs to the P_L and P_S respectively. μ_{SL} and μ_{LS} denote to the transfer rate of P from the P_L to the P_S and from the P_S to the P_L respectively

Their dynamic phosphorus pool simulator (DPPS) model includes labile and stable pools and models the long-term p-input and output, and is thereby able to simulate the p-accumulation in the soil as residual soil P and the p-uptake by plants. Hence their model accounts for the dynamics of phosphorus in the soil because a substantial part of applied phosphorus from fertilizers accumulates in a more or less long-term, stable phosphorus pool in the soil as residual P. This leads to reducing the necessary phosphorus fertilizer inputs in the future by increasing soil fertility and maintaining a high level potential yield. As inputs, they used fertilizer, manure, weathering and atmospheric deposition. P inputs are allocated to the two pools. The model simulates the transfer between the pools, the uptake of phosphorus by plants and the size of both pools. Outflows of the system were p-withdrawal with the harvest and runoff (erosion) (Sattari et.al. 2012).

Residual soil-p results as the difference between P-input (mineral fertilizers, manure, weathering, deposition) and P-output (withdrawal with harvest, P loss by runoff and erosion). The residual P fuels the long-term P-pool able to enhance soil phosphorus status and thereby plant nutrition in the long-term (see figure 16). A large μ_{LS} makes P_L less available for plant uptake and a large μ_{SL} indicates that the stable pool acts as a buffer that replenishes the labile pool (Sattari et.al. 2011).

Van Vuren et al. (2010) used a global phosphorus resource-depletion model to estimate available resources and resource-depletion by estimating the future phosphorus demand under different scenarios (figure. 16 and 17)

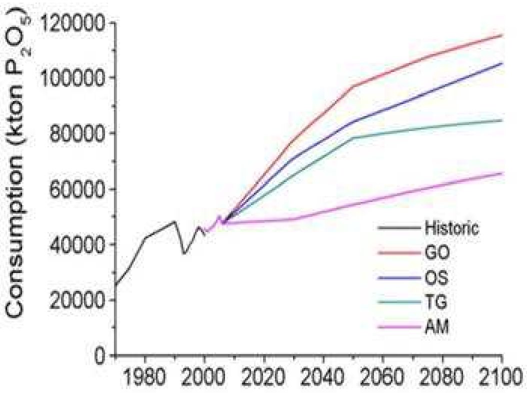

Figure 16: Total P consumption for the MA scenarios from Van Vuuren et al. (2010)

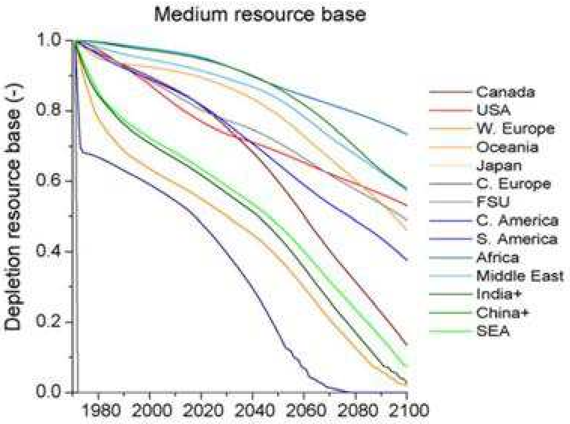

Figure 17: Regional depletion under the GO scenario for medium resource estimates from Van Vuuren et al. (2010)

They integrate an economic model for the estimation of future extraction costs. They differentiate between different extractable resource bases with corresponding extraction costs; thereby simulating increasing production costs in the course of depleting resources. They also include uncertainties in resource estimations, differences in the location of resources and scenario-dependant global distribution of manufactured phosphorus by trade. The world regions are linked by an economic trade model. They build up global phosphorus flows through the agricultural, food and sewage system, including a raw estimation of soil stocks but without a different residual soil phosphorus model. For the scenarios they focused on the four Millennium Ecosystem Assessment (Carpenter 2005) scenarios.

The scenarios have been translated into quantitative numbers for anthropogenic drivers in the model. As results they provide estimations of the global consumption under different scenarios, estimations of global and regional production for the period 2000-2100, estimates for depletion of phosphorus reserves and reserve base on a global and regional scale under low medium and high resource estimates, price-estimations on a global and regional scale under the applied scenarios as well as p-flows (Van Vuren et al. 2010).

This theoretical background will be used in the coming chapters to develop the methodological approach to model and analyze the global phosphorus cycle with special representation of soil phosphorus accumulation and to discuss the estimation regarding phosphorus depletion and options for a global management of phosphorus.

3 Methods

The global P cycle, under anthropogenic use, is defined by flows between temporary stocks. The aims of this thesis are to estimate phosphorus flows and stocks within land use and food systems including the recycling to agricultural used soils by the livestock sector and potential losses to environmental systems. Fertilizer, as an anthropogenic input to the agricultural system, plays a crucial role to maintain soil fertility and an appropriate yield. Phosphorus from fertilizer is partly accumulated in agricultural soils, which has to be represented within our model.

With the underlying methodological approach I build a soil phosphorus accumulation model (SPAM) within a phosphorus module to integrate this phosphorus cycle within the MAgPIE Model to calculate phosphorus stocks and flows within the global phosphorus cycle, future fertilizer use and phosphorus accumulation in the soils under agricultural use within a “middle-of-the-road” scenario. Soil-phosphorus accumulation and fertilizer use are projected on a time-horizon from 1995 to 2050. A sensitivity analysis of the key coefficients of the model is performed to provide a basis for adjustments, improvements and a calibration of the model.

In the following chapter I first provide some general reflections on integrated assessment and integrated modeling (subchapter 3.1). After a description of the LPJmL-MAgPIE-REMIND framework for an integrated assessment (subchapter 3.2), the MAgPIE model (subchapter 3.3), the phosphorus module and the soil phosphorus accumulation model, developed in this thesis, are described (subchapter 3.4). Here I illustrate in detail how phosphorus stocks, flows and budgets are calculated mathematically. Finally I outline the scenario setup under which the model is implemented (subchapter 3.5) and briefly describe the modeling language used (subchapter 3.6).

3.1 Integrated Assessment

Human-environmental systems are working in cross-linked cause-effect chains, feedback loops and complex dynamics. Feedback mechanisms often cause unforeseeable or unnoticed side effects. Time delay of complex processes can amplify or alleviate effects. Hence system dynamic modeling has become an essential tool in analyzing complex Human-Environment Interactions (Sterman 2001).

Weaver and Rotmans (2006) described Integrated Sustainability Assessment as an interdisciplinary, “integrative and active process at the science-policy-society interface” and an appropriate response and approach for analyzing and potentially helping to solve global fundamental and high complex problems. That requires the Development and Provision of “appropriate tools for the combined assessment of environmental, economical and social processes” where these models “help to structure scientific thinking, to focus on the most relevant processes, analyze important trade-offs between conflicting goals, quantify scenarios and make projections of likely future developments” (Lotze-Campen 2008).

Integrated assessment (IA) is a broadly applied tool for the assessment of coping with climate change by the modeling of environmental, social and economic factors that affect future climate change, and thereby the possibilities of climate policy. Integrated assessment is a holistic approach; by integrating multiple disciplines of science in numerical models (Leimbach et al. 2011).

The main feature and advantages of the integrated assessment approach is the combination of different models that display and link biogeochemical, geophysical and socio-economical processes. Lotze-Campen 2008, Leimbach et al. 2011 and Michetti 2012 present a broad outline of integrated assessment models as policy tools for an evaluation of land use, land use change and agriculture in the context of climate change.

A main challenge is the handling of different spatial and timely dimensions of geophysical, biogeochemical and social-economical processes (Lotze-Campen 2008). For that, model coupling and model integration is a necessary step to combine and project different scale, spatial or interdisciplinary processes like socio-economic, bio-physical, bio-geo-chemical or others to an integrated approach of analysis and evaluation. Lotze-Campen (2008) reviews a broad range of existing models, approaches of model-coupling and integrated models for an integrated sustainability assessment.

Mostly, IA models consist of modules for the representation of different parts of the anthroposphere, the biosphere and the climate system. Three different evolution tracks of IA models can be identified. These are economic growth models, energy system models and biophysical models with different solution approaches; like cost-benefit analysis, the multisectoral computable general equilibrium model, combined with climate models and integrated structural models and biophysical impact models. IA models can also be classified as policy evaluation and policy optimization models (Leimbach et al. 2011).

IA models provide good options to integrate land use matters into sustainability or impact assessment (see Leimbach et al. 2011, Michetti 2012). Land use interlinks climate and energy systems with the biosphere and also economy (fig. 18) (Leimbach et al. 2011).

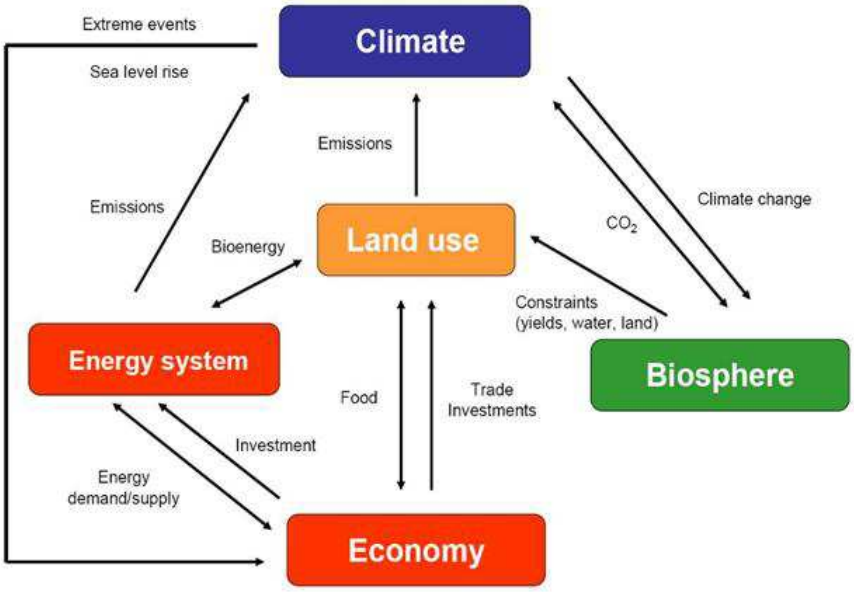

Figure 12: Interlinking of land use with other spheres of an IA model, Leimbach et al. (2011)

Dimensions of agriculture and land use modeling are, for example, agricultural patterns with environmental, economic and socio-cultural conditions and interactions, the demand for land-based products, international trade and biophysical restrictions of plant growth (Leimbach et al. 2011).

3.2 The LPJmL-MAgPIE-REMIND framework for Integrated Assessment

The LPJmL-MAgPIE-REMIND framework for integrated assessment consists of three models (fig. 19)

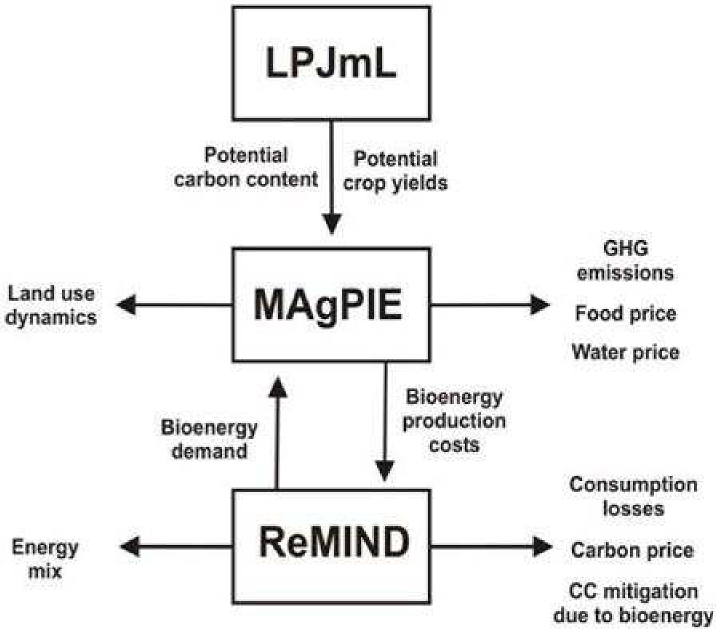

Figure 19: Information flow between LPJmL and MAgPIE, from Lotze-Campen et al. (2008)

The “Lund-Potsdam-Jena dynamic global vegetation and hydrology model with managed Land (LPJmL)” (Sitch et al. 2003, Gerten et al. 2004, Bondeau et al. 2007; Waha et.al. 2012) is a non-equilibrium biogeography-biogeochemistry model. It represents global terrestrial vegetation dynamics, land use change, land-athmosphere carbon and water exchanges as well as agricultural productivity and yields.

It is built in a modular framework (Gerten et al. 2004, Lotze-Campen 2008, Leimbach et al. 2011). Natural vegetation is represented by plant functional types and agriculture by crop functional types. All processes are modeled in a 0.5 x 0.5 degree spatial resolution which corresponds to an approximated 50 x 50 km grid. Interactions between carbon and water cycles are dynamically fully process-based and include agricultural crops and soils (Leimbach et al. 2011).

MAgPIE (Lotze-Campen et al. 2008, Dietrich 2011) is non-linear global land-use allocation model, soft-coupled to LPJmL. It receives spatial explicit data on potential crop yield from LPJmL and takes regional economic conditions and constraints into account. It derives specific land-use patterns, yields and total costs of production (fig. 20) (Leimbach et al. 2011).

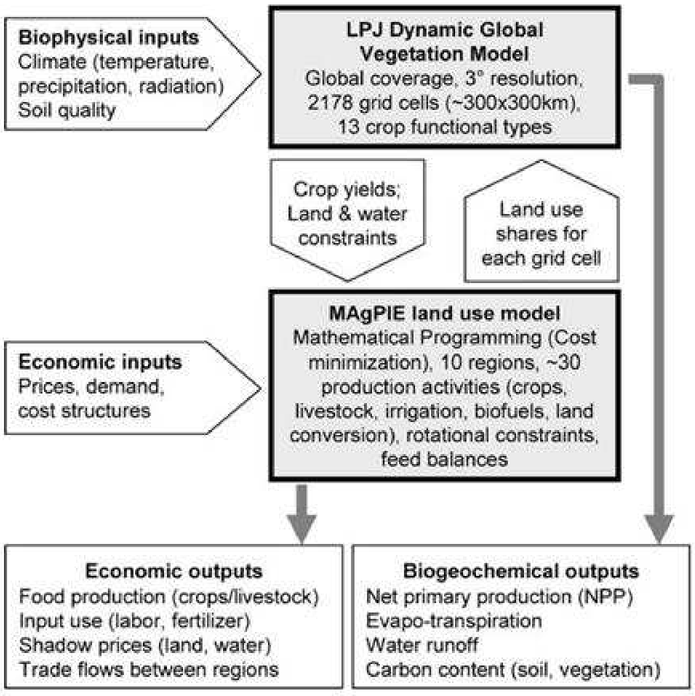

Figure 20: The LPJmL-MAgPIE-REMIND Framework for Integrated Assessment, from Leimbach et al. (2008)

A summarized description and outline is depicted in the next chapter. For a detailed description of the MAgPIE model, see Lotze-Campen et al. (2008) and Dietrich (2011). Popp et al. (2010) applied MAgPIE to analyze food consumption, dietary shifts and associated non-CO_2 GHG-emissions. Popp et al. (2011) used MAgPIE to evaluate the economic potential of bioenergy for climate change mitigation and Popp et al. (2012) to quantify additional CO_2 emissions from land use change. Schmitz et al. (2012) analyzed international trade on its implications to land use, GHG-emissions and the food system.

The REMIND model is an integrative framework, embedding a detailed energy system module into a macro-economic growth module and integrating a climate module for the computation of the effects of GHG emissions. REMIND is completely hard-linked. The solving procedure runs completely simultaneously in an inter-temporal optimization procedure (Leimbach et al. 2011). The REMIND model is not included in the present analysis. A more in depth description can be found in Luderer et al. (2011).

3.3 The MAgPIE Model

MAgPIE is a non-linear mathematical programming approach with GAMS coupled to the grid based biogeochemical dynamic vegetation model LPJmL, for the simulation of spatial explicit land and water use. This provides high flexibility to integrate biophysical constraints into economic decision-making processes, thereby linking monetary and physical units and processes. A main advantage is that in this way an internal value for a resource is visualized by the shadow price of a binding constraint (Lotze-Campen 2008).

The linear objective function of the MAgPIE model minimizes the total cost of production for a given amount of regional food energy demand. Constraints, for example available land or production technology, can be relaxed by drawing on additional resources (from land conversion) or yield-increasing technology (from research & development) at additional costs, thereby increasing production costs and resulting in non-linear constraints (Lotze-Campen 2008).

The model uses time steps of ten years in a recursive dynamic mode for future projections. The optimization result from one period is the initial basis for the optimization process in the next period (Lotze-Campen 2008). MAgPIE uses different spatial scales. Spatially explicit data on yield potential and water availability is provided in a geographic grid resolution from three by three degrees (Lotze-Campen 2008) up to 0.5 x 0.5 degrees (Dietrich 2011). Economic processes with demand, trade and technology are aggregated at a regional level in 10 economic world regions (see figure 21) (Lotze-Campen 2008, Dietrich 2011).

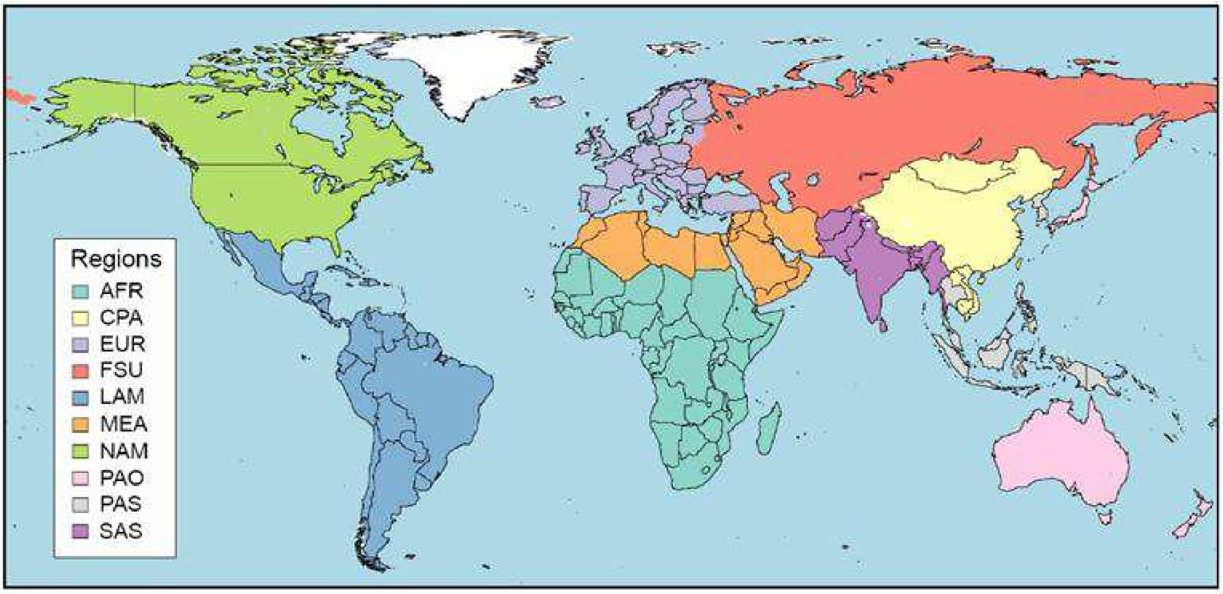

Figure 21: **MAgPIE World Regions, from Lotze-Campen et al. (2008)**

With AFR= AFR = Sub-Sahara Africa, CPA = Centrally Planned Asia (incl. China), EUR = Europe (incl. Turkey), FSU = Former Soviet Union, LAM = Latin America, MEA = Middle East and North Africa, NAM = North America, PAO = Pacific OECD (Australia, Japan and New Zealand), PAS = Pacific Asia, SAS = South Asia (incl. India).

MAgPIE is currently applied in several variants, dependant on the focus of the analysis, for example global trade, livestock production or emission policies (Dietrich 2011). For this, MAgPIE is built up of a main body (*trunk*) and different modules which can partly be switched on and off. For the purpose of this study I constructed a phosphorus module. The phosphorus module is described further down. The main MAgPIE model was applied as follows.

I used three different aggregation-levels (global, regional and grid cells level) with 200 grid cells in ten economic regions (see figure 16). Input resolution (from LPJmL) is 0.5 x 0.5 degree. Output resolution is 200 (grid cells). Agricultural activities are represented by 5 livestock activities and 20 vegetal production activities, from which 19 are crop activities and one is pasture activity.

The objective function is the global sum of all economic costs for all regional farming activities including land conversion costs, technology costs, emission costs and others. This objective function becomes non-linear by different constraints caused by trade, land use, demand, rotation, yield and other specifications. Land expansion and acquisition of technological change is possible at additional costs. The available agricultural area and potential yield is derived from LPJmL. The food demand is inelastic and exogenous given.

The objective function is minimized to allocate land use. For every time step, the value of the goal function depends on the solutions of the previous time steps (t−1, t-2, …, t-x) and the set of time depending parameter (see Dietrich, 2011).

The optimization problem can be described mathematically as follows, in which the goal function is minimized (PIK Land Use Group, 2012):

Objective function:

global economic costs: $\boldsymbol{C_{glo}} = \sum_{\boldsymbol{i=1}}^{\boldsymbol{10}} \boldsymbol{C_{reg_i}} \rightarrow Min.$ eq. 1

with:

regional economic costs: $C_{reg_i} = \dots$ eq. 2

$\dots\sum_{k=1}^{n} C_{prod_k}$ *(production costs)*

$+ \sum_{l=1}^{n} C_{conv_l}$ *(land conversion costs)*

$+ \sum_{k=1}^{n} C_{trans_k}$ *(transport costs)*

$+ C_{tech_i}$ *(technology change costs)*

$+ C_{fert_i}$ *(fertilizer costs)*

$+ C_{emis_i}$ *(emission costs)*

$+ C_{mit_i}$ *(mitigation costs)*

$+ C_{N-imp_i}$ *(N-impact costs)*

$+ C_{irr_i}$ *(irrigation costs)*

$+ C_{trade_i}$ *(trade and taxes costs)*

$+ C_{forst_i}$ *(forestry costs)*

$+ C_{past_i}$ *(pasture costs)*

with:

i = economic region

k = land use activities

l = land type

under following constraints:

(a) global demand:

(for each activity k)

$$\sum_i \boldsymbol{P}^{prod}_{t,i,k}(\boldsymbol{x}_t) \geq \sum_{i,u} \boldsymbol{P}^{ds}_{t,i,k,u}(\boldsymbol{x}_t) \qquad \text{eq. 3}$$

where total production of a commodity has to meet the demand for this product.

(b) trade balance:

(for each region i and product k)

$$\boldsymbol{P}^{prod}_{t,i,k}(\boldsymbol{x}_t) \geq \boldsymbol{r}^{tb} \begin{cases} \sum_u \boldsymbol{P}^{ds}_{t,i,k,u}(\boldsymbol{x}_t) + \boldsymbol{P}^{xs}_{t,i,k} & : \boldsymbol{r}^{sf}_{i,k} \geq \boldsymbol{1} \\ \sum_u \boldsymbol{P}^{ds}_{t,i,k,u}(\boldsymbol{x}_t)\, \boldsymbol{r}^{sf}_{i,k} & : \boldsymbol{r}^{sf}_{i,k} < 1 \end{cases} \qquad \text{eq. 4}$$

where the trade balance constraint acts on a regional level. In an exporting region, where the self-sufficiency ($\boldsymbol{r}^{sf}_{i,k}$) for product k is greater than 1, the production has to meet the domestic demand supplemented by the demand caused due to export ($\boldsymbol{P}^{xs}_{t,i,k}$). In importing regions, where self-sufficiency ($\boldsymbol{r}^{sf}_{i,k}$) is less than 1, the domestic demand is multiplied by the self-sufficiency ($\boldsymbol{r}^{sf}_{i,k}$) to calculate production in the region itself.

(c) land constraints

(for each cluster j)

$$\sum_{v,w} \boldsymbol{X}^{area}_{t,j,v,w} \leq \boldsymbol{P}^{land}_j \qquad \text{eq. 5}$$

$$\sum_{\mathrm{v}} \mathrm{X}^{\mathrm{area}}_{\mathrm{t,j,v,`ir'}} \leq \mathrm{P}^{\mathrm{ir.land}}_{\mathrm{j}} \qquad \text{eq. 6}$$

where the land constraints restrict the land used for production to less than available land. The first equation depicts the general land availability for agricultural production; the second regards areas that are equipped for irrigation.

(d) water constraints

(for each cluster j)

$$\sum_v \boldsymbol{X}^{area}_{t,j,v`ir'} \boldsymbol{r}^{yield}_{t,j,v`ir'} \boldsymbol{r}^{growth}_{t,i,(j)}(\boldsymbol{x}_t) \boldsymbol{r}^{watreq}_{j,v} + \sum_l \boldsymbol{X}^{prod}_{t,j,l} \boldsymbol{r}^{watreq}_{j,l} \leq \boldsymbol{P}^{water}_j \qquad \text{eq. 7}$$

where water demand per cluster must be less or equal to the water available.

(e) rotational constraints

(for each crop rotation group c, cluster j and irrigation type w)

$$\sum_{v_c} \boldsymbol{X}^{area}_{t,j,v,w} \leq \boldsymbol{r}^{rmax}_c \sum_v \boldsymbol{X}^{area}_{t,j,v,w} \qquad \text{eq. 8}$$

$$\sum_{v_c} \boldsymbol{X}^{area}_{t,j,v,w} \geq \boldsymbol{r}^{rmin}_c \sum_v \boldsymbol{X}^{area}_{t,j,v,w} \qquad \text{eq. 9}$$

where the rotational constraints describe typical crop rotations by a maximum and minimum share relative for each vegetal product and cluster.

An extended model description, as well as a broad overview of MAgPIE, can be found in Bodirsky et al. (2012) and Dietrich (2011). The extended model script with all constraints of the objective function written in GAMS can be found in the appendix.

3.4 The Phosphorus module

To reproduce and quantify stocks and flows within the global phosphorus cycle in 1995 as well as in 2050 under special representation of phosphorus accumulation in the soil, I used the method of a material flow analysis and built a phosphorus module within MAgPIE including a soil phosphorus accumulation model (SPAM). The mathematical programming and representation of the material flow analysis is based on the work of Bodirsky et al. (2012), who modeled the global N-cycle within the LPJmL-MAgPIE Model. Different changes and adjustments regarding the p-cycle have been necessary.

The main adjustments and changes were: (1) dry matter flows has to be converged to phosphorus flows by use of phosphorus contents, (2) there is no biological fixation of P, so a biological fixation has been left out in the phosphorus module, (3) the dynamic of phosphorus in the soil totally different from nitrogen (e.g. phosphorus is not as mobile as nitrogen, there are no gaseous emissions from the soil into the atmosphere), (4) there are no gaseous atmospheric components and no climate impacts, (5) there is nearly no leaching of P to the groundwater. Therefore leaching and gaseous emissions have been left out of the model[3]. (6) A very important aspect of P-availability and relation to agricultural productivity is that soils can store and buffer P before making it available to crop growth; leading to a phosphorus accumulation and build-up of the soil fertility status and leading to improved phosphorus availability in further years.

The underlying phosphorus module reproduces the different compartments of the global phosphorus in accordance with the description in chapter 1. The model provides data on stocks and flows of the global phosphorus cycle on a global, regional and cluster cell level. As a first modeling approach, an evaluation, approval and calibration of the model is necessary before going into an in-depth analysis

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[3] In fact, many P-losses from soil are directly bounded to soil particles, wind and water-erosion of soil matter is one of the most relevant factors by which P is distributed to other environmental compartments like surface waters and natural ecosystems. Nevertheless, regarding difficulties of modeling wind and water-erosion, this aspect of environmental losses is left unattended and remains for further works.

of further outcomes. Therefore, and to reduce complexity, just global and in some cases regional data will be provided in this thesis.

Within this thesis the modeled agricultural phosphorus cycle can be characterized by the following stocks and flows (figure 22).

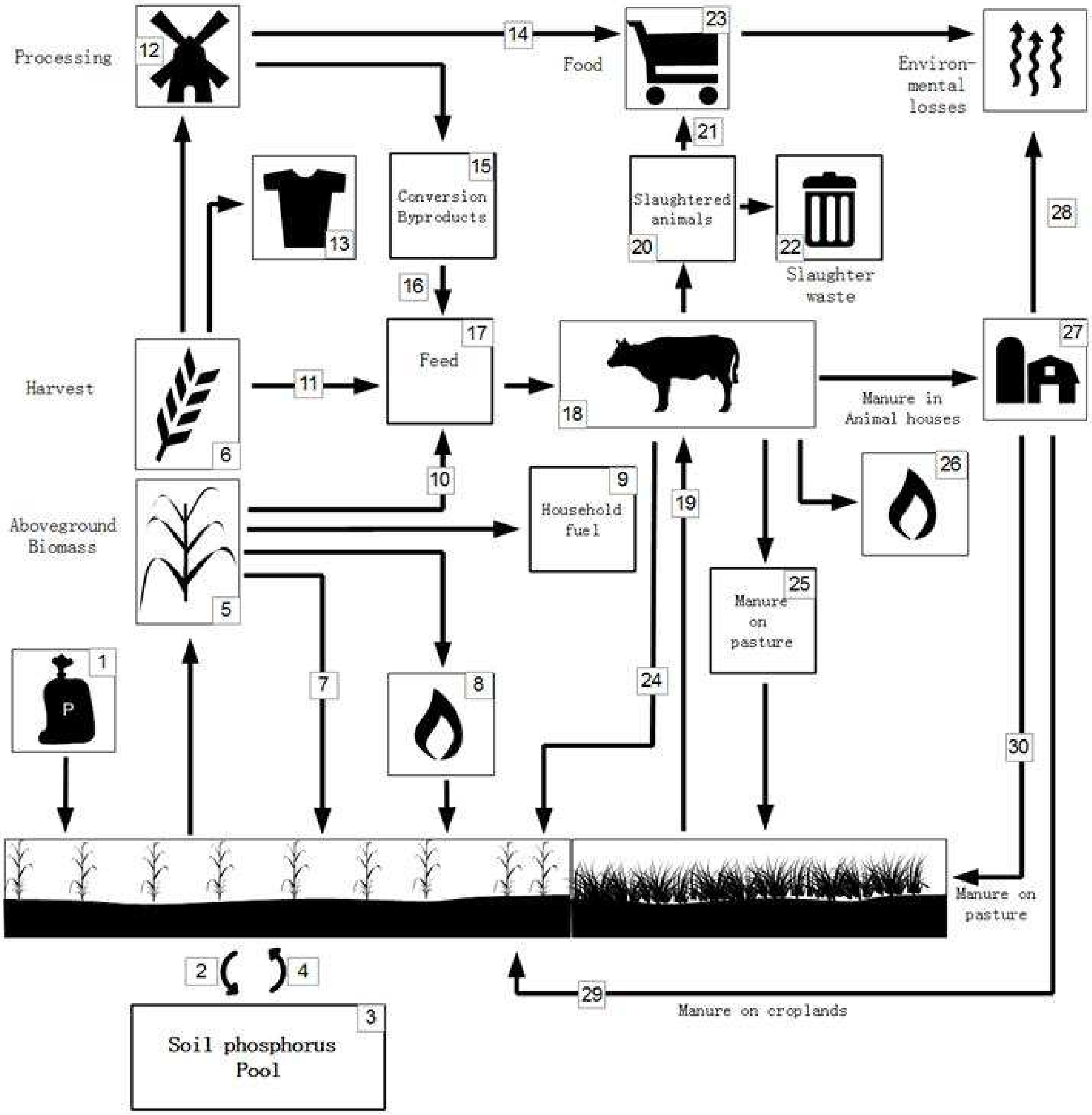

Figure 22: Phosphorus stocks and flows, soil p-accumulation in the p-module

These are: (1) the fertilizer input to croplands, (2) the phosphorus fixation, (3) the soil phosphorus pool, as well as (4) phosphorus release from the soil p-pool, thus representing the complex of mineral phosphorus use and accumulation in the soil. The agricultural production is characterized by (5) the above-ground biomass and (6) the harvested parts of the plant. The different uses of above-ground biomass are represented by (7) above-ground residues returning to the soil directly, (8) above-ground residues burned on field, (9) above-ground residues used for household fuel (in minor parts in developing countries) and (10) above-ground residues used as feed for animals. Harvested crops are used for (11) feed, (12) processing into food and (13) other material use, including waste. The processing of harvested plants generates (14) vegetal food and (15) conversion byproducts. Conversion byproducts can be used as (16) feed for animals. The livestock sector is represented by (17) total feed, (18) livestock and (19) feed supplied by grazing pasture, (20) slaughtered animals, (21) animal food and (22) slaughter waste. (23) Total food lastly ends up as losses through waste and sewage systems. Manure management systems are represented by (24) returns to croplands by stubble grazing, (25) returns to pasture by grazing pasture, (26) losses by uses as household fuel in developing countries and (27) concentrated manure in animal houses. Finally, this manure in confinement is (28) lost to the environment, (29) returns to croplands and to (30) pastures.

For use as a substance flow analysis for phosphorus through the depicted phosphorus cycle, the dry matter flows which are provided by the MAgPIE model have to be converted to P-flows to examine P-contents of the relevant compartments of the p-cycle. The provision of the dry matter amounts run via the MAgPIE vm-variables (for details see the main and the phosphorus module script in appendix 2). In the following, the different stocks and flow will be described mathematically as they are calculated by the model. The indices used in the mathematical description are depicted in table 5.

Set	Description	Elements
T	time steps	y1995 , y2000 ,y2005, y 2010, … . y2050 (in ten year steps)
I	economic world region	AFR, CPA, EUR, FSU, LAM, MEA, NAM, PAO, PAS, SAS
J	Cells	1:200
W	Irrigation	irrigated, rain fed
V	Crops	temperate cereals, maize, tropical cereals, rice, soybeans rapeseed, groundnut, sunflower, oilpalm, pulses, potatoes, tropical roots, sugar cane, sugar beet, fodder crops, fibers, others
L	Livestock	ruminant livestock, non-ruminant livestock, poultry, eggs, milk
K	Products	$v \cup l$
F	feeding systems	grazing on cropland (grazc), grazing on pasture (grazp), animal houses (house)
C	animal waste management systems	anaerobic lagoons, liquid/slurry, solid storage, daily spread, anaerobic digesters, chicken layers, pit storage < 1 month, pit storage > 1 month
U	product use	food (food), feed (feed), seed (seed), other use (other), substitution for byproducts (sby), substitution for aboveground crop residues (sag)
R	AG residue use	feed (feed), recycling to use (rec), burning on field (burn), other use (other)
B	Conversion byproduct use	feed (feed), other use (other)

Table 5: Indices used in the mathematical description

In the following subsections I will describe how the stocks and flows are calculated mathematically within the module. In general, dry matter values are provided by the main module and converged by phosphorus contents to phosphorus flows. Some variables are output variables calculated by the phosphorus module, other stocks and flows are calculated mathematically by the r-script.The parameters for the mathematical model description are depicted in table 6 and table 7 further below.

Parameter	**Description**	**Unit**
Area		
$X_{t,j,v,w}^{area}$	Cropland area under cultivation	Mha
Production		
$M(x_t)_{t,i,v}^{prod}$, $P(x_t)_{t,i,v}^{prod}$	Crop production	Tg DM TgP
$M(x_t)_{t,i,v}^{prod\_ag}$, $P(x_t)_{t,i,v}^{prod\_ag}$	Ag residue production	Tg DM TgP
$M(x_t)_{t,i,v}^{prod\_by}$, $P(x_t)_{t,i,v}^{prod\_by}$	Conversion byproduct production	Tg DM TgP
Domestic supply and its use		
$M(x_t)_{t,i,v,u}^{ds}$, $P(x_t)_{t,i,v,u}^{ds}$	Crop use	Tg DM TgP
$M(x_t)_{t,i,v,r}^{ds\_ag}$, $P(x_t)_{t,i,v,r}^{ds\_ag}$	Ag residues use	Tg DM TgP
$M(x_t)_{t,i,v,b}^{ds\_by}$, $P(x_t)_{t,i,v,b}^{ds\_by}$	Conversion byproduct use	Tg DM TgP
$P(x_t)_{t,i,k}^{fs}$	Food supply	TgP
P-contents		
$r_v^{Pharvest}$	P-content of harvested crops	$\frac{\text{Tg P}}{\text{Tg DM}}$
r_v^{Pag}	P-content of AG residues	$\frac{\text{Tg P}}{\text{Tg DM}}$
r_v^{Pby}	P-content of conversion byproducts	$\frac{\text{Tg P}}{\text{Tg DM}}$
r_l^{Pl}	P-content of livestock products	$\frac{\text{Tg P}}{\text{Tg DM}}$
r_v^{Ppast}	P-content of grazed pasture	$\frac{\text{Tg P}}{\text{Tg DM}}$

Table 6: Parameters for the mathematical model description

Dry matter production

The interface between core model and nutrient module is cropland area ($X_{t,j,v,w}^{area}$), crop and livestock dry-matter production ($M(x_t)_{t,i,k}^{prod}$) and its use ($M(x_t)_{t,i,v,u}^{ds}$), as well as dry matter of conversion-byproducts production ($M(x_t)_{t,i,v}^{prod\_by}$). In the GAMS script the interface of the nutrient module to the core model runs via the vm-variables. The interface between to time steps runs via the p-parameters (see appendix 2).

Phosphorus contents in plant biomass and conversion byproducts

To analyze the global phosphorus cycle and quantify phosphorus flows it is necessary to transform dry matter flows to phosphorus flows within the global cycle.

For the parameterization of the phosphorus flows, I derived p-contents of harvested organs ($r_v^{Pharvest}$) from Wirsenius (2000), Fritsch (2007), FAO (2004), Roy et al. (2006); p-contents of above-ground crop residues (r_v^{Pag}) from Wirsenius (2000), Fritsch (2007), FAO (2004), Eggleston et al (2006), Chan and Lim (1980) and p-contents of conversion byproducts (r_v^{Pby}) from Wirsenius (2000) and Roy et al. (2006). Mathematically, the p-content in crop and residue production and its use can be calculated as:

crop production:

$$P(x_t)_{t,i,v}^{prod} = M(x_t)_{t,i,v}^{prod} \cdot r_v^{Pharvest} \qquad \text{eq. 10}$$

Crop use:

$$P(x_t)_{t,i,v,u}^{ds} = M(x_t)_{t,i,v,u}^{ds} \cdot r_v^{Pharvest} \qquad \text{eq. 11}$$

above-ground residues production:

$$P(x_t)_{t,i,v}^{prod\_ag} = M(x_t)_{t,i,v}^{prod\_ag} \cdot r_v^{Pag} \qquad \text{eq. 12}$$

above-ground residue use

$$P(x_t)_{t,i,v,r}^{ds\_ag} = M(x_t)_{t,i,v,r}^{ds\_ag} \cdot r_v^{Pag} \qquad \text{eq. 13}$$

Conversion byproduct production:

$$P(x_t)_{t,i,v}^{prod\_by} = M(x_t)_{t,i,v}^{prod\_by} \cdot r_v^{Pby} \qquad \text{eq. 14}$$

Conversion byproduct use

$$P(x_t)_{t,i,v,b}^{ds\_by} = M(x_t)_{t,i,v,b}^{ds\_by} \cdot r_v^{Pby} \qquad \text{eq. 15}$$

Food supply

The amount of phosphorus in food supply differs from the amount of phosphorus in harvested crops assigned for food and livestock products assigned for food because of crop use for material demand, losses in crop processing and losses in slaughter waste. To calculate the amount of phosphorus in vegetal food ($P(x_t)_{t,i,v}^{fs}$) supply I subtracted phosphorus content of conversion byproducts ($P(x_t)_{t,i,v}^{prod\_by}$) from harvested crops assigned for food ($P(x_t)_{t,i,v,food}^{ds}$). To calculate the phosphorus content of animal food supply ($P(x_t)^{fs}_{t,i,l}$) I multiplied the amount of phosphorus in livestock products ($P(x_t)^{prod}_{t,i,l}$) by the slaughter factor (r^{sl}_l) and the specific p-content of animals (r^{Pl}_l). The total food supply ($P(x_t)^{fs}_{t,i,k}$) is the sum of the calculated vegetal food and animal food.

$$P(x_t)^{fs}_{t,i,v}=P(x_t)^{ds}_{t,i,v,food} - P(x_t)^{prod\_by}_{t,i,v}) \qquad \text{eq. 15}$$

$$P(x_t)^{fs}_{t,i,l}=M(x_t)^{prod}_{t,i,l} \cdot r^{Pl}_l \cdot r^{sl}_l \qquad \text{eq. 16}$$

$$P(x_t)^{fs}_{t,i,k}=P(x_t)^{fs}_{t,i,v} + P(x_t)^{fs}_{t,i,l} \qquad \text{eq. 17}$$

Phosphorus contents in feeding systems, manure, livestock products & animal waste management

There are three feeding systems (*f*): pasture (grazp), cropland grazing (grazc) and animal houses (house). Phosphorus from pasture is totally ascribed to be consumed by livestock through pasture grazing while phosphorus from feedstock crops and conversion byproducts is ascribed to be fed in confinement houses. Crop residues for feed-use are totally ascribed to animal houses in developed regions, while 25 % are assumed to be fed by stubble grazing in developing regions ($r^{grazC}_{t,i}$).

Parameter	Description	Unit
Livestock		
$r^{fb\_conc}_{t,i,l,v}$	Feedstock crops in feed basket	$\frac{\text{Tg DM}}{\text{Tg DM}}$
$r^{fb\_ag}_{t,i,l,v}$	AG residues in feed basket	$\frac{\text{Tg DM}}{\text{Tg DM}}$
$r^{fb\_past}_{t,i,l}$	Grazed pasture in feed basket	$\frac{\text{Tg DM}}{\text{Tg DM}}$
$r^{fb\_by}_{t,i,l,v}$	Byproducts in feed basket	$\frac{\text{Tg DM}}{\text{Tg DM}}$
$r^{grazC}_{t,i}$	Fraction of feed residues con-sumed during stubble grazing	$\frac{\text{Tg DM}}{\text{Tg DM}}$
$P(x_t)^{feed}_{t,i,l,f}$	Feed P distributed to livestock types in feeding systems	$\frac{\text{Tg P}}{\text{Tg P}}$
r^{sl}_l	Slaughter factor	$\frac{\text{Tg DM}}{\text{Tg DM}}$
$P(x_t)^{sl}_{t,i,l}$	P in whole animal bodies	Tg P
$r^{fs}_{t,i,l,c}$	Fraction of manure in feeding systems (based on $\text{MS}_{(\text{T,S})}$)	$\frac{\text{Tg P}}{\text{Tg P}}$
$r^{cs}_{t,i,l,c}$	Fraction of manure managed in awms (based on $\text{MS}_{(\text{T,S})}$)	$\frac{\text{Tg P}}{\text{Tg P}}$
$P(x_t)^{ex}_{t,i,l,f}$	P in excretion ($\text{Pex}_{(\text{T})}$)	Tg P
$r^{fuel}_{t,i,l}$	Fraction of manure collected for fuel	$\frac{\text{Tg P}}{\text{Tg p}}$
$P(x_t)^{closs}_{t,i}$	Manure P lost in animal houses and waste management	Tg P

Table 7: Livestock parameters and conversion coefficients

That can be described mathematically as follows:

$$P(x_t)^{feed}_{t,i,l,grazp}=r^{fb\_past}_{t,i,l} \cdot M(x_t)^{prod}_{t,i,l} \cdot r^{Ppast} \qquad \text{eq. 18}$$

$$P(x_t)^{feed}_{t,i,l,grazc}=\sum\nolimits_v r^{fb\_ag}_{t,i,l,v} \cdot M(x_t)^{prod}_{t,i,l} \cdot r^{Pag}_v \cdot r^{grazC}_{t,i} \qquad \text{eq. 19}$$

$$\begin{aligned} P(x_t)^{feed}_{t,i,l,house}= \sum\nolimits_v (r^{fb\_by}_{t,i,l,v} \cdot M(x_t)^{prod}_{t,i,l} \cdot r^{Pby}_v \\ + r^{Pharvest}_v \cdot (r^{fb_{conc}}_{t,i,l,v} \cdot M(x_t)^{prod}_{t,i,l} + M(x_t)^{ds}_{t,i,l,v,sby} + M(x_t)^{ds}_{t,i,l,v,sag}) \\ + r^{fb\_ag}_{t,i,l,v} \cdot M(x_t)^{prod}_{t,i,l,} \cdot r^{Pag}_v \cdot (1 - r^{grazC}_{t,i})) \end{aligned} \qquad \text{eq. 20}$$

To estimate the regional livestock specific annual average P excretion, I used the Tier 2 methodology of Eggleston et al. (2006) in line with Bodirsky et al. (2012). I subtracted the amount of P which is incorporated in animal biomass assigned to slaughtering ($P(x_t)^{sl}_{t,i,l}$) from the feed in all feeding systems (*f*) and assumed that remaining P is excreted as manure. To receive phosphorus content in animal biomass assigned to slaughtering, I calculated phosphorus in the animal body ($P(x_t)^{sl}_{t,i,l}$) by the livestock production ($M(x_t)^{prod}_{t,i,l}$) and the ratio of phosphorus content and the slaughter factor ($\frac{r^{Pl}_l}{r^{sl}_l}$).

$$P(x_t)^{sl}_{t,i,l}=M(x_t)^{prod}_{t,i,l} \cdot \frac{r^{Pl}_l}{r^{sl}_l} \qquad \text{eq. 21}$$

$$P(x_t)^{ex}_{t,i,l,f}=P(x_t)^{feed}_{t,i,l,f} - r^{fs}_{t,i,l,f} \cdot P(x_t)^{sl}_{t,i,l} \qquad \text{eq. 22}$$

Excreted phosphorus in animal houses allocates to nine different animal waste management systems (*c*) by the parameter ($r^{cs}_{t,i,l,c}$), based on data from Eggleston et al. (2006) and IPCC (1996)

Losses of phosphorus in animal houses occur in different ways due to leaching or simply manure not being brought back to farmland. For this reason, I used animal waste system specific shares of total amount of managed manure ($r^{loss\_awms}_{l,c}$) not being recycled and lost in leaching or solid and fluid erosion. I used methodology from Bodirsky et al. (2012) with data from IPCC (1996) and Eggleston et al. (2006). In this case, the share of phosphorus losses is assumed to be the same as the share of nitrogen losses minus the share of nitrogen volatilization. However, nitrogen losses include also denitrification, which is not possible for phosphorus. With respect to the precision of representation of phosphorus losses this is a rather rough estimation due to a lack of data. This aspect will require further work.

In developing regions, the remaining manure is totally applied to croplands. In developed regions (NAM and EUR), a fraction ($r_{t,i}^{msplit}$) of 87 % and 66 % respectively is applied on croplands while the rest is used for pasture soils. Also, in developing regions a share of manure excreted on pasture is used for fuel in households ($r_{t,i,l}^{fuel}$), not returning to pasture soil, leaving the considered system boundaries to not be regarded anymore.

Phosphorus losses in animal houses and waste management ($P(x_t)_{t,i}^{closs}$), recycled manure ($P(x_t)_{t,i}^{m}$) and manure entering cropland soils ($P(x_t)_{t,i}^{m\_cs}$) and pasture soils ($P(x_t)_{t,i}^{m\_ps}$) can be calculated like this:

$$P(x_t)_{t,i}^{closs} = \sum_c P(x_t)_{t,i,l,house}^{ex} \cdot r_{t,i,l,c}^{cs} \cdot r_{l,c}^{loss\_awms} \qquad \text{eq. 23}$$

$$P(x_t)_{t,i}^{m} = \sum_c P(x_t)_{t,i,l,house}^{ex} \cdot r_{t,i,l,c}^{cs} \cdot (1 - r_{l,c}^{loss\_awms}) \qquad \text{eq. 24}$$

$$P(x_t)_{t,i}^{m\_cs} = P(x_t)_{t,i}^{m} \cdot r_{t,i}^{msplit} + \sum_l P(x_t)_{t,i,l,grazc}^{ex} \qquad \text{eq. 25}$$

$$P(x_t)_{t,i}^{m\_ps} = P(x_t)_{t,i}^{m} \cdot (1 - r_{t,i}^{msplit}) + \sum_l P(x_t)_{t,i,l,grazp}^{ex} \cdot (1 - r_{t,i,l}^{fuel}) \qquad \text{eq. 26}$$

The soil phosphorus accumulation model (SPAM) and cropland soil phosphorus budgets

One of the main attempts of this thesis is to represent phosphorus accumulation in the soil due to phosphorus fertilization. Therefore, I have built a soil phosphorus accumulation model (SPAM) which characterizes phosphorus accumulation in the soil. The soil-phosphorus model simulates phosphorus fixation from all phosphorus inputs into the plant available soil phosphorus pool towards the stabile phosphorus pool and the release of phosphorus from the stabile soil phosphorus pool to the plant available labile pool. Here I describe how the SPAM works and how different compartments are calculated. The model is depicted in figure 23.

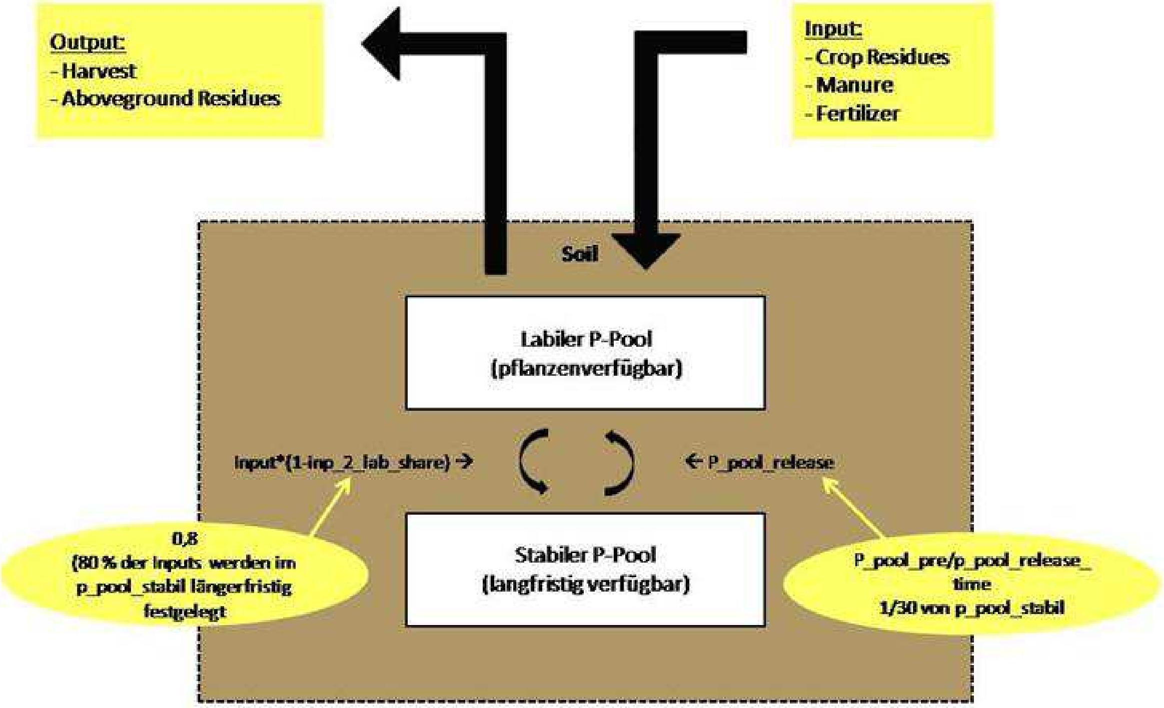

Figure 23: **Soil phosphorus accumulation model (SPAM)**

Phosphorus inputs ($P(x_t)_{t,i,v}^{inp\_soil}$) to croplands in the phosphorus module include inorganic phosphorus fertilizer ($P(x_t)_{t,i}^{fert}$), phosphorus in manure ($P(x_t)_{t,i}^{m\_cs}$), phosphorus from recycled crop residues ($P(x_t)_{t,i,v,rec}^{ds\_ag}$) and phosphorus from burned-on field crop residues ($P(x_t)_{t,i,v,burn}^{ds\_ag}$). The amount of phosphorus which is set free from organic soil matter loss by land conversion is not reproduced by the phosphorus module to reduce complexity to an extent that is easy to handle. This shortage is discussed later in context with the limits of the methodological approach. Phosphorus outputs ($P(x_t)_{t,i,v}^{out\_soil}$) from cropland soil are withdrawals by plant extraction through crop production ($P(x_t)_{t,i,v}^{prod}$) and above-ground residues ($P(x_t)_{t,i,v}^{prod\_ag}$) and seed ($P(x_t)_{t,i,v,seed}^{ds}$). The seed share is subtracted from withdrawals because seeds are also put into cropland soils by sewing, thereby accounting as well as input and output (eq. 29).

$$P(x_t)_{t,i}^{res} = \sum_v P(x_t)_{t,i,v,burn}^{ds\_ag} + P(x_t)_{t,i,v,rec}^{ds\_ag} \qquad \text{eq. 27}$$

$$P(x_t)_{t,i,v}^{inp\_soil} = \sum_v (P(x_t)_{t,i}^{fert} + P(x_t)_{t,i}^{m\_cs} + P(x_t)_{t,i}^{res}) \qquad \text{eq. 28}$$

$$P(x_t)_{t,i,v}^{out\_soil} = \sum_v (P(x_t)_{t,i,v}^{prod\_ag} + P(x_t)_{t,i,v}^{prod} - P(x_t)_{t,i,v,seed}^{ds}) \qquad \text{eq. 29}$$

Parameter	Description	Unit
Soil phosphorus accumulation model (SPAM)		
$P(x_t)_{t,i,v}^{out\_soil}$	Soil P withdrawals	Tg P
$P(x_t)_{t,i}^{inp\_soil}$	Soil P inputs	Tg P
$P(x_t)_{t,i}^{res}$	P in recycled AG residues	Tg P
$P(x_t)_{t,i}^{m\_cs}$	P in manure applied or excreted on cropland soils	Tg P
$P(x_t)_{t,i,v}^{prod\_ag}$	Residue production	Tg P
$P(x_t)_{t,i,v}^{prod}$	Crop production	Tg P
$P(x_t)_{t,i,v,seed}^{ds}$	Seed production	Tg P
$P(x_t)_{t,i}^{fert}$	Inorganic P fertilizer	Tg P
$P(x_t)_{t,i}^{soilp\_lab}$	Soil labile pool	Tg P
$P(x_t)_{t,i}^{p\_pool}$	Soil stabile pool	Tg P
$P(x_t)_{t,i}^{p\_rel}$	Phosphorus release from p-pool	TgP
$P(x_t)_{t,i}^{p\_fix}$	Phosphorus fixation	TgP
$r^{inp\_2\_lab}$	Input to labile share	

Table 8: SPAM parameters

I constructed two phosphorus pools in the soil. The labile pool ($P(x_t)_{t,i}^{soilp\_lab}$) contains plant available soil phosphorus. All phosphorus for the plant growth (output) is extracted from this pool. Therefore, the output equals the flow through the labile pool.

The other pool is the stabile pool ($P(x_t)_{t,i}^{p\_pool}$), which characterizes soil phosphorus accumulation. Phosphorus in this pool is not directly plant available but a defined share is released ($P(x_t)_{t,i}^{p\_rel}$) in each time step towards the labile pool, thereby becoming plant available over a long time.

The labile pool is fed by a defined share ($r^{inp\_2\_lab}$) of phosphorus inputs to croplands plus the phosphorus release from the longtime available phosphorus pool.

To dedicate phosphorus available for plant growth within each time step, all inputs, including fertilizer, are weighted by the inputs-to-labile-share factor or the other way round, phosphorus fixation towards the second, stable soil p-pool is calculated by inputs multiplied with the reciprocal input-to-labile share ($1 - r^{inp\_2\_lab}$). Thereby phosphorus from the labile pool is modeled to be fixed in a certain percentage of the labile pool each time-step ($P(x_t)_{t,i}^{p\_fix}$) into the second, stabile pool. In this way the stable pool fills up with phosphorus from the labile pool building a reservoir of residual phosphorus. This second pool ($P(x_t)_{t,i}^{p\_pool}$) is not available as plant nutrition in the short term, but in the long-term phosphorus from the stable pool can be made plant available by replenishing the labile pool with a certain amount each time step ($P(x_t)_{t,i}^{p\_rel}$).

Modeling a long-term solvation of phosphorus from that stabile pool I used a p-pool release time ($r^{pp\_rel\_time}$) of 30 years. The amount of phosphorus release each time step ($P(x_t)_{t,i}^{p\_rel}$) is ($\frac{1}{r^{pp\_rel\_time}}$) of the stabile p-pool. In this way the stabile p-pool works as a buffer for phosphorus accumulation and therefore for the applied phosphorus fertilizer for use in later years.

$$P(x_t)_{t,i}^{p\_rel}=P(x_t)_{t,i}^{p\_pool} \cdot (1/r^{pp\_rel\_time}) \qquad \text{eq. 30}$$

$$P(x_t)_{t,i}^{p\_fix} = P(x_t)_{t,i,v}^{inp} \cdot (1-r^{inp\_2\_lab}) \qquad \text{eq. 31}$$

$$P(x_t)_{t,i}^{soilp\_lab}=P(x_t)_{t,i,v}^{inp} \cdot (1-r^{inp\_2\_lab}) + P(x_t)_{t,i}^{p\_rel} \qquad \text{eq. 32}$$

$$P(x_t)_{t,i}^{p\_pool}=P(x_t)_{t-1,i}^{p\_pool} + P(x_t)_{t,i}^{p\_fix} - P(x_t)_{t,i}^{p\_rel} \qquad \text{eq. 33}$$

Calibration of the soil accumulation model

Phosphorus fertilizer is calculated by the MAgPIE-Model endogenously by the needs for phosphorus from plant growth due to the optimization process. Due to the lack of high quality data for the plant available phosphorus content of soils, the phosphorus retention potential, a long term available phosphorus pool or other applicable data in a spatial explicit global range I used a solution to parameterize the initial soil p-pool and to calibrate the model by available fertilizer-use data of 1995. To determine the amount of phosphorus fertilizer totally applied to soils in 1995, I calculated the aggregated amounts of inorganic p-fertilizers in line with Bodirsky et al. (2012) with data from IFA (2011) for the ten MAgPIE regions.

For the calibration of the model and to calculate the initial soil P-pool in the first time step fertilizer, I used fertilizer input as an exogenous variable. I fixed the amount of applied phosphorus fertilizer in 1995 ($P(x_t)_{t=1,i}^{fert}$) to real world data. That means that for the first time step $t=1$ I applied the model to calculate and quantify the initial phosphorus pool ($P(x_t)_{t=1,i}^{pool}$). That means that for the first time step fertilizer consumption ($P(x_t)_{t,i}^{fert}$) is an exogenous given variable, while the soil phosphorus pool ($P(x_t)_{t,i}^{pool}$) is an endogenous variable. For all other time steps (t >1) fertilizer consumption is an endogenous variable, calculated by the model while soil phosphorus pool becoming the exogenous variable received from the previous time step $t-1$.

3.5 Scenario and set-up

I applied a scenario concerning global future development parameters orientated on the SSP2 scenario by Kriegler et al. (2012, 2013) and equivalent to the baseline-scenario from Bodirsky et al. (2012). The scenario can be described as a „middle-of-the-road“ scenario within the broadly used IPCC *SRES*-storyline scenarios, which characterize different storylines of global future development within a economic vs. ecologic and globalized vs. decentralized coordinate system (Nakicenovic et al. 2000). Influencing variables in these scenarios are population growth, dietary habits assumptions, trade patterns, economic development

3.6 Modeling language GAMS, data extraction and analysis with Rup

The models used in this thesis, LPJmL and MAgPIE, are written in different programming languages. For the data extraction other programming approaches have been used. LPJmL is written in C, while MAgPIE is written in GAMS („General Algebraic Modeling System“), which is mainly used for the modeling of optimization problems (Brooke et al. 1988, McCarl et al. 2008), e.g. economic cost minimization or profit maximization problems. The GAMS syntax is kept simple, thereby becoming apllicable by a bigger number of users. The disadvance of this feature is that some mathematical calculations cannot performed by GAMS. Therfore some calculations are outsourced to other scripts embracing the GAMS code (Dietrich 2011). I developed a script written in R (Venables and Smith 2009) to extract and analyse data (see appendix).

4 Results

With the modeling of the phosphorus cycle in MAgPIE by the phosphorus module, including the soil phosphorus accumulation model (SPAM), it is possible to reproduce stocks and flows within the global phosphorus cycle as well as phosphorus accumulation in the soils due to fertilization and thereby, to quantify these stocks and flows. In this chapter I will present the results of the model run. These are estimations of stocks and flows, including losses to environmental systems as well as fertilizer use and soil phosphorus accumulation from 1995 to 2050. To estimate the ability of the soil phosphorus accumulation model (SPAM) to reproduce phosphorus accumulation and phosphorus dynamics in a reasonable way, I set up a sensitivity analysis and changed coefficients of the model to draw some conclusions on how the model reacts on a change in basic assumptions, and how it can be adjusted and improved for further works. The chapter provides the main results in a compact and summarized form, mostly on the global level. Detailed results, including animal and cropland budgets, losses as well as more regional information on parts of the phosphorus cycle, can be found in the appendix.

4.1 General results - stocks and flows in the global p-cycle, fertilizer use, soil phosphorus accumulation and losses to the environment

In table 9, the stocks and flows within the phosphorus cycle, fertilizer use, soil phosphorus accumulation and losses from 1995 to 2050 are summarized.

Parameter	**TgP**							
Year	1995	2000	2005	2010	2020	2030	2040	2050
Fertilizer (1)	13.51	20.06	19.70	23.60	36.64	17.71	29.59	23.17
AG-Biomass (5)	6.60	7.05	7.58	8.38	10.31	11.69	12.23	12.54
AG-res rec cropl (7)	3.05	3.17	3.37	3.68	4.83	5.73	6.05	6.53
AG-res burn cropl (8)	1.40	1.48	1.57	1.70	2.02	2.21	2.22	2.18
AG-res household burn (9)	0.40	0.42	0.43	0.44	0.48	0.45	0.38	0.30
AG-res for feed (10)	1.76	1.98	2.21	2.55	2.98	3.30	3.59	3.53
AG res rc cropl. (total)	4.44	4.65	4.94	5.39	6.86	7.94	8.26	8.71
Harvest (6)	13.05	14.26	15.60	17.40	20.72	23.61	26.36	28.89
Feed conc & foddr crops (11)	4.90	5.33	5.84	6.81	8.85	10.77	12.40	13.63
Material use and losses (13)	1.44	1.57	1.70	1.83	2.09	2.33	2.51	2.66
Crop prod/processing (12)	6.27	6.79	7.30	7.76	8.69	9.56	10.33	10.97
Seed	0.42	0.45	0.49	0.55	0.67	0.77	0.86	0.94
Conversion byproducts (15)	2.59	2.81	3.01	3.19	3.55	3.88	4.16	4.38
Conv_by use for feed (16)	2.07	2.29	2.49	2.67	3.03	3.36	3.64	3.86

Conv_by for oth. use	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51
Slaughtered animals	2.58	2.86	3.14	3.62	4.56	5.37	5.98	6.44
Livestock products (21)	1.79	2.00	2.20	2.56	3.25	3.84	4.29	4.63
Other use	0.29	0.3	0.33	0.35	0.42	0.48	0.51	0.54
Slaughter waste	0.50	0.56	0.61	0.71	0.89	1.05	1.18	1.27
Vegt prod/food (14)	3.68	3.98	4.29	4.57	5.14	5.68	6.17	6.59
Total Food (23)	5.47	5.98	6.49	7.13	8.39	9.52	10.46	11.22
Total Bioenergy	0.01	0.13	0.27	0.45	0.42	0.18	0.25	0.69
Feed total / livestock (18)	22.33	24.84	27.28	31.10	37.24	41.90	44.81	46.16
Feed from pasture (19)	12.33	13.68	14.88	16.65	19.36	21.30	22.18	22.40
Feed from concentrate (11)	2.83	3.18	3.58	4.41	6.15	7.70	8.95	9.72
Feed from fodder	2.08	2.14	2.26	2.40	2.70	3.07	3.45	391
Feed from animal	0.10	0.10	0.11	0.12	0.16	0.20	0.22	0.23
…Feed from residues (10)	1.76	1.98	2.21	2.55	2.98	3.30	3.59	3.53
…Feed from convby	2.07	2.29	2.49	2.67	3.03	3.36	3.64	3.86
…Feed from scavenging	1.27	1.56	1.87	2.43	3.02	3.17	3.00	2.74
Total manure	19.75	21.98	24.14	27.48	32.69	36.53	38.83	39.72
Manure graz past (25)	10.45	11.58	12.59	14.17	16.86	18.90	19.85	20.19
Manure graz cropl (24)	0.41	0.44	0.47	0.49	0.46	0.42	0.36	0.27
Manure/household fuel (26)	2.14	2.54	2.92	3.52	3.82	3.54	3.04	2.46
Manure in confinement	6.76	7.42	8.16	9.30	11.55	13.67	15.58	16.79
Conf rec cropl (29)	5.85	6.46	7.05	7.88	9.34	10.56	11.54	11.94
Conf rec pasture (30)	0.60	0.70	0.81	1.05	1.63	2.32	3.05	3.71
Total manure on cropland	6.26	6.90	7.52	8.37	9.80	11.02	11.90	12.21
Total manure on pasture	11.05	12.28	13.40	15.22	18.49	21.22	22.90	23.90
Soil p-pool (3)	438.98	490.48	535.49	593.73	818.51	835.34	952.04	985.26
In from p_pool (4)	14.48	14.63	16.35	17.85	19.79	27.28	27.84	31.73
Out_2_p_pool (2)	19.04	24.93	25.35	29.50	42.27	28.97	39.52	35.06
Total losses	11.40	12.63	13.92	15.69	17.90	19.08	19.98	20.85
Losses awms	0.72	0.71	0.76	0.86	1.04	1.21	1.35	1.42
Losses sl.waste	0.50	0.56	0.61	0.71	0.89	1.05	1.18	1.27
Losses by food	5.47	5.98	6.49	7.13	8.38	9.52	10.46	11.22
Losses bioenergy	0.42	0.54	0.70	0.89	0.89	0.63	0.63	1.00
Losses convby	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52
Losse material	1.64	1.78	1.92	2.06	2.35	2.60	2.81	2.97
Losse manure fuel	2.14	2.54	2.92	3.52	3.82	3.54	3.04	2.46

Table 95: Stocks and Flows in the global P-Cycle (results)

The global phosphorus cycle with quantifications, summarized in the previous section, is depicted for the years 1995 and 2050 in figure 24. The figure includes; stocks and flows, soil phosphorus accumulation and fertilizer input into agricultural systems. Not included in the graphical description are the total losses to environmental systems. These are quantified and described further below.

The development of stocks and flows within the global phosphorus cycle is characterized by an increase of the total inputinto agricultural systems by fertilizer use - by 71% - from 13.5 TgP in 1995 to 23.2 TgP in 2050.Total biomass production (5+6) accounts for 19.6 TgP in 1995 and 41.4 TgP in 2050;an increase of 111%. Food processing (12) increased by 74%, from 6.3 TgP to 11.0 TgP; vegetal products for food use (14) by 78%, from 3.7 TgP to 6.6 TgP; while crop production for feed use (11) increased by 177%, from 4.9 TgP to 13.6 TgP, this accounting for an increased demand for animal products for food use. In 1995,animal products accounted for 33% of total food, while animal food in 2050 accounts for 42% of total human nutrition (23).

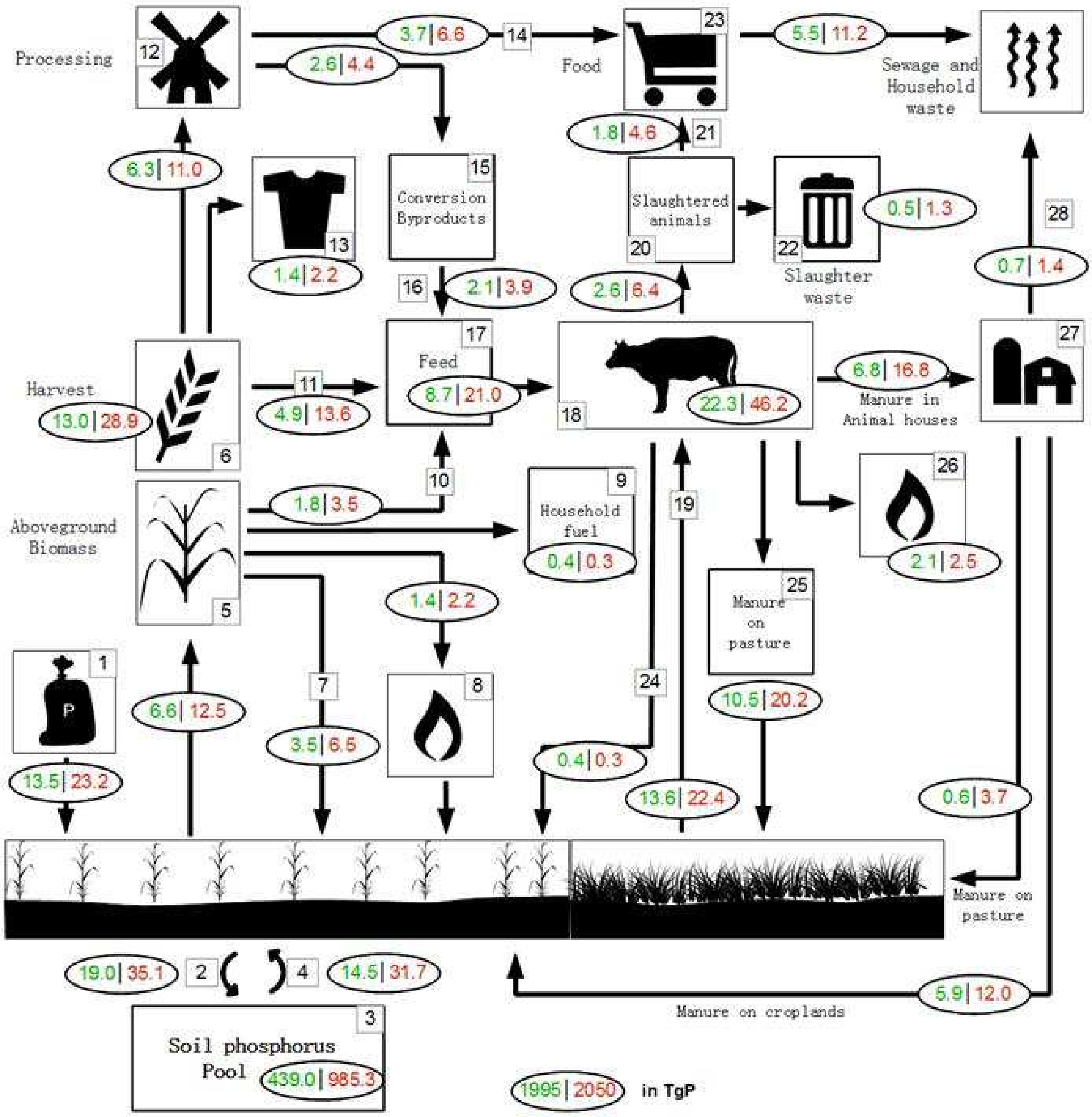

Figure 24: Stocks and flows in the global P-cycle (results)

Total food for human nutrition increased by 103%, accounting for 5.5 TgP in 1995 and 11.2 TgP in 2050, lastly ending in sewage systems and thereby losses to the environment and waterbodies. In contrast to feed from cropland, total feed use from pasture merely increased by 82%, from 12.3 TgP to 22.4 TgP. Total manure increased by 101%, from 19.75 TgP to 39.72 TgP, due to a change towards a more industrial livestock system. Therefore, manure in confinement increased by 150%, from 6.8 TgP to 16.8 TgP, leading to an increase of losses to the environment from confinement by 100%, from 0.7 TgP to 1.4 TgP. Manure recycling from confinement to cropland increased by 1003%, from 5.9 TgP to 12 TgP, while recycling from confinement to pasture increased by 516%, from 0.6 TgP to 3.7 TgP, due to the change towards more industrialized livestock and animal waste management systems. Total losses to the non-agricultural environment increased by 83%, from 11.4 TgP in 1995 to 20.85 TgP in 2050. The more detailed description follows in the sections below.

4.1.1 Fertilizer use on a global and regional level

The results concerning fertilizer use on a regional level are depicted in table 10 and figures 25 and 26.

Region	**TgP from years 1995 to 2050**							
Year	1995	2000	2005	2010	2020	2030	2040	2050
AFR	0.27	1.05	2.31	3.32	6.88	3.98	6.16	7.13
CPA	4.03	5.62	4.45	5.26	7.97	4.38	10.09	2.42
EUR	2.14	2.46	2.04	2.03	1.79	1.29	1.73	1.55
FSU	0.33	0.05	0.82	0.76	1.06	0.18	0.84	0.62
LAM	1.10	2.14	2.05	2.99	7.25	1.52	2.12	3.29
MEA	0.47	0.69	0.55	0.76	0.99	0.51	0.85	0.31
NAM	2.08	3.70	3.45	3.75	3.34	2.15	2.87	2.90
PAO	0.87	0.76	0.32	0.31	0.41	0.25	0.19	0.33
PAS	0.62	0.85	0.82	0.76	1.09	0.62	0.22	0.59
SAS	1.60	2.74	2.89	3.67	5.86	2.84	4.51	4.02
SUM	**13.51**	**20.06**	**19.70**	**23.60**	**36.64**	**17.71**	**29.59**	**23.71**

Table 10: Fertilizer use (results)

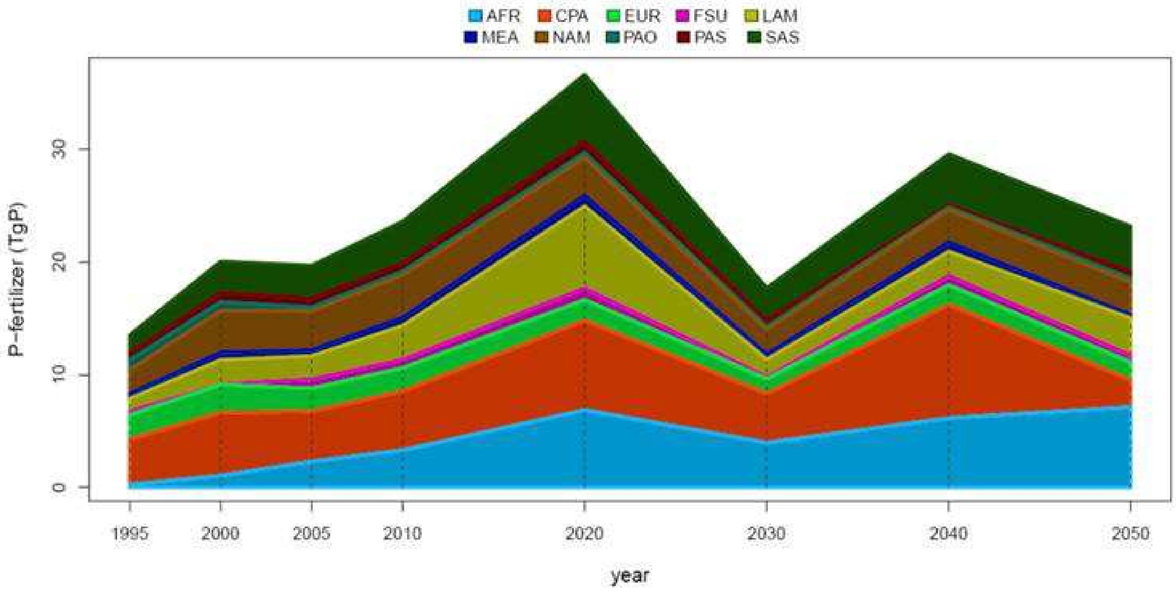

Figure 25: **Fertilizer use – global (results)**

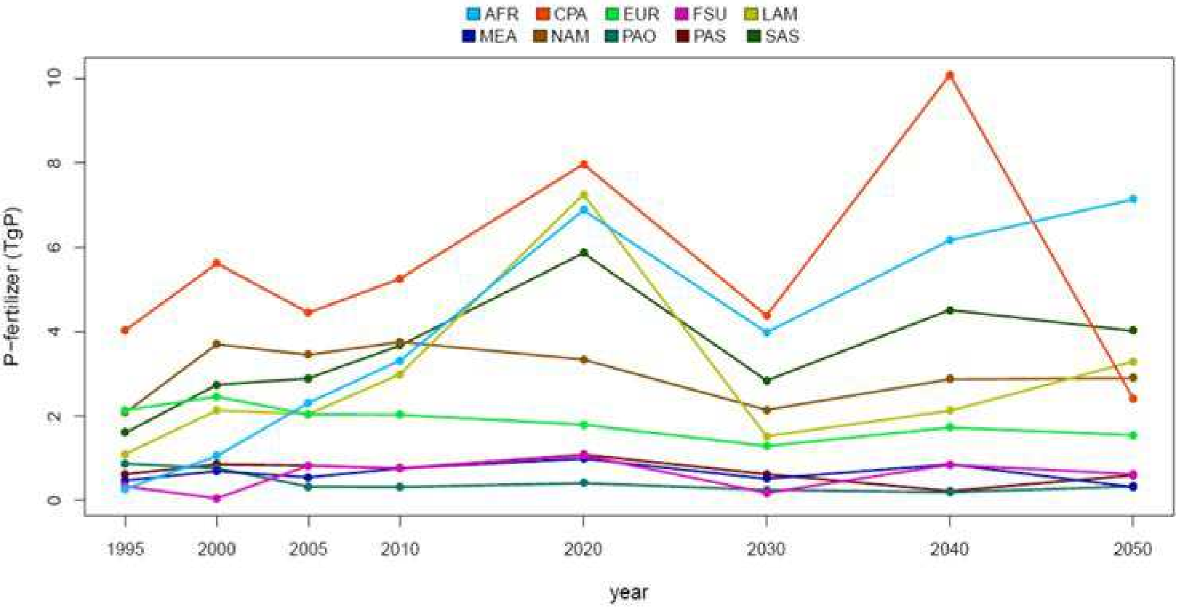

Figure 26: **Fertilizer use – regional (results)**

Phosphorus fertilizer use is increasing on a global scale from 13.51 TgP in 1995 to 36.64 TgP in 2020, followed by a strong decrease and an oscillation between17.71 TgP and 29.59 TgP. This could be due to the model set-up. A sensitivity analysis has been done to improve and calibrate the model for further setups. The sensitivity analysis will be discussed in chapter 5.1.3. On the regional level, some high input regions can be identified. These are CPA; including China, AFR, LAM and SAS including

India. NAM can be evaluated as a middle input region, followed by EUR and FSU, PAO. MEA and PAS are low input regions. The results concerning fertilizer use are discussed in depth in chapter 5.

4.1.2 Phosphorus accumulation including fixation and release

4.1.2.1 Soil p-pool

The results concerning soil p-pool are depicted in table 11 and figures 27 and 28.

Region				**TgP**				
Year	1995	2000	2005	2010	2020	2030	2040	2050
AFR	27.71	29.74	37.02	47.92	98.67	113.91	145.25	178.58
CPA	69.03	86.09	96.51	109.99	160.57	170.46	228.43	208.11
EUR	66.71	72.23	75.30	77.97	80.55	77.99	79.18	78.06
FSU	34.68	32.96	34.92	36.36	41.68	38.02	40.69	4020
LAM	47.08	53.42	58.92	68.35	126.22	124.41	128.06	138.17
MEA	11.59	14.01	15.59	18.13	24.88	26.47	31.04	30.27
NAM	88.45	97.39	104.23	111.33	119.42	114.73	116.60	117.55
PAO	10.56	13.58	14.36	15.02	17.02	17.18	16.75	17.52
PAS	20.31	22.48	24.26	25.62	31.40	32.63	30.38	32.30
SAS	62.85	68.58	74.39	83.06	118.10	119.54	135.68	144.51
SUM	**438.98**	**490.48**	**535.49**	**593.73**	**818.51**	**835.34**	**952.04**	**985.26**

Table 11: Soil P-pools (results)

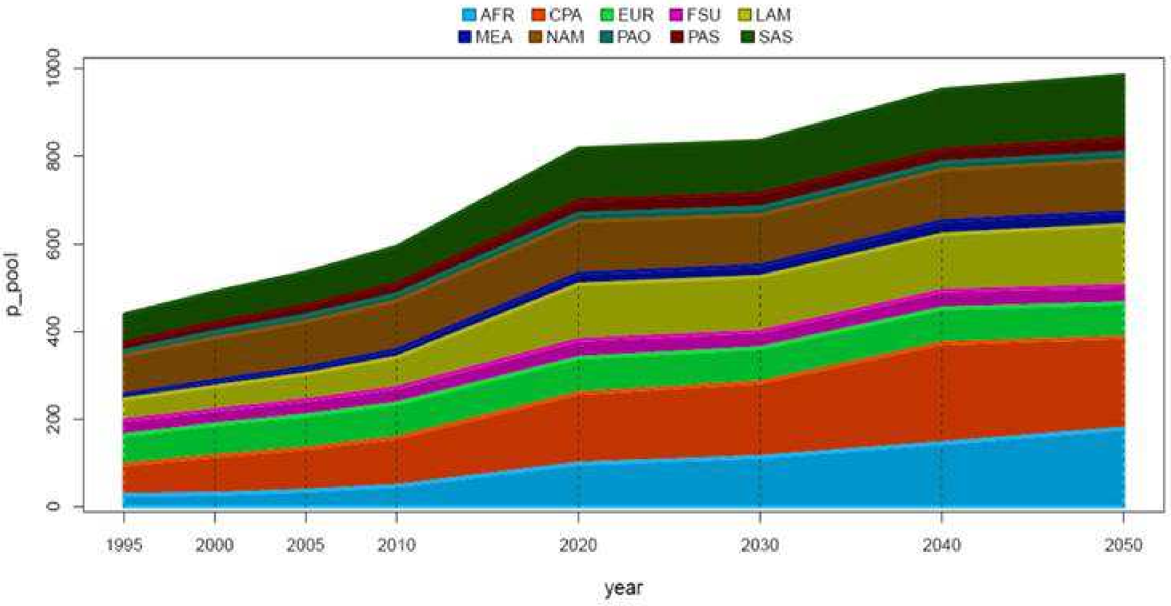

Figure 27: Soil P-Pool – global (results)

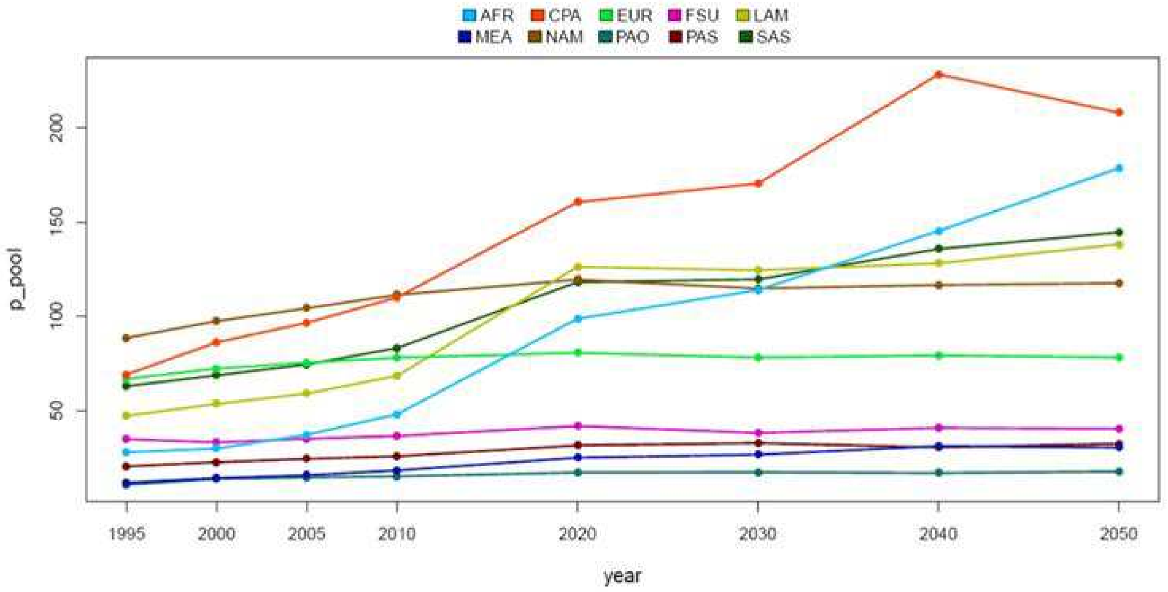

Figure 28: Soil P-Pool – regional (results)

The global soil phosphorus pool is accumulating; from total 438.98 TgP in 1995 to 985.26 TgP in 2050. Some regions accumulate strongly like AFR, CPA, LAM and SAS. Others, like FSU, PAS, MEA and PAO nearly maintain their low level. EUR and NAM nearly maintain their initial middle to high level.

4.1.2.2 Soil phosphorus fixation

Phosphorus fixation is depicted in table 12 and figure 29.

Region				TgP				
Year	1995	2000	2005	2010	2020	2030	2040	2050
AFR	0.63	1.33	2.45	3.41	6.67	4.81	6.93	8.18
CPA	4.25	5.71	4.95	5.91	8.72	6.34	11.48	5.58
EUR	3.04	3.33	3.02	3.04	2.86	2.43	2.72	2.53
FSU	1.12	0.81	1.49	1.45	1.74	1.02	1.53	1.31
LAM	1.86	2.84	2.88	3.85	8.07	4.03	4.51	5.28
MEA	0.65	0.87	0.78	1.03	1.28	0.99	1.34	0.96
NAM	3.32	4.74	4.61	4.89	4.52	3.51	4.01	3.98
PAO	1.04	0.96	0.61	0.61	0.70	0.58	0.53	0.64
PAS	0.90	1.11	1.11	1.08	1.43	1.17	0.86	1.20
SAS	2.22	3.24	3.45	4.21	6.27	4.08	5.60	5.41
SUM	**19.04**	**24.93**	**25.35**	**29.50**	**42.27**	**28.97**	**39.52**	**35.06**

Table 12: Soil phosphorus fixation (results)

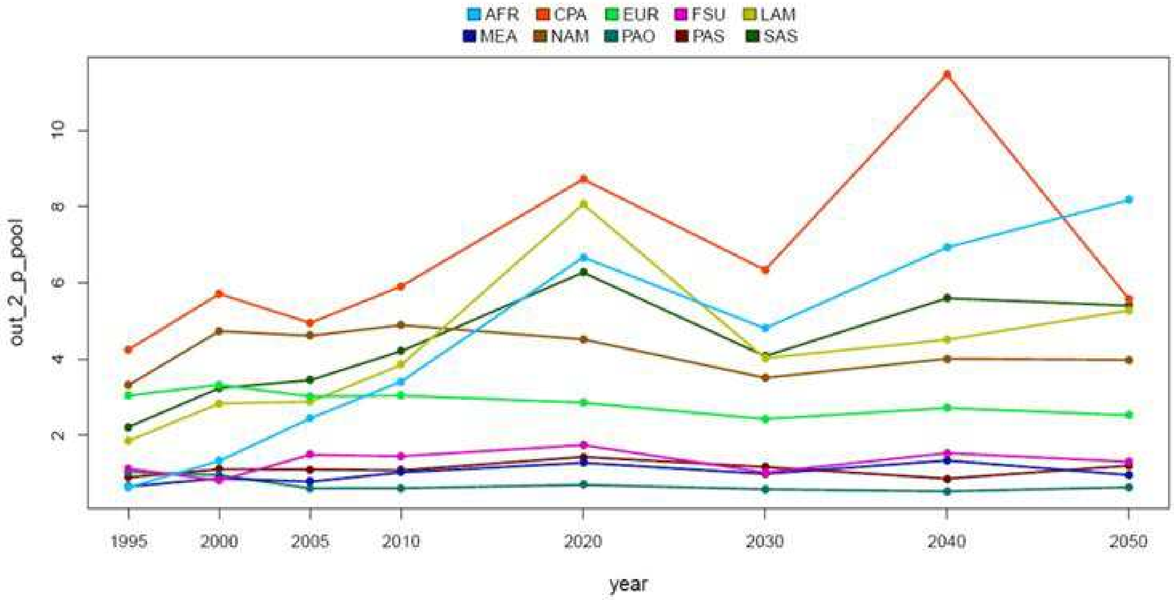

Figure 29: **Soil phosphorus fixation (results)**

The total phosphorus fixation has increased from 19.04 TgP in 1995 to 42.27 TgP in 2020, with the following oscillation between 28.97 TgP and 39.52 TgP. Thereby, phosphorus fixation tothe p-pool follows the characteristics ofthe fertilizer inputs with some differences. The oscillation is not as strong as in fertilizer input.

Like in fertilizer input, as well as for the p-pool, different region groups can be identified. A region group including AFR, CPA, SAS and LAM is characterized by a strong increase in fixation (corresponding to a high fertilizer input). EUR and NAM are maintaining their initial medium to high level of phosphorus fixation (with the same evaluation in fertilizer input). FSU, MEA, PAS and PAO maintain a low level of phosphorus fixation, corresponding to low levels of fertilizer input and a low phosphorus pool.

4.1.2.3 Phosphorus release

The phosphorus release is depicted in table 14 and figure 30

Region				TgP				
Year	1995	2000	2005	2010	2020	2030	2040	2050
AFR	0.93	0.92	0.99	1.23	1.60	3.29	3.80	4.84
CPA	2.23	2.30	2.87	3.22	3.67	5.35	5.68	7.61
EUR	2.20	2.22	2.41	2.51	2.60	2.68	2.60	2.64
FSU	1.16	1.16	1.10	1.16	1.21	1.39	1.27	1.36
LAM	1.56	1.57	1.78	1.96	2.28	4.21	4.15	4.27
MEA	0.38	0.39	0.47	0.52	0.60	0.83	0.88	1.03
NAM	2.94	2.95	3.25	3.47	3.71	3.98	3.82	3.89
PAO	0.33	0.35	0.45	0.48	0.50	0.57	0.57	0.56
PAS	0.67	0.68	0.75	0.81	0.85	1.05	1.09	1.01
SAS	2.09	2.10	2.29	2.48	2.77	3.94	3.98	4.52
SUM	**14.48**	**14.63**	**16.35**	**17.85**	**19.79**	**27.28**	**27.84**	**31.73**

Table 13: Phosphorus release from P-Pool (results)

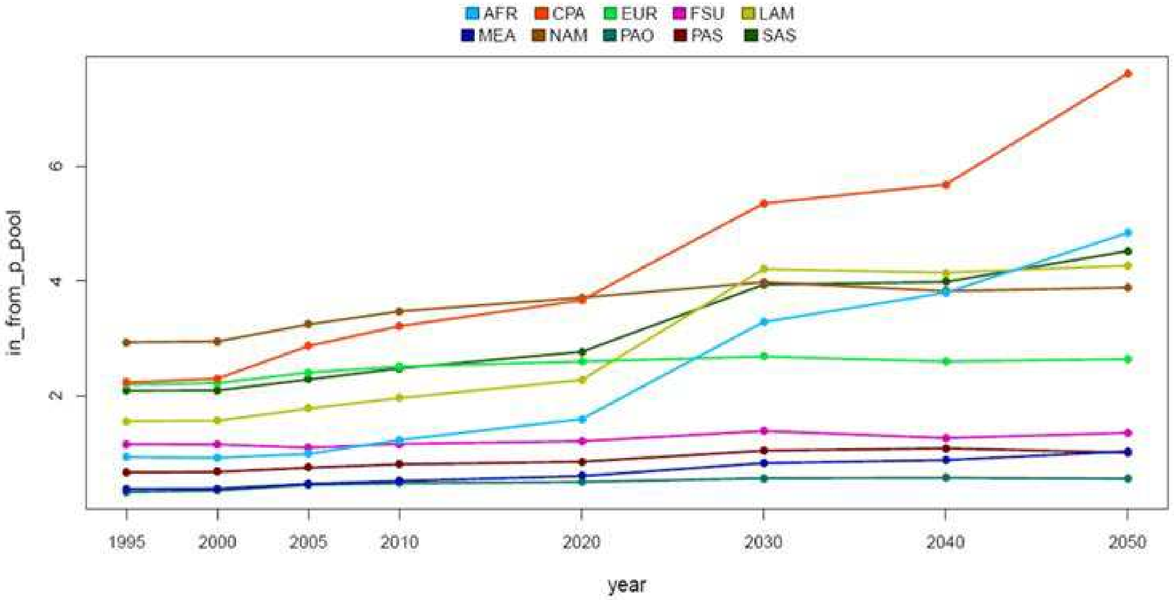

Figure 30: Phosphorus release from P-Pool (results)

Phosphorus release follows the phosphorus pool as modeled in the SPAM. It is therefore not surprising that AFR, CPA, LAM and SAS show a strong increase in phosphorus release from the p-pool. EUR and NAM maintain on their initial medium to high level and FSU, PAO, PAS and MEA are maintaining a low level of phosphorus release.

4.1.3 Total food, livestock and manure production

4.1.3.1 Total crop production

The results concerning total crop production are depicted in table 14 and figure 31.

Region				TgP				
Year	1995	2000	2005	2010	2020	2030	2040	2050
AFR	0.61	0.72	0.95	1.27	2.04	2.85	3.65	4.70
CPA	2.34	2.68	2.99	3.46	4.37	5.17	6.34	6.67
EUR	2.16	2.24	2.13	2.39	2.42	2.41	2.43	2.41
FSU	1.05	1.00	1.08	1.13	1.23	1.23	1.23	1.25
LAM	1.16	1.33	1.47	1.69	2.28	2.85	3.24	3.90
MEA	0.38	0.43	0.48	0.57	0.68	0.80	0.92	0.97
NAM	2.78	3.06	3.27	3.49	3.57	3.56	3.53	3.55
PAO	0.42	0.42	0.43	0.45	0.48	0.51	0.50	0.50
PAS	0.53	0.58	0.63	0.67	0.77	0.87	0.84	0.85
SAS	1.62	1.80	1.98	2.28	2.86	3.36	3.69	4.08
SUM	**13.05**	**14.26**	**15.60**	**17.40**	**20.72**	**23.61**	**26.36**	**28.89**

Table 14: Total crop production (results)

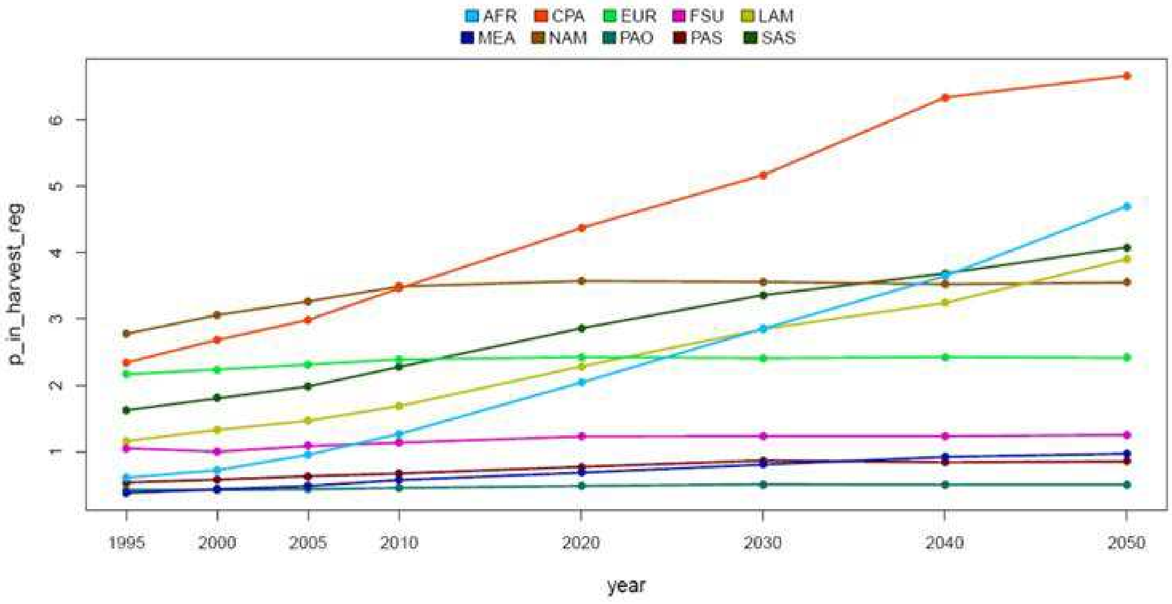

Figure 31: Total crop production (results)

The global crop production has increased from 13.05 TgP in 1995 to 28.89 TgP in 2050. Of all regions, AFR shows an increase of 670% from a very low initial level to the second largest producer in 2050. With a total of more than plus 4 TgP, AFR and CPA show nearly the same absolute growth, followed by LAM with plus 2.74 TgP and SAS with 2.46 TgP;an increase of 236% and 151% respectively. EUR and NAM maintain their relatively high initial level of crop production but show no substantial increase. PAO, PAS and FSU nearly maintain their low initial level of crop production. In contrast to these last three regions, MEA shows a substantial increase of 155% in crop production from a very low initial level.

4.1.3.2 *Total feed livestock production*

The results concerning total fee/livestock production are depicted in table 15 and figures 32.

Region				**TgP**				
Year	1995	2000	2005	2010	2020	2030	2040	2050
AFR	2.25	2.50	2.87	3.24	4.09	5.21	6.45	7.48
CPA	2.24	2.83	3.27	4.16	5.59	6.11	6.39	6.70
EUR	2.93	2.97	2.99	3.01	3.01	2.95	2.79	2.58
FSU	1.57	1.37	1.48	1.52	1.61	1.64	1.62	1.44
LAM	4.60	5.15	5.34	5.72	6.60	7.79	8.66	8.61
MEA	0.63	0.74	0.82	0.96	1.14	1.36	1.54	1.65
NAM	2.26	2.42	2.53	2.52	2.39	2.25	2.03	1.80
PAO	0.98	0.98	0.99	1.01	1.02	1.01	0.97	0.92
PAS	0.57	0.62	0.68	0.77	1.06	1.38	1.35	1.49
SAS	4.29	5.26	6.30	8.20	10.72	12.19	13.01	13.50
SUM	**22.33**	**24.84**	**27.28**	**31.10**	**37.24**	**41.90**	**44.81**	**46.16**

Table 15: Feed/livestock production (results)

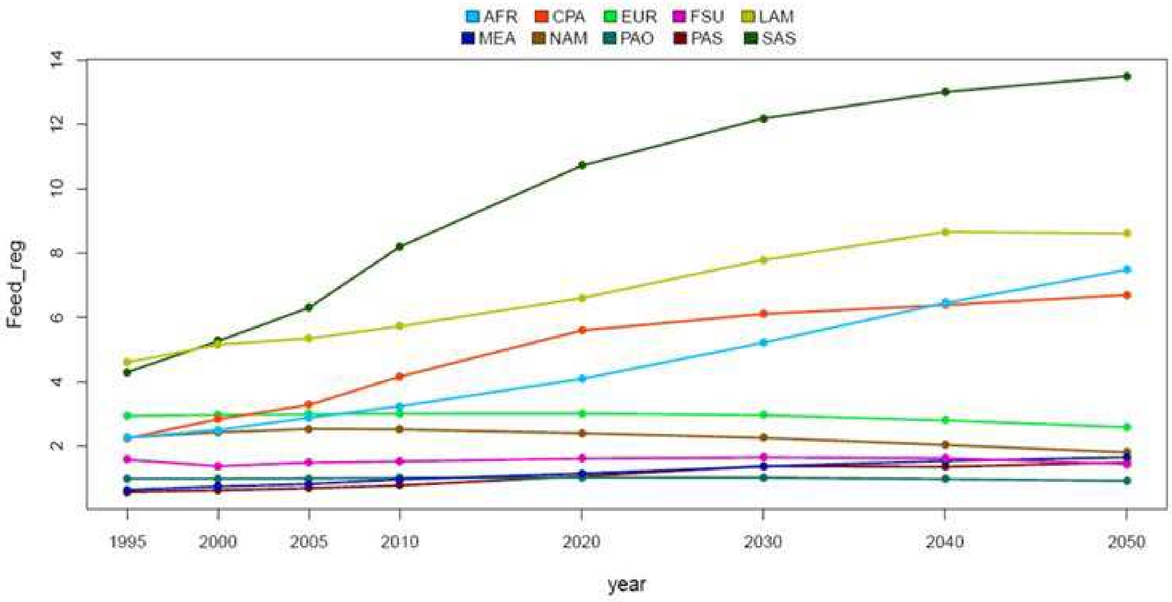

Figure 32: Feed/livestock production (results)

4.1.3.3 *Total plant products for food use*

The results concerning the total plant products for food use are depicted in table 16 and figure 33.

Region	TgP							
Year	1995	2000	2005	2010	2020	2030	2040	2050
AFR	0.39	0.45	0.53	0.61	0.78	0.98	1.18	1.37
CPA	0.99	1.04	1.08	1.09	1.08	1.06	1.06	1.04
EUR	0.35	0.37	0.39	0.40	0.43	0.46	0.49	0.51
FSU	0.18	0.18	0.20	0.20	0.20	0.19	0.19	0.20
LAM	0.10	0.11	0.12	0.12	0.13	0.14	0.15	0.16
MEA	0.34	0.38	0.42	0.46	0.54	0.61	0.68	0.72
NAM	0.10	0.12	0.12	0.13	0.16	0.18	0.20	0.23
PAO	0.09	0.09	0.09	0.09	0.10	0.10	0.11	0.11
PAS	0.27	0.30	0.32	0.35	0.39	0.42	0.45	0.46
SAS	0.87	0.95	1.03	1.13	1.33	1.51	1.67	1.79
SUM	**3.68**	**3.98**	**4.29**	**4.57**	**5.14**	**5.68**	**6.17**	**6.59**

Table 16: Total plant production for food use (results)

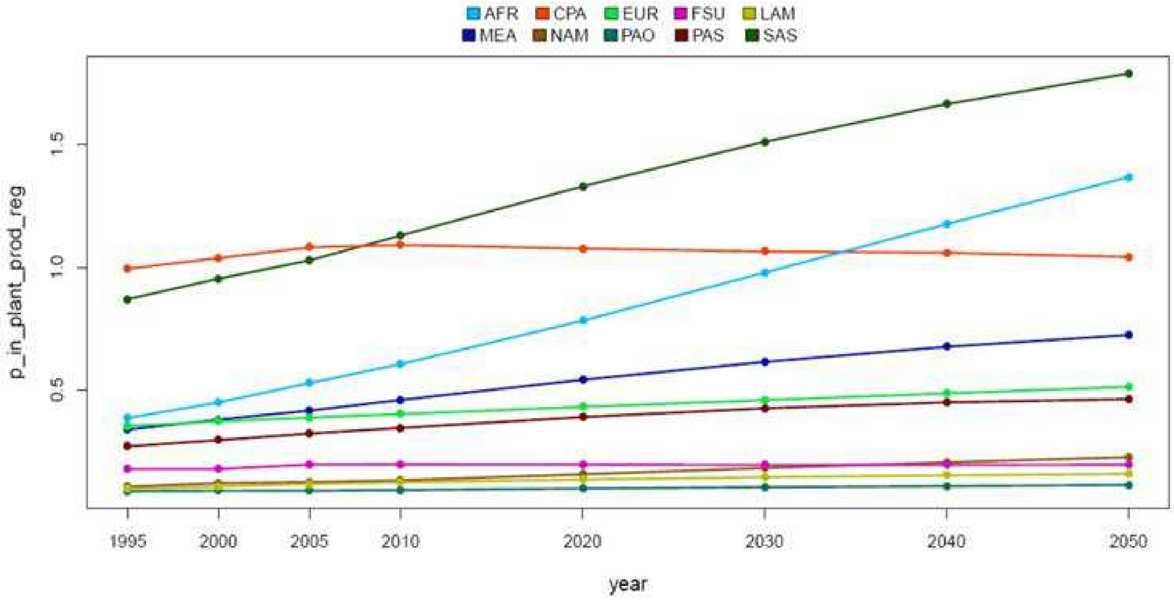

Figure 33: Total plant production for food use (results)

4.1.3.4 *Total livestock production*

The results concerning soil total livestock production are depicted in table 17 and figure 34.

Region	TgP							
Year	1995	2000	2005	2010	2020	2030	2040	2050
AFR	0.07	0.08	0.10	0.13	0.20	0.32	0.48	0.69
CPA	0.33	0.42	0.50	0.66	0.96	1.12	1.11	1.02
EUR	0.40	0.41	0.42	0.43	0.44	0.44	0.43	0.40
FSU	0.13	0.12	0.13	0.14	0.17	0.19	0.19	0.19
LAM	0.23	0.27	0.29	0.33	0.41	0.48	0.53	0.57
MEA	0.07	0.08	0.09	0.11	0.15	0.21	0.26	0.30
NAM	0.29	0.32	0.34	0.35	0.34	0.33	0.32	0.30
PAO	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.06
PAS	0.07	0.07	0.08	0.10	0.15	0.20	0.25	0.30
SAS	0.14	0.16	0.19	0.24	0.35	0.49	0.64	0.79
SUM	**1.79**	**2.00**	**2.20**	**2.56**	**3.25**	**3.84**	**4.29**	**4.63**

Table 17: Livestock products for use (results)

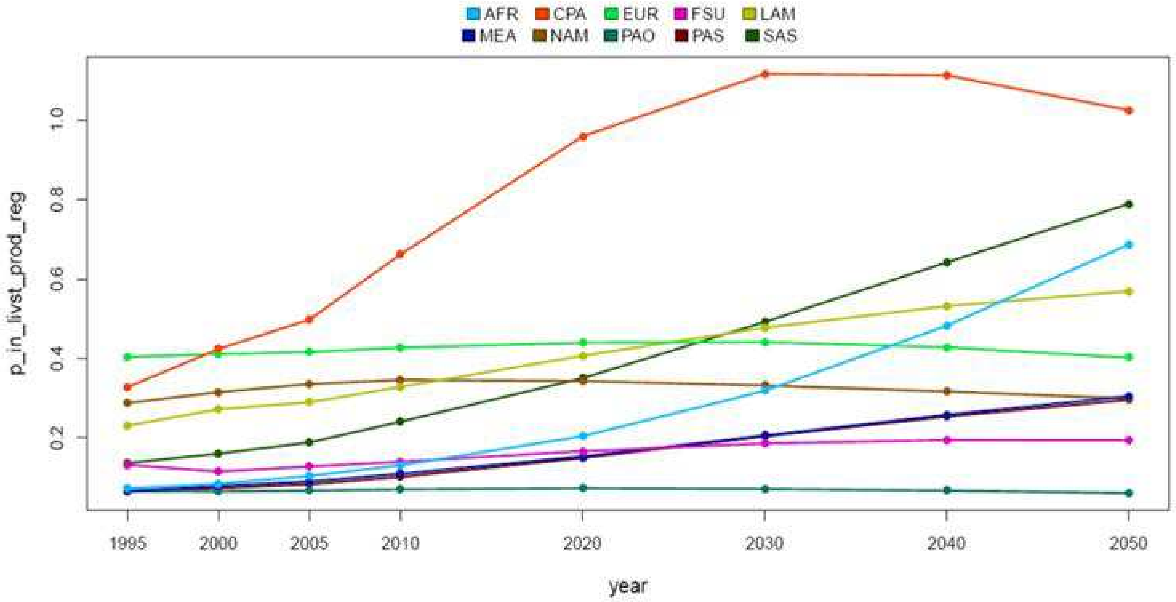

Figure 34: Livestock products for use (results)

Total livestock production for food use has increased from 1.79 TgP in 1995 to 4.63 TgP in 2050. Concerning livestock products for food use, CPA shows the biggest increase. AFR and SAS also show a substantial increase towards 2050. LAM on a medium level, and MEA as well as PAS, from a low initial level; show a significant increase in livestock products for food use. EUR and NAM from a rather high initial level maintain their initial level in the beginning followed by a small decrease towards

2050. FSU shows a small increase from a low initial level and PAO do not show a substantial increase from a very low initial level.

4.1.4 Losses

I calculated total losses to the non-agricultural environment to increase by 83%, from 11.4 TgP in 1995 to 20.85 TgP in 2050 (fig.9). Total losses include losses from the animal waste management system (awms), losses from slaughter waste, losses from food (sewage systems), bioenergy losses, losses from conversion byproducts, material losses and losses from manure used as fuel in developing countries.

The losses from awms are estimated to increase from 0.72 TgP in 1995 to 1.42 in 2050. The losses via slaughter waste increased from 0.5 TgP to 1.27 TgP. Losses via food plays a major role for total losses, and increased from 5.47 TgP in 1995 to 11.22 TgP in 2050. Losses by bioenergy increased from 0.42 TgP in 1995 to 1 TgP in 2050. Losses of conversion byproducts remain static, due to their calculation at the level of 0.52 TgP. Material losses increase from 1.64 to 2.97 TgP. Losses from manure used as a fuel in developing countries also play a substantial role within total losses, and increase from 2.14 up to 3.82 in 2020, afterwards declining due to the change towards more a industrialized food system, down to 2.46 TgP.

4.2 Sensitivity analysis

This soil phosphorus model was the very first approach to represent phosphorus accumulation in cropland soils and to quantify phosphorus fertilizer use. The results of the sensitivity analysis show that the results are strongly dependant on the coefficients for phosphorus fixation and release. The following have been subject to the sensitivity analysis; (1) the initial amount of fertilizer use which has been used in the first timestep to calculate the initial soil p-pool, (2) the input to labile share which characterizes the intensity of phosphorus fixation and (3) the phosphorus release time, which characterizes the intensity of phosphorus release from the soil p-pool. The initial amount of fertilizer has been changed plus 10% and minus 10% from the default, as fertilizer statistics are rather inaccurate. The input to labile share, which has been 0.2 in the default, has been decreased to 0.1 and increased to 0.4. The phosphorus release time, which has been assumed to be 30 years in the default, has been changed to 15 years and 60 years, respectively. The results of the sensitivity analysis are shown in subsection 4.2.1 to 4.2.4 in tables 19 -22 and figures 35-38.

4.2.1 Results of the sensitivity analysis under different set-ups

4.2.1.1 Fertilizer use

The results of the sensitivity analysis concerning fertilizer use are shown in table 18 and figure 35. As table 18 shows, a change in the initial fertilizer amount for the calculation of the initial p-pool does not influence the fertilizer use in further years. Due to implausible negative values for the low input-to-labile share, and the fast-release version, these are excluded from the depiction in the figures.

	Fertilizer Use							
Set up	1995	2000	2005	2010	2020	2030	2040	2050
Default	13,51	20,06	19,70	23,60	36,64	17,71	29,59	23,17
Low labile	13,51	27,37	15,47	31,50	47,20	-23,62	139,47	-239,33
High labile	13,51	16,37	17,29	19,63	26,28	24,34	24,14	24,89
Low fert	12,16	18,95	19,49	23,53	36,39	17,89	29,53	22,69
High fert	14,85	21,19	19,93	23,60	36,54	18,01	29,35	22,91
Slow rel	13,51	20,48	24,19	30,04	45,14	38,02	34,48	33,44
Fast rel	13,51	19,29	11,57	21,64	27,88	1,03	65,75	-81,02

Table 18: Fertilizer use (sensitivity analysis)

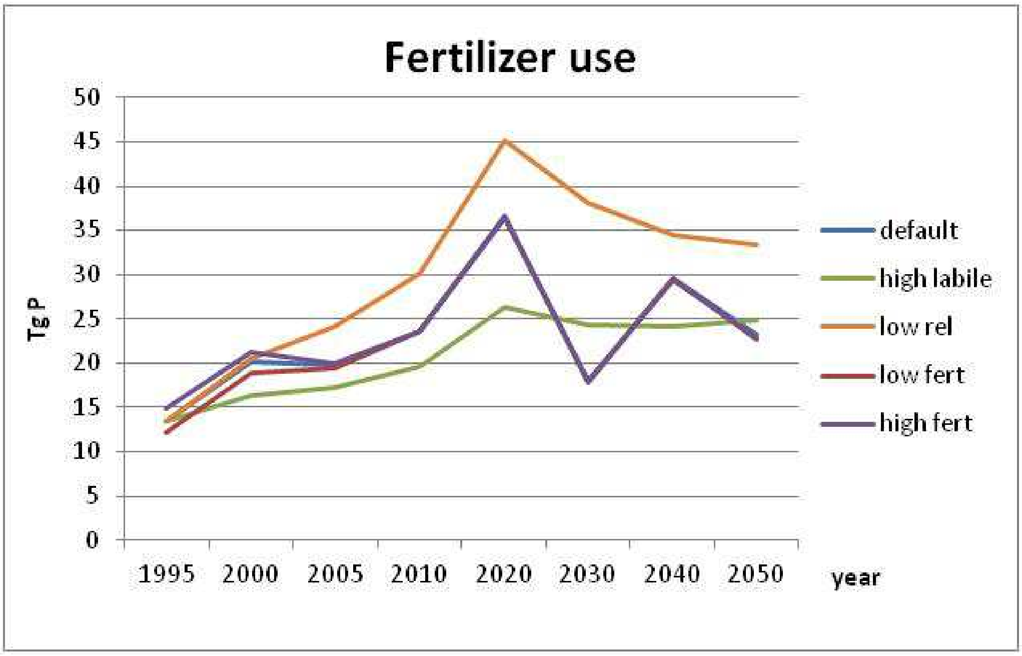

Figure 35: Fertilizer use (sensitivity analysis)

4.2.1.2 P-Pool

Table 19 and figure 36 show the results of the sensitivity analysis concerning the phosphorus pool. As well as with fertilizer use, the results for the values for the p-pool show implausible negative values for the low input-to-labileshare and the fast-release version. A change in the initial fertilizer amount does not influence the p-pool in further years in anylarge amount.

				P-Pool				
Set up	1995	2000	2005	2010	2020	2030	2040	2050
Default	438,98	490,48	535,49	593,78	818,51	835,34	952,04	985,26
Low labile	510,38	598,43	622,27	720	1050,46	654,27	1870,5	-719,97
High labile	296,19	329,23	362,21	400,59	521,91	605,25	667,8	719,19
Low fert	446,37	492,39	536,5	594,53	817,4	837,03	954,65	985,48
High fert	432,18	489,33	535,48	593,71	817,7	837,54	952,67	984,38
Slow rel	873,41	927	994,48	1084,91	1394,71	1614,24	1780,22	1917,52
Fast rel	221,77	269,4	273,76	322,23	459,47	309,29	787,78	-219,7

Table 19: P-pool (sensitivity analysis)

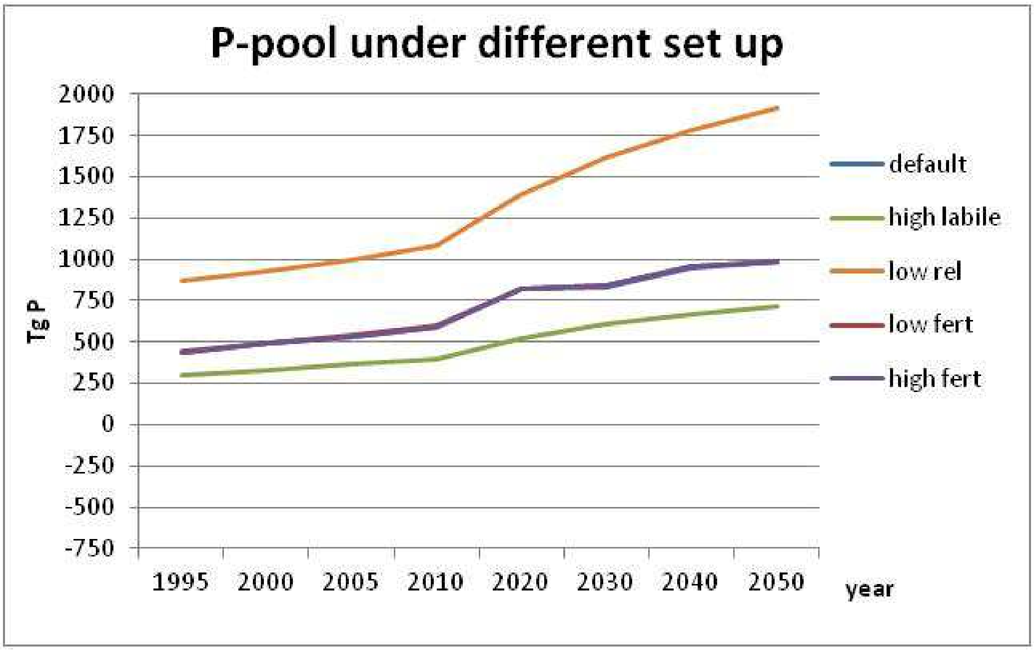

Figure 36: P-pool (sensitivity analysis)

4.2.1.3 P-Fixation

The results concerning the phosphorus fixation in the sensitivity analysis are depicted in table 20 and figures 37.

	P-Fixation							
Set up	1995	2000	2005	2010	2020	2030	2040	2050
Default	19,04	24,93	25,35	29,50	42,27	28,97	39,52	35,06
Low labile	21,42	34,62	24,72	40,29	57,05	-4,60	143,43	-196,70
High labile	14,28	16,48	17,57	19,75	25,49	25,73	26,43	27,40
Low fert	18,01	24,08	25,23	29,49	42,10	29,21	39,66	34,90
High fert	20,11	25,84	25,54	29,49	42,19	29,24	39,43	34,93
Slow rel	19,04	25,28	28,95	34,66	49,06	45,20	43,50	43,40
Fast rel	19,04	24,31	18,83	27,94	35,21	15,61	68,47	-48,23

Table 20: P-fixation (sensitivity analysis)

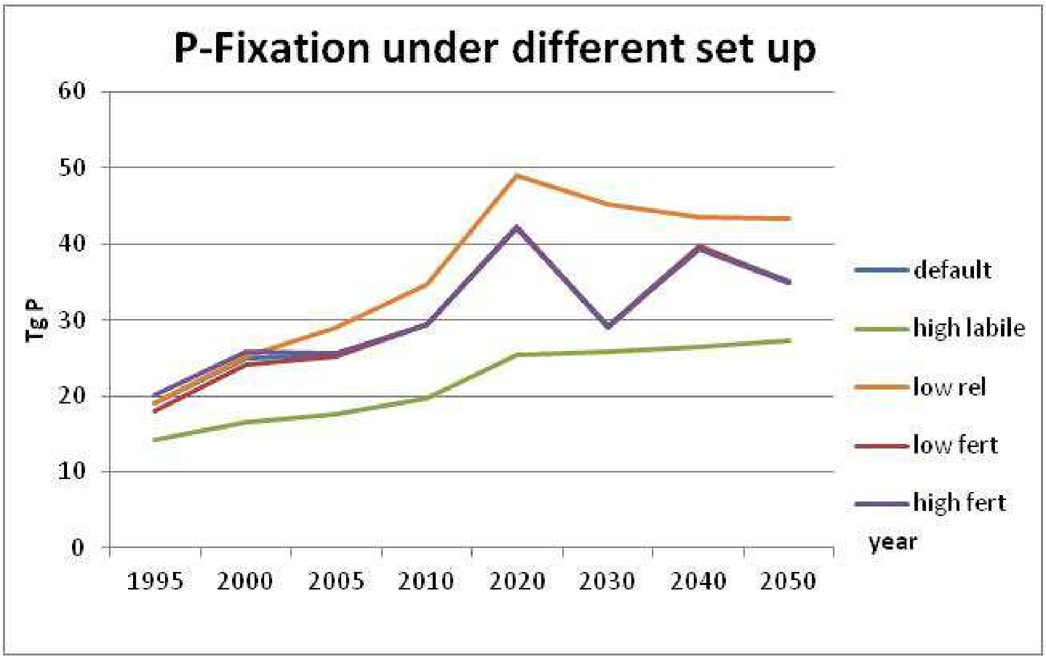

Figure 37: P-fixation (sensitivity analysis)

4.2.1.4 P-release

The results concerning the phosphorus release in the sensitivity analysis are depicted in table 21 and figure 38.

	P-Release							
Set up	1995	2000	2005	2010	2020	2030	2040	2050
Default	14,48	14,63	16,35	17,85	19,79	27,28	27,84	31,73
Low labile	16,86	17,01	19,95	20,74	24,00	35,02	21,81	62,65
High labile	9,27	9,87	10,97	12,07	13,35	17,40	20,18	22,26
Low fert	14,77	14,88	16,41	17,88	19,82	27,25	27,90	31,82
High fert	14,21	14,41	16,31	17,85	19,79	27,26	27,92	31,76
Slow rel	14,48	14,56	15,45	16,57	18,08	23,25	26,90	29,67
Fast rel	14,48	14,78	17,96	18,25	21,48	30,63	20,62	52,52

Table 21: P-release (sensitivity analysis)

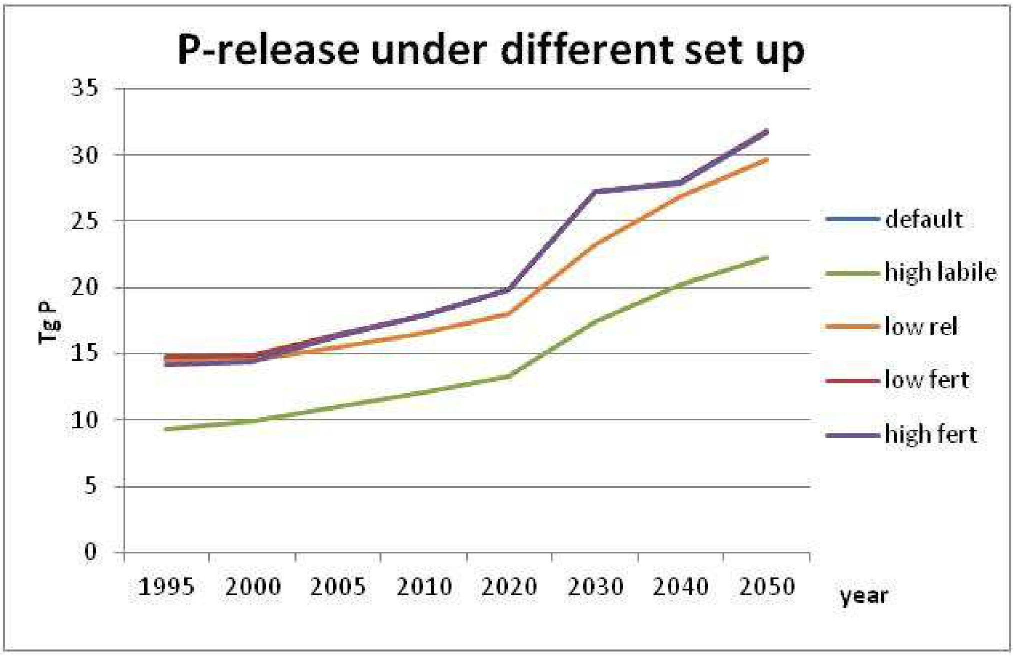

Figure 38: P-release (sensitivity analysis)

4.2.2 Effects of changes in coefficients in the sensitivity analysis

4.2.2.1 Initial fertilizer input and initial soil phosphorus content

The sensitivity analysis concerning the initial amount of phosphorus fertilizer use shows a more or less independent of the results from the initial phosphorus fertilizer amount. It is noticeable that with an increasing initial phosphorus fertilizer amount, the total **phosphorus fixation** in the first decades increases while phosphorus fixation in the later years decreases slightly but with some regional differences. Even the soil **phosphorus release** responds just to a very small extent to a change in the amount of initial phosphorus fertilizer. With low initial phosphorus fertilizing, phosphorus release is higher in the first decades and just a bit lower in later years than with a higher initial amount of phosphorus fertilizer. The same performance can be stated for the **soil p-pool**. An increase in the p-pool is apparent, but with just some small differences in the first decades, where a change in the initial amount of fertilizer contributes first of all to an opposing change of soil p-pool in the first time-step. The strongest response to a change in the initial amount of phosphorus fertilizer can be observed within the **fertilizer use**. A lower initial fertilizer amount causes a lower fertilizer use in the first decades while the fertilizer use in the later years is slightly enhanced.

Over all it can be stated that a change in the initial phosphorus fertilizer amount has little influence on the performance of the different parameters of the soil phosphorus model.

4.2.2.2 Coefficient for the input-to-labile share

Concerning the sensitivity analysis of the input to labile share, the following results and meanings can be stated. The oscillating scheme which can be observed in the default set-up for the model is strongly and unrealistically exaggerated under the low input-to-labile share of 0.1 for all parameters (fertilizer use, p-pool, p-fixation, as well as p-release) while the version with an input-to-labile share of 0.4 performs in a distinctly more balanced way in general.

Fertilizer use in the default set-up performs with an increase in the first timesteps until 2020, from 14 TgP to 36 Tgp per year, and a following oscillation between 17 TgP and 30 TgP per year, with a seemingly slight trend to fall. Under the low input-to-labile share of 0.1, fertilizer use in the first timesteps until 2020 is increasing from 15 TgP per year to 47 in 2020; later timesteps are oscillating between positive and negative numbers. With a high input-to-labile share of 0.4, fertilizer use performs in a much more balanced way, and near to real fertilizer use, until 2010 and within a realistic range for an estimation of fertilizer use in 2020; increasing from 13,5 TgP in 1995 to 26 TgP in 2020. In the later timesteps until 2050 fertilizers use ranges with a slight tendency to decrease in a range between 24 TgP and 25 TgP per year.

Regarding the **p-pool,** comparable patterns can be observed. Under the default scenario, the p-pool is strictly increasing with a changing slope but with a continuous growth from around 438 TgP in 1995 to 985 TgP in 2050, with a slightly trend for saturation at this level. This general scheme is strongly pronounced and balanced under the high input-to-labile share model set-up, but at a strictly lower level, with an increase of soil p-pool from 296 TgP in 1995 to 719 TgP in 2050. Under the low input-to-labile share model set-up, an oscillating scheme can be observed leading to an increase from 510 TgP in 1995 up to 1050 TgP in 2020, but with a following oscillation between 654 TgP an 1870 TgP and impossible negative values in 2050.

The **phosphorus fixation** in the soil nearly reproduces fertilizer use patterns. While fixation increases from 19 TgP in 1995 to 42 TgP per year in 2010 and afterwards oscillating between 29 TgP an 39 TgP with a slight tendency to fall until 2050 under the default scenario, fixation increases from nearly 15 TgP per year in 1995 to 25 TgP in 2020 and afterwards leveling to between 25 TgP and 27 TgP with a slight tendency to increase up to 2050 under the high input-to-labile share. In contrast, under the low input-to-labile share, the p-fixation in the soil is more or less increasing from 21 TgP in 1995 to 57 TgP in 2020. From this, fixation oscillates unrealistically between 143 TgP and 196 TgP indicating a non-functional model set-up.

Concerning the **phosphorus release** from the soil p-pool the different variations of the sensitivity analysis show an increase of phosphorus from the soil p-pool to the plant available phosphorus. The default set-up, with a moderate input-to-labile share, shows an exponential increase from 14.5 TgP in 1995 up to 27 TgP in 2030 and a slight increase up to 31 TgP in 2050. Within the low input-to-labile share set-up version, the model shows an exponential increase of phosphorus release at a higher level from nearly 17 TgP per year in 1995 to 35 TgP per year in 2030, followed by a significant drop down to 21 TgP per year in 2040 and a strong increase of 200% to 62 TgP per year in 2050, indicating an oscillation in this model version. Within the high input-to-labile share version, phosphorus release from the soil phosphorus pool is distinctly lower and increasing in a continuous, more linear or vague exponential pattern from nearly 10 TgP per year in 1995 to 22 TgP per year in 2050.

4.2.2.3 Coefficient for phosphorus release time

The performance of the model set-up versions differing in the coefficient for the phosphorus release from the soil p-pool is strongly comparable to the input-to-labile share, where a fast release performs like the low input-to-labile share and slow release equals performs like the high input-to-labile share, but with differing total amounts of TgP per year and slightly different sloping, respectively.

Regarding the **fertilizer use,** the fast release set-up version performs with an increase of fertilizer input from 13 TgP to 27 TgP per year on a lower level compared to the default set-up version in the first timesteps up to 2020, and a stronger oscillation between 65 TgP and impossible negative numbers of -81 TgP between 2030 and 2050. Compared with this, the slow release set-up version performs with a substantially higher level and increases from 13 TgP to 45 TgP in 2020, with a continuous decrease down to 33 TgP in 2050, resulting in a distinct peak in 2020.

Concerning the **p-pool,** a fast release from the soil p-pool leads to a reduction in the total level of p-pool compared to the default version. The p-pool increases from 221 TgP in 1995 to 459 in 2020, followed by an oscillation between positive (787 TgP in 2040) and negative (-219 TgP in 2050) numbers. In contrast, a fast release leads to a higher level of p-pool in general and a continuous increase from 873 TgP in 1995 to 1917 in 2050, with a slight tendency for saturation.

The **fixation of phosphorus** in the soil p-pool under the fast release set-up version performs with an increase from 19 TgP in 1995 up to 35 TgP in 2020, this laying below the values ofthe default version. This is followed by an oscillation between 68 TgP (2040) and -48 TgP (2050). The slow release version in general performs at a higher level than the default version with an increase from 19 TgP in 1995 to 49 TgP per year in 2020, followed by a slow decrease down to 43 TgP per year in 2050.

Phosphorus release under the fast release set-up shows a slightly higher level of values than the default version, with an increase from 14.5 TgP released in 1995 to 30 TgP in 2030, a drop down to 20 TgP and a final rush up to 52 TgP, indicating an oscillation in the later timesteps. Under the slow release version, phosphorus release performs on a slightly lower total level than default, but within a slightly more convex pattern; from 14.5 TgP in 1995 to 29 TgP in 2050.

The effects of the change in the coefficients of the soil phosphorus accumulation model (SPAM) are discussed in chapter 5.1.3 and a summary of these effects are depicted in table 22.

4.3 Total phosphorus consumption from 2010 to 2050 for the estimation of reserves depletion

The total fertilizer use by my model was strongly dependant on the set-up of the model shown in the sensitivity analysis in chapter 4.2 and discussed in further detail in chapter 5.1.

Estimations of total phosphorus demand for fertilizer from 2010 to 2050 under the default set-up versions with medium model coefficients are 1096.64 TgP. To evaluate the sensitivity of these results I applied a sensitivity analysis, described in the chapter before. Under the other two more or less reasonable model set-up versions, total phosphorus fertilizer demand was 991.51 TgP fertilizer use for the high labile-to-input share of 0.4 and 1525.54 TgP total fertilizer demand from 2010 until 2050 for the model set-up version with a slow release (60 years p-pool release time).

Assuming a total of 30% content of P_2O_5 in beneficiated phosphate rock and a conversion factor of 0.4364 for P_2O_5 to P, this accounts for at least 8376 Tg phosphate rock to be necessary for fertilizer production until 2050 under the default model version. For the 991.51 TgP under the high labile-to-input share, this would account for 7573 Tg phosphate rock and for the 1525.54 TgP under the slow release model set up, for 11652 Tg phosphorus rock. This total phosphorus demand from 2010 until 2050 will be discussed in chapter 5.2.1 concerning the depletion of global phosphorus reserves.

5 Discussion

This thesis aims to provide (1) an estimation on stocks and flows in the global phosphorus cycle up to 2050 including losses to the environment, (2) a representation of phosphorus accumulation in the soil within this phosphorus cycle, (3) an estimation of phosphorus fertilizer demand and (4) an estimation of depletion of global phosphorus reserves on the basis of calculated fertilizer demand. I therefore used the method of a nutrient flow analysis and expanded the given MAgPIE model by a phosphorus module including a soil phosphorus accumulation model (SPAM). I used a sensitivity analysis on critical coefficients of the SPAM to draw conclusions for the improvement and adjustment of the model for further works. In the following chapter I will discuss the given results and compare them to other author's estimations and concerning implications of global boundaries of phosphorus use and global phosphorus management. In subchapter 4.1 I will discuss phosphorus fertilizer use and the depletion of global reserves. In subchapter 4.2 I will discuss the global phosphorus cycle, including phosphorus contents in crop production, livestock production and manure as well as phosphorus accumulation in the soil and losses to the environment. In subchapter 4.3 I will discuss the results regarding global boundaries of phosphorus and global phosphorus management. In subchapter 4.4 I will discuss the developed soil phosphorus accumulation model (SPAM) critically, and in subchapter 4.5 I will draw some conclusions for further research and an improvement of the model.

5.1 Discussion of model limitations

Integrated assessment is an approach for analyzing global fundamental and complex problems at the science-policy-society interface (WEAVER AND ROTMANS, 2006). It uses functional models to represent environmental, economic and social processes to structure scientific thinking, to focus on the most relevant processes and analyze important trade-offs between conflicting goals (LOTZE-CAMPEN 2008). But according toMEADOWS et al. (1972, p. 20), "a model is simply an ordered set of assumptions about a complex system…. The model we have constructed is, like every model imperfect, oversimplified, and unfinished."

It has to be noted that this is the first modeling approach for the global phosphorus cycle in MAgPIE and a soil phosphorus accumulation model. While the phosphorus module is a translation and adjustment of the nitrogen module in MAgPIE (BODIRSKY et al. 2012), proved by scientific work, the SPAM is developed in this thesis and integrated in the phosphorus module on the basis of different modeling approaches regarding the global phosphorus cycle and phosphorus accumulation (FILLIPELLI 2002, LIU et al 2008, VILLALBA et al. 2008 CORDELL et al. 2009, BOUWMAN et al. 2009, BOUWMAN et al. 2013, VAN VUREN et al. 2010, SATTARI et al. 2009).

5.1.1 Scenario use and recommendations for further works

Concerning the MAgPIE scenario assumptions, I applied a scenario concerning global future development parameters orientated on the SSP2 scenario by KRIEGLER et al. (2012, 2013) and equivalent to the baseline-scenario from BODIRSKY et al. (2012). The scenario can be described as a “middle-of-the-road” scenario within the broadly used IPCC *SRES*-storyline scenarios, which characterize different storylines of global future development within an economic vs. ecologic and globalized vs. decentralized coordinate system (NAKICENOVIC et al. 2000). Influencing variables of these scenarios are population growth, dietary habits assumptions, trade patterns and economic development.

Other authors primarily used different scenarios for the evaluation of future development, e.g. BOUWMAN et al. (2011) used a baseline scenario from the International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD) by MCINTYRE et al. (2009) and different variations of this scenario. BOUWMAN et al. (2009) use the Millennium Ecosystem Assessment (MEA) Scenarios described in CARPENTER (2005).

For further investigations and applications of this phosphorus model it would be of strong interest to use differentiated scenarios for future development, in lieu of the *SRES*-storylines, to compare results of this work with other studies on future phosphorus use or to integrate results into other works.

5.1.2 Data availability for the model calibration and validation of soil p-pool

The methodological objective of this thesis was to realize a first modeling approach to reproduce phosphorus accumulation within a soil p-pool to phosphorus fixation. Therefore, a quantification of the initial soil p-pool is necessary. But the level of p-pool is highly uncertain and there is a lack of data for soil phosphorus content in differing plant available phosphorus pools. I used an approach to calculate soil p-pool by using the model in a reverse mode for the first timestep, like discussed in subchapter 2.4. This enabled the calculation of a soil phosphorus pool in general and to quantify soil phosphorus fixation as a part of nutrient input, but not to quantify the dimension of the phosphorus content in the soil p-pool. There remains the question ofhow the robustness of the model can be proved. The level of p-pool should be validated once data is available. As discussed insubchapter 1.3.1, there have been great efforts to provide spatially explicit soil phosphorus data for global biogeochemical modeling approaches (Batjes, 2005; Batjes, 2008; Batjes 2011a; Batjes, 2011b; Omuto et al., 2013). So far, soil phosphorus information is not yet able to provide the spatially explicit data to provide an initial soil phosphorus content, there is hope that further research and the merging of different soil information data can promote useful data for modeling soil phosphorus dynamics in more depth in the very near future.

5.1.3 Discussion of the sensitivity analysis

This soil phosphorus model was the very first approach to represent phosphorus accumulation in cropland soils and to quantify phosphorus fertilizer use. To evaluate this model, a sensitivity analysis concerning the initial amount of fertilizer and the coefficient for the input-to-labile share and p-pool release time has been realized. The results of the sensitivity analysis show that the results are strongly dependant on the coefficients for phosphorus fixation and release, while the initial fertilizer use, which correlates with the initial soil p-pool, has a rather small influence on the performance of the output variables.

5.1.3.1 Initial fertilizer input and soil phosphorus content

The long term equilibrium of the model does not depend on the initial amount of phosphorus fertilizer. It is noticeable that with an increasing initial phosphorus fertilizer amount the total phosphorus fixation in the first decades increases and vice versa. With a low initial phosphorus fertilizer amount, phosphorus release is higher in the first decades. The same performance can be stated for the soil p-pool. A change in the initial amount of fertilizer first of all contributes to an opposing effect of soil p-pool in the first timestep. A low initial fertilizer amount causes a lower fertilizer use in the first decades, while a high initial fertilizer increases fertilizer use in the first decades. Overall, it can be stated that a change in the initial phosphorus fertilizer amount has a less influence on the performance of the different parameters of the soil phosphorus model. It is not important for the calibration of the model.

5.1.3.2 Coefficient for the input-to-labile share

The input-to-labile share highly influences the outputvariables and the performance of the soil phosphorus accumulation model (SPAM). Under the low input-to-labile share, the output variables fertilizer use, soil p-pool, phosphorus fixation and phosphorus release oscillate strongly. This oscillating scheme can also be observed in the default set up for the SPAM. With a high input-to-labile share all output variables perform in a distinctly more balanced way, shown in subchapter 3.2.

5.1.3.3 Coefficient for the phosphorus release time

Aswell as the labile share, the coefficient for the phosphorus release from the soil p-pool strongly influences the output variables of the SPAM. A fast release leads to an oscillating scheme of fertilizer use, soil p-pool, p-fixation and release. A slow release coefficient leads to a more balanced and higher fertilizer use, a more balanced and higher phosphorus fixation, a more balanced and lower p-release and a more balanced and higher p-pool.

5.1.3.4 Conclusions for better estimations of model parameters and model fitting

The general effects of changes in the modified coefficients are condensed in table 22.

Coefficient/set up version	**Effect**	**1995→2050 (TgP)**
P pool		
Default		430 → 980
fast release	↓, osc.	200 → 780
slow release	↑	870 → 1800
high labile	↓	300 → 700
low labile	↑, osc.	500 → 1800
low fert	→	430 → 980
High fert	→	430 → 980
Fixation		
Default		19 → 42
fast release	↓, osc.	19 → 35 (68)
slow release	↑, equ., peak.	19 → 49
high labile	↓, sm., equ.	14 → 27
low labile	↑, osc.	21 → 57 (143)
low fert	→, (osc.)	20 → 42
High fert	→, (osc.)	18 → 42
P release		
Default		14 → 31
fast release	↑ osc.	14 → 52
slow release	↓ sm.	14 → 29
high labile	↓ sm	9 → 22
low labile	↑↑ osc. exp	16 → 62
low fert	→ (exp.)	14 → 31
high fert	→ (exp.)	14 → 31
Fertilizer		
Default		13 →36
fast release	↓ osz.	13 → 27 (65)
slow release	↑ peak.	13 → 45
high labile	↓ sm.	13 →20
low labile	↓ osc.	13 → 47 (139)
low fert	→	12 → 36
high fert	→	14 → 36

↓ = decreasing; ↑increasing; → no effect; osc.= oscillating; sm = smoothing; equ = equalizing, peak = peaking, brackets = slight effect

Table 22: Summary of effects of different set-up versions

Some set-up versions lead to impossible oscillations between positive and negative numbers. Particularly, a fast release from the phosphorus pool and a low input-to-labile share cause these oscillations. Regarding fertilizer use, a slow release leads to more peaking behavior and higher values, while a high input-to-labile share causes a smoothing and a reduction in the values.

The sensitivity analysis should not be used to calibrate the model. However, it indicates which parameters and processes are of great importance and require a better estimation. These two relevant coefficients are the labile-to-input share and the phosphorus release time. Therefore, these two coefficients should be estimated better.

It can be discussed if the soil phosphorus model could be adjusted and improved to represent soil phosphorus dynamics and soil-chemical dynamics in a better way. For a sole examination of phosphorus use and depletion, what soil dynamics are will be of less interest, but the soil phosphorus model has to reproduce phosphorus accumulation and provision. This could be reached by an improved soil phosphorus model, calibrated and fitted to historical fertilizer use and possibly soil phosphorus contents, retention potentials and phosphorus supply. For example,SYERS et al. (2008) describe different soil phosphorus release models on the basis of extractable phosphorus (p-Olsen). They describe a halving of p-Olsen in the soil within 9 years under completely extractive land use without any phosphorus compensation (see figure 39).

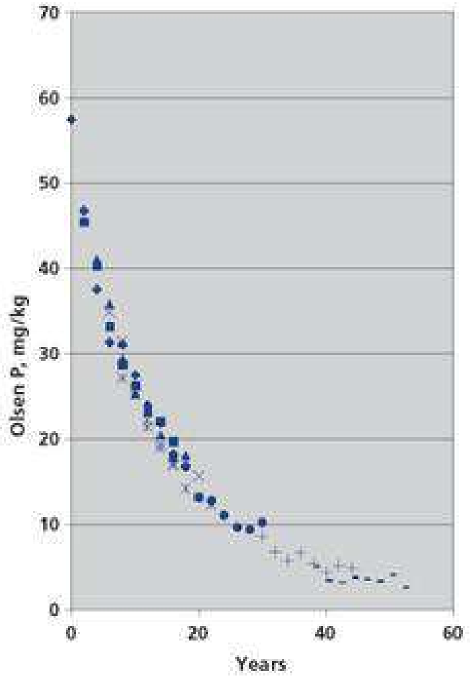

Figure 39: Decline of p-olsen under extractive land use, from SYERS et al. (2008)

They estimated it would take 50 years for Olsen P to decline from 60 to 5 mg per kg with a half-life of 9 years. They also provided a four-pool soil phosphorus model to represent soil phosphorus dynamics (see figure 40) (SYERS et al. 2008). It could be appropriate to fit the underlying soil phosphorus model to these soil properties

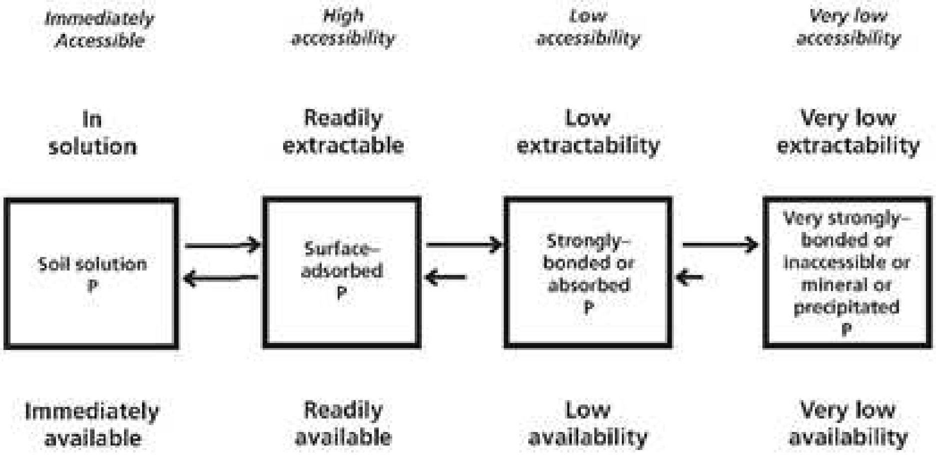

Figure 40: Conceptual diagramm fort he forms of inorganic P in soils categorized in terms of accesibility, extractability and plant availability, from Syers (2008)

For an examination towards a more environmental or agricultural-productive interested point of view, on-spot soil dynamics become more relevant. The question of soil phosphorus status and supply is a particularly interesting matter for an evaluation regarding not only agricultural productivity, but also environmental issues. Concerning the soil related aspects of this issue, it would be of great interest to integrate global soil information in a spatially explicit availability, for example the soil phosphorus retention potential of different soils (BATJES 2011a, BATJES 2011b) to represent p-release dynamics underlying soil-chemical, environmental and climatic circumstances. For a more holistic environmental, biogeochemical and biophysical representation of global phosphorus flows, it could perhaps be logical that physical and chemical processes are integrated in another part of the global model, like LPJmL.

5.1.4 Limitations and criticism of the model

A process which has not yet been represented, neither within the soil phosphorus model directly nor within the phosphorus module in general, is the whole complex of phosphorus release by soil organic matter loss in the context of land conversion and the following dynamics of phosphorus availability, phosphorus retention in soils after land conversion, plant uptake or potential losses by erosion in the context of land use change. This complex, with its dynamics, is of crucial relevance in land conversion regions, where under former vegetation phosphorus circulated in a close cycle between vegetation and organic litter, while the soil phosphorus status was generally low. By conversion,large amounts of phosphorus was released into agricultural cycles, including to a greater extent the soil as an intermediary for the provision of phosphorus, to agricultural crops. There is a high risk of phosphorus losses to the environment within the process of land conversion and land use change which hasto be represented by the model in order tobe calculated. There is no representation of soil organic matter loss in my model which has to be adjusted for further development.

Another aspect which is not represented in the current model version is the whole complex of erosion, including particular and soluble wind and water erosion as a considerable factor of phosphorus losses from agricultural to environmental systems and waterways. This aspect should be implemented in improved versions of the model. This would include a modeling of soluble and particular transport processes, runoff and a quantification of wind and water erosion. Another aspect associated with this is the atmospheric or environmental deposition of phosphorus by wind and water. Therefore, an inclusion of an erosion model and a linkage to water-models is needed.

5.2 Phosphorus use and depletion

By my modeling approach I provide a calculation of phosphorus fertilizer use and phosphorus demand for agricultural activities until 2050, under the representation of phosphorus accumulation in the soil. On the basis of these calculations, I present estimations on global phosphorus reserves depletion. I discuss these quantifications in chapter 5.2.1 and compare them to other authors under different scenarios in chapter 5.2.2. In chapter 5.2.3, I reflect on phosphorus use under economic aspects and the market situation and potential drivers of total global future phosphorus consumption.

5.2.1 Fertilizer use and estimations of phosphorus reserves depletion

The total fertilizer use, used in my model, was strongly dependant on the setup of the model shown in the sensitivity analysis in chapter 4.3 and discussed in further detail in chapter 5.1.

The results will be summarized here and compared to the results of the other reasonable model setup versions to reflect the range of phosphorus fertilizer use and depletion on the basis of the estimations in this thesis. Therefore, results are also compared with estimations of other authors.

Estimations of phosphorus demand for fertilizer from 2010 to 2050 under the default set-up versions with medium model coefficients are 1096.64 TgP. Under the other two more or less reasonable model set-up versions, total phosphorus fertilizer demand is 991.51 TgP fertilizer use for the high labile-to-input share of 0.4 and 1525.54 TgP total fertilizer demand from 2010 until 2050 for the model set-up version with a slow release (60 years p-pool release time).

Assuming a total of 30% P_2O_5content in beneficiated phosphate rock, and a conversion factor of 0,4364 for P_2O_5 to P, this accounts for at least 8 376 Tg phosphate rock to be necessary for fertilizer production until 2050 under the default model version. For the 991.51 TgP fertilizer demand under the high labile-input share, this would account for 7 573 Tg phosphate rock and for the 1525.54 TgP fertilizer demand under the slow release model set-up, for 11 652 Tg phosphorus rock.

I elaborated that estimations of phosphorus reserves and the reserve base are rather unclear due to a small number of different sources on global phosphorus reserves (USGS 2014), a reevaluation of phosphorus reserves in 2010, including a redefinition of reserves and reserve base (VAN KAUWENBERGH 2010, USGS 2014), and of controversy between different authors on evaluations of these reserves (EDIXHOVEN et al. 2013). To represent the range of estimations and the ambiguity for phosphorus reserves, estimations for reserves depletion will be discussed as well for the 2009 declaration of global phosphorus reserves (18 000 Tg phosphate rock) and the 2013 declaration of global phosphorus reserves (68 000 Tg phosphate rock). This is also necessary to compare the results with other authors who refer to the 2009 declarations of reserves. Nevertheless, phosphorus reserves can be supposed to be with a high probability on the higher end of the estimations described by the 2013 reserves declarations (USGS 2014).

Under the estimation of the 2009 declaration of 18 000 Tg global phosphate rock reserves,a global fertilizer use of 1096.64 TgP or 8376 Tg phosphate rock accounts for a 46.5 % depletion of reserves by 2050. Under the assumption that the soil phosphorus accumulation model (SPAM) has to be better estimated for further works, it is interesting to noteon which dimension these estimationsare dependant from the model set-up. With a 991.51 TgP fertilizer use or 7 573 Tg phosphate rock demand under the high labile-inputshare, this would account for 42% of total global phosphorus reserves by 2050. Under the 1525.54 TgP total fertilizer use or 11 652 Tg phosphate rock demand under the slow release model set-up, this would account for 64%. With an extrapolation of the 2050 fertilizer use of 23.17 TgP under the default model set-up, or 177 Tg phosphate rock demand per year, global reserves could last for a further 54 years, until 2104.

Under the estimation of the 2013 declaration of 68 000 Tg global phosphate rock reserves,a global fertilizer use of 1096.64 TgP or 8376 Tg phosphate rock accounts for a 12.3 % depletion of reserves by 2050. With a 991.51 TgP fertilizer use or 7 573 Tg phosphate rock demand under the the high labile-input share, this would account for 11% of total global phosphorus reserves by 2050. Under the 1525.54 TgP total fertilizer use or 11 652 Tg phosphate rock demand under the slow release model set-up, this would account for 17%. With an extrapolation of the 2050 fertilizer use of 23.17 TgP fertilizer use under the default model set-up, or 177 Tg phosphate rock demand per year, global reserves could last for further 336, years until 2386.

These estimations correspond to most of other author’s indications.

STEEN (1998) estimated a 2.5% annual growth of phosphorus consumption due to a 2-2.5% increase in crop yield per year, leading to a global annual consumption of 26-31 Tg P in 2050, which is in line with my estimations of between 23 TgP and 33 TgP, depending on the SPAM set-up. BOUWMAN et al. (2009) and BOUWMAN et al. (2011) calculate a total P use of between 23 and 33 Tg per year in 2050, which also corresponds with my estimations. SATTARI et al. (2012) estimate the global P input required for cropland is 1 200 Tg P for the 2008-2050 period, which lays just in line with my estimations of 1096.64 TgP fertilizer use from 2010 to 2050 in the default model set-up, but far below my estimations when total phosphorus input into cropland are accounted for. They estimate global inorganic fertilizer use in 2050 to be 20.8 Tg per year, which is significant for my estimations under the default model set-up.

CORDELL et al. (2009) estimate that existing phosphate rock reserves could be exhausted in the next 50-100 years. Under the assumption of 2009 - phosphate rock reserves of 18 000 Tg, this could be confirmed by my calculations of reserves depletion in 2104. CORDELL et al. (2009, 2011) calculated that global phosphorus production will peak in 2033. This picture can nearly be reproduced by the model estimations elaborated in this thesis with a peak in 2020, nevertheless the peak - discussed by CORDELL et al. (2009, 2011) - is argued to be induced by supply and increasing extraction costs due to an ongoing depletion, while the peak in my estimations is induced by the demand from agricultural activities and they therefore cannot be compared with one another. Kauwenbergh (2010) accounted phosphorus rock reserves to be available for the next 300 to 400 years on the basis of the reevaluation of global phosphate rock reserves. This is also in-line with my estimations; that phosphorus reserves would last for further 336 years, from 2050 until 2386, on the basis of 68 000 Tg phosphate rock reserves.

5.2.2 Reserves depletion under different scenarios

For my estimations I used a “middle-of-the-road” – baseline scenario. These estimations are strongly dependant on the scenario assumptions. For further research work, this baseline scenario could be modified to other scenarios described in chapter 5.1.1. The estimations of my baseline scenario can be compared to other author’s estimations calculated under different scenario assumptions.

Rosemarin et al (2011) estimates, on the basis of 60 000 Tg phosphate rock,for global phosphorus reserves to last for 235 years under the assumption of a 1% exponential increase in phosphorus use per year for the next 50 years, followed by zero increase. They calculated a 172-year period for depletion, with UN-estimated global population growth; with stabilization by 2100 and 126 years if Africa develops its agriculture and 48 years if, in addition, bio-energy crops are given high priority.

Van Vuuren et al. (2009) used Millennium Ecosystem Assessment (MEA) scenarios to estimate phosphorus reserves depletion under different global future development pathways. He calculated aggregate P consumption to be roughly around 37 TgP or 280 Tg phosphate rock per year by in 2100 in Techno garden (TG) scenario, and 28 TgP or 220 Tg phosphate rock per year under the Adapting Mosaic (AM). He estimated total consumption in 2100 to be roughly 46 TgP under the order from strength (OS) scenario, and roughly 50 TgP under a global orchestration (GO) scenario, equivalent to 350 and 380 Tg phosphate rock, respectively (Van Vuuren et al. 2009). This lies highly above my estimations for the year 2050. Under the estimation of a 18 000 Tg phosphate rock reserve and a reserve base of about 51 000 Tg phosphate rock, he estimates that under the GO-scenario about half of the current reserves could be depleted, and the other half before the end of the century.

Bouwman et al. (2009) calculates estimations for global phosphorus use and fertilizer input to crop soils on the basis of phosphorus soil balances for the period 1970 to 2050, with use of the Millennium Ecosystem Assessment (MEA) scenarios. Regarding the estimated phosphate reserve and reserve base of 18 000 Tg phosphate rock and 50 000 Tg phosphate rock, he calculated that 64% of the reserves would be depleted in 2100 in the GO, 52% in the OS, 46% in the TG and 35% in the AM scenarios.

5.2.3 Reflections on phosphorus markets

Total future phosphorus consumption will be dependent on different variables. In my model, some of these variables have been assumed to behave in a particular way. They have been defined as the scenario assumptions; for example population growth, dietary habits, economic development, income growth and other socio-economic variables, as well as biophysical and climatic conditions for agricultural production. I used a “middle-of-the-road” scenario for a first evaluation of the model and a general estimation of phosphorus stocks and flows within the global cycle, and fertilizer use. Other variables are subject to the optimization process within the model, for example constraints, indicating limitations to the optimization. These constraints are demand, trade, land, water and rotation, defined on a cellular level in the model as described in chapter 3.4. Within the optimization process total crop and livestock production is optimized by a minimization of total costs. Fertilizer use is calculated as the phosphorus that is necessary to maintain the biophysical production under the socio-economic and geophysical constraints.

In reality,the phosphorus market is dependent on elasticities, which are not represented in the model. The concept of elasticities has been described in subchapter 2.1.2. The supply, as well as the demand, is more or less elastic in the shortrun. In the long run, supply as well as demand will not be elastic; supply, due to its limited resources, demand, due to its non-substitutability in agricultural production. These aspects, and its consequences on future phosphorus markets, will be discussed in subchapters 5.2.3.1 to 5.2.3.3.

Due to the optimization character of the model, shadow prizes for the constraints are calculated. These provide the value for a relaxation of the constraint by one unit and thereby a quantification of “how hard the constraint bites”. Therefore, the shadow prices could be used for a quantification of the elasticity of the output variables regarding the constraints. This could be used for an in-depth economic analysis of the model outcomes, which is above the scope of this thesis.

5.2.3.1 Demand

The demand of phosphorus will be strongly dependant on different global development variables, described in subchapter 2.1.2.3. As a limited substitutable factor, essential for the global food and agricultural system, global population growth will be of crucial relevance, as well as coming dietary habits and consumption patterns (METSON et al. 2012). The latter is crucially influenced by growing wealth and increasing per capita incomes.

It can be argued that phosphorus release from soil organic matter loss, especially in the context of land use change and landconversion of forests and pasture lands, can play a substantial role relaxing the phosphorus demand on a global scale. This biophysical aspect has not been integrated in this modeling approach, but should be represented in an improved model. A main factor examined in this work is the accumulation of phosphorus in agricultural soils which acts as a buffer for phosphorus and therefore has implications on the long-term elasticities of phosphorus demand.

The priceof demand can be assumed to be highly elastic in the short-run. This can be underpinned by figure 3-6 in chapter 2.1.1. Figure 6 shows world market prices, which show that within the world financial crisis fertilizer prices increased by 400 to 800 percent. This price shock can be assumed to have triggered the severe decrease in fertilizer use in the same year, which can be seen in nearly all world regions (fig. 3-5). Although world market prices did not return to the low level of the before-crisisyears, fertilizer use increased to former levels, indicating a low elasticity in the long-run. Actually, this is reasonable due to the high elasticity of soils to phosphorus fertilization in the short-run, but in the long-run a compensation for the extraction of nutrients is necessary.

5.2.3.2 Supply

The supply will be mainly a function of production costs, in particular, extraction costs. Also, a potential backstop technology could cap the costs of production with influence on the market price. These aspects have been described in depth in chapter 2.1.1.2. Potential alternative technologies or management approaches for phosphorus recycling or global phosphorus efficiency management could also potentially influence prices. If there is an evaluation of external costs, for example environmental pollution costs which could be internalized to phosphorus production, is a matter of political circumstances and global phosphorus governance.

In general, the supply will increase with the interest rate as described in the intertemporal optimization model for resource extraction (see chapter 2.1.2.1). But nonetheless it will react to changes of world market prices and dependant on general socio-economic circumstances in which the phosphorus mining industry is embedded; for example commodity markets and the financial sector, as the financial crisis in 2008 shows.

5.2.3.3 Market equilibrium and total phosphorus consumption

Total phosphorus consumption, as the quantities which balance market supply and demand, is dependent on the above mentioned influencing variables. It can be assumed that phosphorus consumption will increase with global population, changing dietary habits, income growth and increasing wealth. Rising prices due to increasing extraction costs will act as incentives to reduce phosphorus consumption and to look out for possibilities for a global management and improved global governance. An increasing importance of phosphorus pollution on environmental systems can influence phosphorus markets by an internalization of external effects. The role of residual soil phosphorus, the enrichment of phosphorus in the soil, as well as land use change and expansion and technological change which changes the phosphorus use efficiency, will influence phosphorus markets.

That total phosphorus consumption is strongly dependant on the interaction of complex socio-economic conditions can be discussed by analyzing the historical phosphorus consumption in different countries or world regions during the last 25 years (see fig. 3-5).

In many developed countries, a reduction in phosphorus consumption can be observed; for example in Australia and Northern America. Europe significantly reduced its high level of consumption. It was highlighted in chapter 2.1.1 that this could partly be caused by the phosphorus accumulation in high fertilized soils in Western Europe. The strong reduction of phosphorus fertilizer use in central and Eastern Europe is considered to be caused by the breakdown of the former Soviet Union and the associated economies. This highlights the importance of socio-economic conditions for fertilizer use in agricultural systems and underlining the argument that with economic development in developing countries, phosphorus fertilizer use will strongly increase in the future with the transformation of agricultural systems towards more industrialized patterns. This also indicates the high dependence of fertilizer use from external shocks accounting for a great uncertainty of future phosphorus use.

Future fertilizer consumption will therefore strongly depend on developing regions with a great relevance of some particular countries, like Brazil, India and China (BIC), which performed with an enormous increase in the last decade (fig. 5). But also the development potential of other regions - especially Africa and Western Asia - will be of crucial importance. While it can be stated that Brazil, India and China are obviously in a period of strongly linear or exponential increase in phosphorus fertilizer consumption, it matters how long this growth will hold on and at which stage consumption will turn towards a more or less static state. This remains unclear. In the case of other developing countries, it can be hypothesized that future phosphorus fertilizer use will be strongly a question of economic circumstances and economic development. The economic and agricultural potential of Africa seems nearly `unlimited´. In contrast, historical phosphorus fertilizer use was very low. With an assumption of the future expansion of Africa´s agricultural potential, it can be presumed that the potential for phosphorus use for agricultural activities could be at least as big as China´s or India´s historical development pathways. This has to be encouraged by further research and exploration.

Summarizing, the future total phosphorus consumption is highly uncertain, depending on future development pathways of different world regions and countries, described in figure 41 and 42.

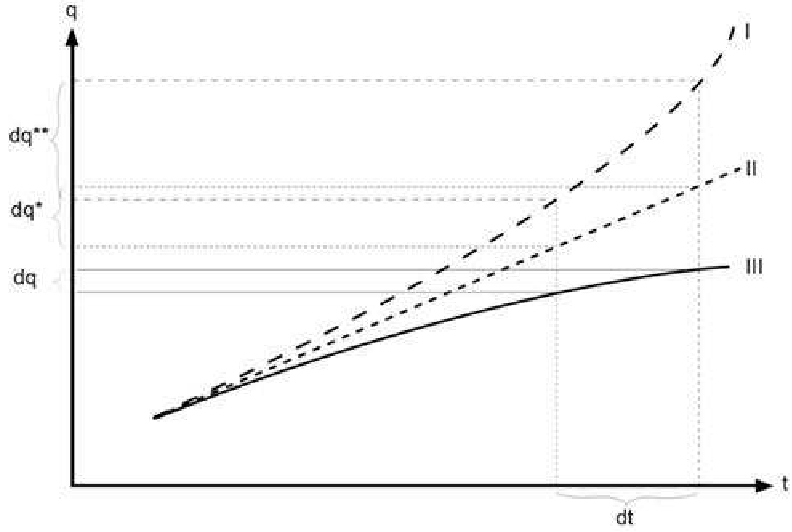

Figure 41: Development pathways for phosphorus consumption I, own elaboration

Path I describes an exponential increase, like Brazil, India and China, performed in the last decade. Path II describes a linear growth. Path III describes a growth with repletion on a certain level. These schema can be extended towards a longer timescale, leading to distinguishable periods (see fig. 42).

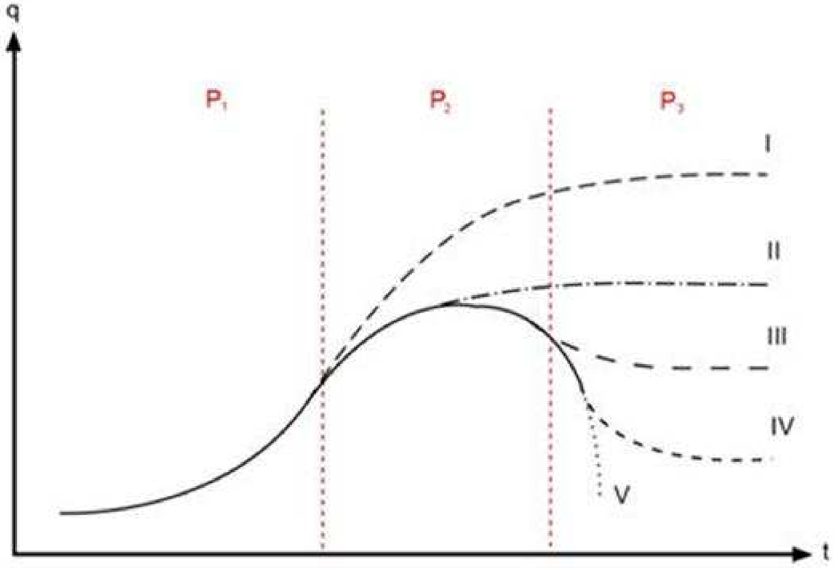

Figure 42: Development pathways for phosphorus consumption II, own elaboration

In P_1 an exponential, orat least linear, growth of phosphorus use can be supposed, followed by P_2 with a declining growth of fertilizer input into a more or less constant input, whereas the level of input remains unclear (pathway I or II), and a third phase P_3 with a constant or decreasing fertilizer input depending on different external influences (pathways II to V). In conclusion, the performance of the pathway in P_3 will strongly depend on various factors like phosphorus accumulation in soils, phosphorus efficiency of agricultural systems, global population, dietary habits, total global wealth and total phosphorus reserves and extraction costs.

The figure above also depicts the concept of peak phosphorus, strongly thematized by Cordell (2009) and Cordell et al. (2011). Due to increasing extraction costs and a depletion of global reserves, prices for phosphorus will strongly increase, while demand and total consumption up to a particular point will turn downward. In this concept, not the absolute physical depletion of reserves becomes pivotal but the proportions of production costs, demand, substitution and markets. The concept of peak phosphorus puts not the absolute depletion central to assessment but the point at which high qualitative and easily exploitable reserves are largely exhausted to the center of consideration. Up from this point, extraction costs will increase heavily and demand will turn downwards (Cordell et al. 2009, 2011).

5.3 The global phosphorus cycle, phosphorus flows and comparison to other authors

In this thesis I used the approach of a material flow analysis (MFA) to calculate stocks and flows in the global phosphorus cycle, including fertilizer use and phosphorus accumulation in the soil, as well as losses to the environment from 1995 to 2050. CORDELL et al. (2009, 2011) characterized an MFA as a set of stocks and the appropriate flows connecting these stocks or reservoirs. They emphasized the utility of the MFA as a planning tool that could be improved by using it as a predictive model. This aspect has been the subject of this thesis. The results are described in depth in chapter 4.1 (table 9 and fig. 24), but summarized here to be discussed and compared with other author´s estimations.

The results will be compared with BOUWMAN et al. (2013), Bouwmann et al. (2009), STEEN (1998), SATTARI et al. (2012), Metson et al. (2012); VILLALBA et al. (2008). The results of other authors are summarized in table 23.

Issue	**Quantity& range (TgP/year) in 1995**	**Quantity & range (TgP/year) in 2050**	**Source**
Fertilizer production and use	14-14.7	10-24	CORDELL et al.(2009), VILLALBA et al. (2008), BOUWMAN et al. (2013) BOUWMAN et al. (2009) SATTARI et al. (2012)
Crop uptake	12-12.7		CORDELL et al.(2009), LIU et.al. (2008)
Crop residues to soil	2-2.2		CORDELL et al.(2009), LIU et.al. (2008)
Crop residues for feed	1.1		LIU et al. (2008)
Industrial byproducts and kitchen waste to animals	1		LIU et al. (2008)
Erosion losses from arable soils	8-19.3		CORDELL et al.(2009), LIU et al. (2008)
Crops harvested for food, feed, fiber	7		CORDELL et al.(2009)
Losses from crops to environment	3		CORDELL et al.(2009)
Crops fed to animals	2.6-2.9		CORDELL et al.(2009), LIU et al. (2008)
Post harvest losses	0.9		CORDELL et al.(2009)
Total fed to animals (non grazing)	6		LIU et al. (2008)
Crops for food	3.5		CORDELL et al.(2009)
Food use for human nutrition	3		CORDELL et al.(2009)
Organic waste from food	1.2		CORDELL et al.(2009)
Organic waste reflow to arable soils	0.2		CORDELL et al.(2009)
Organic waste to environment	1		CORDELL et al.(2009)
Pasture grazing to animals	12.1		CORDELL et al.(2009)
Animals to food	0.6		CORDELL et al.(2009)
Total animal manure	15-20	25-29	LIU et.al. (2008), SMIL (2000), Cordell et al.(2009), BOUWMAN et al. (2013)
Human excreta	3-3.3		CORDELL et al.(2009), LIU et al. (2008)
Human excreta to environment	2.7		CORDELL et al.(2009)
Animal manure to environment	7		CORDELL et al.(2009)

Total organic fertilizer on croplands	6.2		Liu et al. (2008)
Total input to croplands	20-31	29-50	Liu et al. (2008), Bouwman et al. (2013), Bouwman et al. (2009)
Total input to soil (all)	18.5		Villalba et al. (2008)
p-withdrawals	19	30-31	Bouwman et al. (2013)
Net accumulation	7.3		Liu et al. (2008)
p-budget	11	6-18	Bouwman et al. (2013)
p-runoff	4	6	Bouwman et al. (2013)
Total flow to in-land/coastal waters	4-22		Cordell et al.(2009), Cordell et al. (2008), Liu et al. (2008), Fillipelli (2002)

Table 23: Estimations of results of different authors

The quantity of fertilizer use in my estimations increased from 13.5 TgP in 1995 to 23.2 TgP in 2050; by 71%. This estimation for 2050 is strictly under Steen (1998), who estimated 30 TgP fertilizer use in 2050, but in line withBouwman et al. (2013), who calculated 23 TgP in their baseline scenario within the range of 18 to 24 TgP under different IAASTD scenarios in 2050. Bouwman et al. (2009) estimated 10 to 33 TgP fertilizer use in 2050 under different MEA scenarios. Sattari et al. (2012) calculated an increase of fertilizer application under the assumption of soil phosphorus accumulation from currently 17.8 TgP per ha to 16.8 to 20.8 TgP per ha in 2050; depending on the MEA scenario. Sattari et al. (2012) also estimated that between 2008 and 2050, a global phosphorus application to croplands of 700-790 kg per ha will be required tomaintain crop yields. This, summing up to 1 070 – 1 200 TgP, which lay near to my estimations of 1096.64 TgP, is totally necessary from 2010 to 2050 for agricultural p-fertilizer. Metson et al. (2012) calculated that the demand for P could increase by 68% to 141% in 2050 (that is between 27.1 and 39.1 Tg P compared to a 2007 value of 16.1 Tg P).

My estimations for total biomass production (5+6) account for 19.6 TgP in 1995 and 41.4 TgP in 2050, thereby increasing by 111%. This is way above the range of 12.0 to 12.6 TgP in crop uptake for 1995, calculated by Cordell et al. (2009) and Liu et al. (2008).

Also, my estimation on harvested crops accounting for 13 TgP in 1995 and 28.9 TgP in 2050, is way above estimations of 7 TgP for crops harvested for food, feed and fiber in 1995 by Cordell et al. (2009).

I calculated food processing (12) to increase by 74%, from 6.3 TgP to 11.0 TgP, and vegetal products for food use (14) by 78%, from 3.7 TgP to 6.6 TgP, while Cordell et al.(2009) estimated 3.5 TgP, which can be compared to the first value.

Crop production for feed use (11) in my estimations increased by 177%, from 4.9 TgP to 13.6 TgP, this lay above the range of 2.6 to 2.9 in 1995 given by Cordell et al. (2009) and Liu et al. (2008).

Total food for human nutrition increased by 103%, accounting for 5.5 TgP in 1995 and 11.2 TgP in 2050, lastly ending in sewage systems and thereby losses to the environment and waterbodies, while CORDELL et al. (2009) calculated 3 TgP in 1995.

Total feed use from pasture merely increased by 82%, from 12.3 TgP to 22.4 TgP. CORDELL et al. (2009) estimated total 12.1 TgP in 1995 which is in line with my estimations.

Total manure increased by 101%, from 19.75 TgP to 39.72 TgP. While different authors (Liu et al. 2008, Smil 2000, Cordell et al. 2009, BOUWMAN et al. (2009), BOUWMAN et al. (2013))estimate that the total animal manure in 1995 was between 15 to 20 TgP, which is in line with my estimations, BOUWMAN et al. (2013) estimates total manure to be 26 TgP and BOUWMAN et al. (2009) between 24 to 32 per year in 2050 TgP, depending on the scenario, which is above my estimations.

My estimations for total phosphorus input into croplands are 24.7 TgP in 1995 and 54.2 TgP in 2050. This estimation lies in the middle of the estimations of 18.5 TgP (VILLALBA et al. 2008), 20 TgP (LIU et al. 2008), 31 TgP (BOUWMAN et al. 2013) and 21 TgP(BOUWMAN et al. 2009)in 2000, and slightly above the range of 47 to 50 TgP in 2050 by the different scenarios of BOUWMAN et al. (2013) and way above the range of 29 to 46 TgP in 2050 by the different scenario estimations of BOUWMAN et al. (2009).

My calculated total withdrawals are 19.6 TgP in 1995 and 41.4 TgP in 2050, while Bouwman et al. (2013) calculated p-withdrawals of 19 TgP for the year 2000, which is comparable to my estimations, and for 31 TgP per year in 2050, which is below my calculations.

I estimated a phosphorus fixation/accumulation of residual phosphorus to the soils of 19 TgP in 1995 and 35.1 TgP in 2050, while the calculated 8 TgP per year in 2000 and 12 TgP per year in 2050 of Bouwman et al. (2013) lies far below these quantities. Bouwman et al. (2009) estimated the accumulation of phosphorus in cropland soils to increase from 9 TgP a^{-1} in 2000 to a range of 10 to 23 TgP a^{-1}in different scenarios in 2050. Compared to my results this is rather low.

I calculated total losses to the non-agricultural environment to increase by 83%, from 11.4 TgP in 1995 to 20.85 TgP in 2050. Total losses include losses from the animal waste management system (awms), losses from slaughter waste, losses from food (sewage systems), bioenergy losses, losses from conversion byproducts, material losses and losses from manure used as fuel in developing countries.

The losses from awms are estimated to increase from 0.72 TgP in 1995 to 1.42 in 2050. The losses via slaughter waste increased from 0.5 TgP to 1.27 TgP. Losses via food plays a major role for total losses, and increased from 5.47 TgP in 1995 to 11.22 TgP in 2050. Losses by bioenergy increased from 0.42 TgP in 1995 to 1 TgP in 2050. Losses of conversion byproducts remain static, due to their calculation at the level of 0.52 TgP. Material losses increase from 1.64 to 2.97 TgP. Losses from manure used as a fuel in developing countries also play a substantial role within total losses, and increase from 2.14 up to 3.82 in 2020, afterwards declining due to the change towards more a industrialized food system, down to 2.46 TgP.

The losses of phosphorus in confinement are calculated with the methodology from BODIRSKY et al. (2012), with data from IPCC (1996) and EGGLESTON et al. (2006). I assumed them to be the same as the share of nitrogen losses, minus the share of nitrogen volatilization, because nitrogen losses also include denitrification, which is not possible for phosphorus. With respect to the precision of representation of phosphorus losses, this is a rather rough estimation due to a lack of data. This has to be noted as a criticism of the model and has to be addressed in an improvement of the model for further works.

Food is assumed to end up in sewage systems or as waste. Nevertheless, in whichever way food is (un-)used, it can be assumed to end up in the environment either by wastewater systems or by waste dump. This is acceptable within the scope of this thesis as a proxy for environmental losses of phosphorus via sewage systems and food waste. Nonetheless, it has to be noted that this is a rather improper reproduction of the environmental destination, because of different environmental impacts and possibilities for management of phosphorus as a soluble or concrete material. This aspect also remains for a better ascertainment of phosphorus losses and impacts to the environment.

BOUWMAN et al. (2009) calculated soil balances for P to indicate p-losses to the environment for the 1970 to 2000 balances of 11 and 15 TgP a^{-1}, respectively, which is, for 1995, more or less in line with my estimations. The surplusses increased rapidly from 18 to 35 TgP a^{-1} in 2050, which is rather far above my estimations. It has to be noted that these estimations did not account for soil phosphorus accumulation. Bouwman et al. (2013) assumes that surface runoff, which is not represented in my model, is the only loss pathway for p and will count for 6 TgP per year in 2005.

In general, it has to be noted that there is a difficulty in comparing some of these results, because the calculation of stocks and flows differs between different authors. This is especially the case for the calculation of phosphorus accumulation by soil budgets and the calculation of losses to the environment, for example by erosion or runoff, because the definition of the system boundaries matters greatly and is, in some cases, not clear or not comparable. For example, positive phosphorus soil budgets can be interpreted as losses to the environment or as an accumulation of soil phosphorus, being available for coming times. This matters as well in my model for example erosion, and therefore a potential loss of phosphorus has not yet been modeled. For a better quantification of the environmental impacts of phosphorus losses, the system boundaries have to be defined more clearly and with a better quantification of losses, for example by erosion, has to be integrated into the model.

5.5 Outlook and further research

Summarizing the above discussed aspects of the model - the estimations of stocks and flows within the global phosphorus cycle, the estimations for phosphorus fertilizer use until 2050, my calculations regarding the depletion of global phosphorus reserves and the discussion of phosphorus demand and supply, as well as the drivers of global phosphorus markets - some concluding remarks on further research activities and model improvements can be stated.

(1) With the reevaluation of global phosphorus reserves in 2010, the “phosphorus problem” switched from a depletion problem to an environmental problem. My calculations of global phosphorus reserves depletion on the basis of the 2009 estimations of global phosphorus reserves (18 000 Tg phosphate rock) and 2013 estimations (68 000 Tg phosphate rock),show that under the first assumption total phosphorus depletion would has been realistic within the range of the next 100 years. Indeed, the reevaluation of global reserves changed the perspective, and phosphorus can be expected to be available for agricultural activities for the next 300 to 400 years. This is actually not relaxing the problem but rather tightening it, regarding increased phosphorus consumption in the global agricultural system and therefore increased phosphorus losses to the environment. As depicted in chapter 2.1 and discussed in chapter 5.2.3, phosphorus consumption will increase with the detection of new reserves and reduced extraction costs. As my model estimation shows, global phosphorus consumption will greatly increase until 2050 due to the influencing variables, like population growth, changing dietary habits and income growth. This requires a better quantification of phosphorus losses to environmental systems within the global phosphorus cycle, as well as global phosphorus management.

(2) As described in chapter 3.4 and discussed in chapter 5.1.4, my model does not represent the aspect of soil erosion and a differentiation of soluble and concrete phosphorus losses towards waterbodies, via rivers, that end up in marine ecosystems. It also does not represent the role of phosphorus release by soil organic matter loss within land use change and land conversion. What happens to phosphorus after land conversion? Does it accumulate in a soil phosphorus pool, or is it affected by runoff to above-ground waterbodies? This is deeply interrelated with agricultural systems and a modeling of wind and weather. Therefore, an erosion model may be necessary. These aspects have to be integrated into the model, as well as a more indepth quantification of other environmental losses and a better definition of regarded system boundaries.

(3) The aspect of residual phosphorus and the accumulation of phosphorus in the soil was a main aspect of my modeling approach. Like the sensitivity analysis shows, the model set-up strongly influences the results concerning fertilizer use, phosphorus accumulation and phosphorus release. As discussed in chapter5.1.3.4, for a better quantification the model can be adjusted and improved to represent soil phosphorus dynamics and soil-chemical dynamics in a better way. This could be reached by an improved soil phosphorus model, calibrated and fitted to historical fertilizer use and possibly soil phosphorus contents, retention potentials and phosphorus supply. As described in chapter 2.3.1, phosphorus availability is dependent on a large number of variables. There have been different efforts to provide global, spatially explicit soil phosphorus information for modeling. On a global scale, none of them is yet able to provide spatially explicit data that could be used, but the merging of different soil information data can promote future useful data. It would be very usefulif advanced soil phosphorus could be integrated into the model.

(4) As shown in chapter 2.1.1.3 and discussed in chapter 5.2.3.3, phosphorus demand is strongly dependant on socio-economic interactions. For an in depth analysis of drivers and triggers of phosphorus demand, it would be of interest and an interesting further research approach to analyze these aspects by factor analysis on drivers of phosphorus demand and fertilizer use. A factor analysis could extract influencing external factors to fertilizer consumption including social and economic databases, for example the Human Development Indices database or other interdisciplinary databases, to extract social and economic drivers for fertilizer consumption. As a basis for further economic investigations, as well as for further data-based modeling approaches, an econometric time-series analysis of historic fertilizer consumption and an estimation of future trends could also be of interest. For an economic discussion and estimation of future phosphorus prices and demand, an indepth analysis of demand, supply with its related elasticities, and the underlying drivers and external factors could be of great interest.

6 Conclusion

The subject of this thesis is the "story of phosphorus" (CORDELL et al. 2009) and its "global boundaries" (ROCKSTRÖM et. al 2009). These boundaries have two major dimensions, each with serious implications on global socio-environmental systems and the whole earth system as such – the depletion of global phosphorus reserves and the environmental impact of an increase of flows and losses within the global phosphorus cycle. The main aims of this thesis were to provide a modeling approach to quantify stocks, flows and losses within the agricultural phosphorus cycle up to 2050, to estimate future phosphorus fertilizer use and the depletion of phosphorus reserves. My estimations and the following discussion show that the global "phosphorus problem" switches from a depletion problem to a pollution problem. With an increase of global phosphorus flows and losses within the global phosphorus cycle, global boundaries, described by control variables and critical values concerning the definition of the safe operating space for humanity (ROCKSTRÖM et al 2009), could be severely transgressed. This becomes more serious as global phosphorus reserves are estimated not to restrict phosphorus use over the next decades by my model. ROCKSTRÖM et al (2009) define the phosphorus inflow to oceans as the control variable to avoid a major oceanic anoxic event, with impact on marine ecosystems and unpredictable further implications to global biogeochemical systems and the potential mass extinctions of marine life. They estimate, that currently around 8.5 to 9.5 million tonnes are transported by rivers into the oceans – a rate approximately eight times higher than the natural background rate of influx. I calculated that total losses to the non-agricultural environment will increase from 11.4 TgP in 1995 to 20.85 TgP in 2050. ROCKSTRÖM et al (2009) estimate the threshold of phosphorus inflow, that should not be exceeded at some 11 million tons (TgP). Although my estimation is a rather rough estimation, it can be considered as a proxy for the phosphorus load ending up in water ways.

Consequently, a globallyl integrated management of phosphorus emerges as a prerequisite for the future sustainable phosphorus use. For example, CORDELL et al. (2011) outlined an integrated systems framework for analyzis and identification of key stakeholders, system boundaries, different phosphorus recovery systems and techniques, logistics of collection, storage, transport and use, potential synergies and conflicts. Such an integrated, sustainable and system-oriented future global phosphorus management has to integrate different scales and technologies.

Furthermore, the necessary institutional arrangement will be of crucial importance. It can be argued that under a "phosphorus depletion problem", markets would have been an adequate instrument to optimize intertemporal utility, as depicted in chapter 2.1.2 under the aspects discussed in chapter

5.2.3, as long as markets work in an approximately “ideal” way. Under the consideration of a “phosphorus pollution problem”, to reach a sustainable use over time and find an optimal solution is a much more complex challenge. Here, environmental costs as well as the threats to the whole earth system has to be quantified and integrated. As long as actors are acting self-interestedly and under the assumption of unknown boundaries and limited knowledge on the resilience of the earth system as a whole regarding the impacts of an increase of flows and losses within the phosphorus cycle, multiplied efforts of the scientific, as well as of the international political community, are desperately needed. This requires a global governance of phosphorus and global phosphorus management.

This aspect is far beyond the scope of this thesis, but the results of my work underpin the necessity to look out for a much more in-depth integrated assessment of the “phosphorus problem”, as described in this thesis, to find corresponding solutions.

A sustainable management system must, in addition to returning of extracted nutrients, take care and minimize all other losses by wind and water erosion and stabilize the cycle of recycling the existing nutrients. The entering of human borne phosphorus to surface waterbodies, rivers, coastal and marine ecosystems and oceans has to be reduced. The impact of an increase in phosphorus demand on global food, energy and environmental or climate systems has to be taken into account. Under this scope, the possibility remains to address global challenges and elaborate ways towards a sustainable future use of phosphorus.

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Appendices

Appendix 1: Mathematical model description – MAgPIE

Main:

```
$title magpie
* 16 time slices until 2145
* Regional feed grain balances
* Water constraints: requirements for irrig. vs. discharge
* Cost structures to be linked to GDP?
* No climate change effects on yields
* Endogenous TC

*##################### R SECTION START (VERSION INFO) ##########################
*Used data set: GLUES2-sresa2-constant_co2-miub_echo_g_rev17
*
*Low resolution: n200
*High resolution: 0.5
*
*Total number of cells: 200
*
*Number of cells per region:
* AFR CPA EUR FSU LAM MEA NAM PAO PAS SAS
* 28 16 12 48 24 13 37 11 4 7
*
*lpj2magpie settings:
** Used data set: GLUES2-sresa2-constant_co2-miub_echo_g
** Revision: 17.0
*
*aggregation settings:
** Inputresolution: 0.5
** Outputresolution: n200
** (clustering) n-repeat: 5
** (clustering) n-redistribute: 0
*
*Last modification (input data): Mon Apr 22 23:22:49 2013*
*
*###################### R SECTION END (VERSION INFO) ###########################

$offupper
$offsymxref
$offsymlist
$Offlisting

********************************************************************************
*** WARNING **** WARNING **** WARNING **** WARNING **** WARNING **** WARNING ***
********************************************************************************

* PLEASE DO NOT PERFORM ANY CHANGES HERE! ALL SETTINGS WILL BE AUTOMATICALLY
* SET BY MAGPIE_START.R BASED ON THE SETTINGS OF THE CORRESPONDING CFG FILE
* PLEASE DO ALL SETTINGS IN THE CORRESPONDING CFG FILE (e.g. config/default.cfg)

********************************************************************************
*** WARNING **** WARNING **** WARNING **** WARNING **** WARNING **** WARNING ***
********************************************************************************

**************************MODEL SPECIFIC SCALARS********************************
* Key parameters during model runs

$setglobal max_timesteps 3

scalars s_use_calib      use of regional calibration factors (1:yes 0:no)  / 1 /
        sm_use_gdx       use of gdx files                                  / 2 /
        sm_maxiter       maximal solve iterations if modelstat is >2      / 3 /
        sm_with_climate  use of climate scenarios (1:yes 0:no)             / 0 /
;

*******************************MODULE SETUP*************************************
$setglobal scenarios SSP2_june13
$setglobal interest_rate glo
$setglobal maccs on_MAI13_AllLand
$setglobal nitrogen june13
$setglobal carbon normal
$setglobal methane ipcc1996
$setglobal phosphorus off
```

```

$setglobal nr_impact off

$setglobal crop dynamic
$setglobal pasture dynamic
$setglobal forestry static
$setglobal forest dynamic2
$setglobal urban static
$setglobal other dynamic

$setglobal factor_costs old

$setglobal landconversion calib_APR13

$setglobal presolve off

$setglobal residues detailed

$setglobal processing detailed

$setglobal livestock normal

$setglobal tc endo_APR13

$setglobal trade tb_old

$setglobal transport on

$setglobal area_equipped_for_irrigation endo_APR13

$setglobal water_availability surface_only

$setglobal water_demand standard

$setglobal bioenergy standard
scalars sm_biodem_level bioenergy demand level (1: regional 0: global)    / 1 / ;

*******************************END MODULE SETUP*********************************

***************************PREDEFINED MACROS************************************
$include "./core/macros.gms"
********************************************************************************
*************************BASIC SETS (INDICES)***********************************
$include "./core/sets.gms"
$batinclude "./modules/include.gms" sets
********************************************************************************
**********INTRODUCE CALCULATION PARAMETERS, VARIABLES AND EQUATIONS*************
$include "./core/declarations.gms"
$batinclude "./modules/include.gms" declarations
********************************************************************************
*****************************IMPORT DATA FILES**********************************
$include "./core/input.gms"
$batinclude "./modules/include.gms" input
********************************************************************************
********************OBJECTIVE FUNCTION & CONSTRAINTS****************************
$include "./core/equations.gms"
$batinclude "./modules/include.gms" equations
********************************************************************************

model magpie / all / ;

magpie.optfile = 0 ;
magpie.scaleopt= 1 ;
magpie.solprint = 2 ;
magpie.holdfixed = 1 ;

option lp = cplex ;
option qcp = cplex ;
option nlp= conopt ;
option iterlim= 100000 ;
option reslim = 100000 ;
option sysout = Off ;
option limcol = 0 ;
option limrow= 0 ;
option decimals = 3 ;
option savepoint = 1 ;

```

```
*****************************VARIABLE SCALING***********************************
$include "./core/scaling.gms"
$batinclude "./modules/include.gms" scaling
********************************************************************************

***************************GENERAL CALCULATIONS*********************************
$include "./core/calculations.gms"
********************************************************************************

*** EOF magpie.gms ***
```

Sets:

```
*************************BASIC SETS (INDICES)***********************************

*###############################################################################
*######################## R SECTION START (SETS) ###############################
*THIS CODE IS CREATED AUTOMATICALLY, DO NOT MODIFY THESE LINES DIRECTLY
*ANY DIRECT MODIFICATION WILL BE LOST AFTER NEXT INPUT DOWNLOAD
*CHANGES CAN BE DONE USING THE ARCHIVE DOWNLOADER UNDER SCRIPTS_INTERN
*THERE YOU CAN ALSO FIND ADDITIONAL INFORMATION

sets

   i all economic regions /AFR,CPA,EUR,FSU,LAM,MEA,NAM,PAO,PAS,SAS/

   j number of LPJ cells /

AFR_1*AFR_28,
CPA_29*CPA_44,
EUR_45*EUR_56,
FSU_57*FSU_104,
LAM_105*LAM_128,
MEA_129*MEA_141,
NAM_142*NAM_178,
PAO_179*PAO_189,
PAS_190*PAS_193,
SAS_194*SAS_200/

   cell(i,j) number of LPJ cells per region i
/
AFR . AFR_1*AFR_28
CPA . CPA_29*CPA_44
EUR . EUR_45*EUR_56
FSU . FSU_57*FSU_104
LAM . LAM_105*LAM_128
MEA . MEA_129*MEA_141
NAM . NAM_142*NAM_178
PAO . PAO_179*PAO_189
PAS . PAS_190*PAS_193
SAS . SAS_194*SAS_200
/

;
*######################### R SECTION END (SETS) ################################
*###############################################################################

***SOCIOECONOMIC SCENARIOS***
set all_scen socioeconomic scenarios available for MAgPIE
    / A1, A2, B1, B2, b2_ethics, default, scratch, SSP1, SSP2, SSP3, SSP4, SSP5,
planetary_boundaries /;

***TIME STEPS***
set t_ext extended vector of 5-year time periods
    / y1995, y2000, y2005, y2010, y2015, y2020, y2025, y2030, y2035, y2040,
      y2045, y2050, y2055, y2060, y2065, y2070, y2075, y2080, y2085, y2090,
      y2095, y2100, y2105, y2110, y2115, y2120, y2125, y2130, y2135, y2140,
     y2145, y2150, y2155, y2160, y2165, y2170, y2175, y2180, y2185, y2190,
     y2195, y2200, y2205, y2210, y2215, y2220, y2225, y2230, y2235, y2240,
y2245, y2250 /

   t_all(t_ext) 5-year time periods
   / y1995, y2000, y2005, y2010, y2015, y2020, y2025, y2030, y2035, y2040,
     y2045, y2050, y2055, y2060, y2065, y2070, y2075, y2080, y2085, y2090,
     y2095, y2100, y2105, y2110, y2115, y2120, y2125, y2130, y2135, y2140,
y2145, y2150 /;

```

```
set t(t_all) used time periods
$If "%max_timesteps%"==  "less_TS"/y1995,y2005,y2010,y2015,y2020,y2025,y2030,y2035,y2040,
y2045,y2050,y2055,y2060,y2070,y2080,y2090,y2100,y2110,
y2130,y2150/;
$If "%max_timesteps%"=="test_TS" /y1995,y2005,y2010,y2020,y2030,y2040,y2050,y2070,y2090
y2110,y2130,y2150/;
$If "%max_timesteps%"== "TS_benni" /y1995,y2000,y2010,y2020,y2030,y2040,y2050/;
$If "%max_timesteps%"=="1" /y1995/;
$If "%max_timesteps%"=="2" /y1995,y2005/;
$If "%max_timesteps%"== "3" /y1995,y2005,y2015/;
$If "%max_timesteps%"== "4" /y1995,y2005,y2015,y2025/;
$If "%max_timesteps%"== "5" /y1995,y2005,y2015,y2025,y2035/;
$If "%max_timesteps%"== "6" /y1995,y2005,y2015,y2025,y2035,y2045/;
$If "%max_timesteps%"==  "7" /y1995,y2005,y2015,y2025,y2035,y2045,y2055/;
$If "%max_timesteps%"==  "8" /y1995,y2005,y2015,y2025,y2035,y2045,y2055,y2065/;
$If "%max_timesteps%"==  "9" /y1995,y2005,y2015,y2025,y2035,y2045,y2055,y2065,y2075/;
$If "%max_timesteps%"== "10" /y1995,y2005,y2015,y2025,y2035,y2045,y2055,y2065,y2075,
y2085/;
$If "%max_timesteps%"== "11" /y1995,y2005,y2015,y2025,y2035,y2045,y2055,y2065,y2075,y2085,
y2095/;
$If "%max_timesteps%"== "12" /y1995,y2005,y2015,y2025,y2035,y2045,y2055,y2065,y2075,y2085
y2095,y2105/;
$If "%max_timesteps%"== "13" /y1995,y2005,y2015,y2025,y2035,y2045,y2055,y2065,y2075,y2085,
y2095,y2105,y2115/;
$If "%max_timesteps%"== "14" /y1995,y2005,y2015,y2025,y2035,y2045,y2055,y2065,y2075,y2085,
y2095,y2105,y2115,y2125/;
$If "%max_timesteps%"== "15" /y1995,y2005,y2015,y2025,y2035,y2045,y2055,y2065,y2075,y2085
y2095,y2105,y2115,y2125,y2135/;
$If "%max_timesteps%"== "16" /y1995,y2005,y2015,y2025,y2035,y2045,y2055,y2065,y2075,y2085
y2095,y2105,y2115,y2125,y2135,y2145/;

alias(t,z);

sets

***ACTIVITIES***
Kbiobiomass production
/ tece_cropby, tece, tece_convby, trce_cropby, trce, trce_convby,maiz_cropby, maiz,
maiz_convby, rice_cropby, rice_pro, rice_convby1,rice_convby2, others, brewer,
potato_cropby, potato, cassav_cropby,cassav_sp, puls_pro, soybean_cropby, soybean,
soybean_convby,rapeseed_cropby, rapeseed, rapeseed_convby, groundnut_cropby,
groundnut, groundnut_convby, sunflower_cropby, sunflower,sunflower_convby, oilpalm,
cottn_pro, cottn_convby, sugr_beet_cropby,sugr_beet, sugr_beet_convby1,
sugr_beet_convby2, sugr_cane_cropby,sugr_cane, sugr_cane_convby1, sugr_cane_convby2,
livst_rum, livst_pig,livst_chick, livst_egg, livst_milk, non_eaten_food, scavenging,
foddr, pasture,begr, betr /

k(kbio) production activities
/ tece, maiz, trce, rice_pro, soybean, rapeseed, groundnut, sunflower, oilpalm,
puls_pro, potato, cassav_sp, sugr_cane, sugr_beet, others,foddr, pasture, cottn_pro,
begr, betr, livst_rum, livst_pig,livst_chick, livst_egg, livst_milk /

k_trade(k) production activities for which trade is allowed
/ tece, maiz, trce, rice_pro, soybean, rapeseed, groundnut, sunflower, oilpalm,
puls_pro, potato, cassav_sp, sugr_cane, sugr_beet, others,cottn_pro, begr, betr,
livst_rum, livst_pig,livst_chick, livst_egg, livst_milk /

k_notrade(k) production activities
/ foddr, pasture /

kve(k) vegetal production activities
/ tece, maiz, trce, rice_pro, soybean, rapeseed, groundnut, sunflower, oilpalm,
puls_pro, potato, cassav_sp, sugr_cane, sugr_beet, others,foddr, pasture,
cottn_pro, begr, betr /

kcr(kve) crop activities
/ tece, maiz, trce, rice_pro, soybean, rapeseed, groundnut, sunflower,oilpalm,
puls_pro, potato, cassav_sp, sugr_cane, sugr_beet, others,foddr, cottn_pro, begr,
betr /

kli(k) livestock activities
/ livst_rum, livst_pig, livst_chick, livst_egg, livst_milk /

kli2(kli) livestock activities
/ livst_rum, livst_pig, livst_chick, livst_egg, livst_milk /

kfo(kcr) food crop activities
```

```
/ tece,maiz,trce,rice_pro, soybean,rapeseed,groundnut,sunflower,oilpalm,
puls_pro,potato,cassav_sp,sugr_cane,sugr_beet,others /

*** conversion byproducts
faoconvby fao_byproduct producing commodities from fao
/ brans, molasses, cake_soy, cake_groundnut, cake_oilpalm, cake_rape, cake_sunflower,
cake_cotton, cake_others /

***Livestock subsystems***
sub Livestock subsystems
/ dairy_reproducer, dairy_growing, beef_reproducer, beef_growing, pig_all, hen,
chicken /

***Energy densities***
ener Nutrient and Energy densities/ ME, NEl, NEm, NEg /

***TYPE OF WATER SUPPLY***
w water supply type            / rainfed, irrigated /

***WATER SOURCES***
 wat_src water sources         / surface, ground, technical /

***WATER DEAMND sectors***
wat_dem water demands          / agriculture, industry, electricity, domestic, ecosystem /

***CROP ROTATION TYPES***
crp crop rotation types
    / cereals_r, rice_r, cer_rice_r, fieldoil_r, soybean_r, rapeseed_r,sunflower_r,
groundnut_r, oilpalm_r, puls_r, potato_r, cassava_r, roots_r, sugr_cane_r,
sugr_beet_r, others_r, foddr_r, fiber_r, begr_r, betr_r /

***LAND POOLS***
land land pools                / crop, past, forestry, forest, urban, other /

si suitability classes         / si0, nsi0 /

***Forestry**
wt wood type                   / ind_roundwood,woodfuel /

ac age classes
/ ac5,ac10,ac15,ac20,ac25,ac30,ac35,ac40,ac45,ac50,180 ac55,ac60, ac65,ac70,ac75,ac80,
ac85,ac90,ac95,ac100,ac105,ac110,ac115,ac120,ac125,ac130,ac135,ac140,ac145,ac150,
ac155,ac160,ac165,ac170,ac175,ac180,ac185,ac190,ac195,ac200,ac205,ac210,ac215,ac220,
ac225,ac230,ac235,ac240,ac245,ac250,ac255,ac260,ac265,ac270,ac275,ac280,ac285,ac290,
ac295,acx /

flt forest land types                                / sown, protected, harvestable /

fkt function of planted age-class forest             / raw, carb /

when temporal location relative to optimization      / before, after /

tp time period                                       / present,future /

ws wood source                                       / ac,nac /

chap_par chapman-richards parameters                 / k,m /

*** Nutrients
attributes product attributes                        /dm,ge,nr,p,k,wm/
*dry matter, gross energy, reactive nitrogen, phosphorus, potash, wet matters
dm_ge_nr(attributes) attribtues relevant for nutrition
/ dm,ge,nr /

*** Crop residues
res_use use of crop residues
    / recycle,feed,burn,bioenergy,other /

cgf residue production functions
    /slope, intercept, bg_to_ag/

***Emissions ***
ghg Greenhouse gases
/n2o_n, ch4, co2_c/

emis emission sources
/inorg_fert_n2o, man_crop_n2o, awms_n2o, resid_n2o, man_past_n2o, som_n2o,
```

```
rice_bonus_n2o, rice_ch4, ent_ferm_ch4, awms_ch4, crop_vegc, crop_litc, crop_soilc,
past_vegc, past_litc, past_soilc, forestry_vegc, forestry_litc, forestry_soilc,
forest_vegc, forest_litc, forest_soilc, urban_vegc, urban_litc, urban_soilc,
other_vegc, other_litc, other_soilc/
emis_cell(emis) celllular emission sources
/crop_vegc, crop_litc, crop_soilc, past_vegc, past_litc, past_soilc, forestry_vegc,
forestry_litc, forestry_soilc, forest_vegc, forest_litc, forest_soilc, urban_vegc,
urban_litc, urban_soilc, other_vegc, other_litc, other_soilc/
emis_reg(emis) regional emission sources
/inorg_fert_n2o, man_crop_n2o, awms_n2o, resid_n2o, man_past_n2o, som_n2o,
rice_bonus_n2o, rice_ch4, ent_ferm_ch4, awms_ch4/
emis_n2o(emis_reg) N2O emission sources
/inorg_fert_n2o, man_crop_n2o, awms_n2o, resid_n2o, man_past_n2o, som_n2o,
rice_bonus_n2o/
emis_ch4(emis_reg) CH4 emission sources
/rice_ch4, ent_ferm_ch4, awms_ch4/
emis_co2(emis_cell) CO2 emission sources
/crop_vegc, crop_litc, crop_soilc, past_vegc, past_litc, past_soilc, forestry_vegc,
     forestry_litc, forestry_soilc, forest_vegc, forest_litc, forest_soilc, urban_vegc,
     urban_litc, urban_soilc, other_vegc, other_litc, other_soilc/
emis_co2_forestry(emis_cell) forestry CO2 emission sources
    /forestry_vegc, forestry_litc, forestry_soilc/

c_pools carbon pools
/vegc,litc,soilc/

***TECHNICAL STUFF***
type type of output          / level, marginal, upper, lower /

***RELATIONSHIPS BETWEEN DIFFERENT SETS***

ghg_to_emis(ghg,emis)
/ n2o_n   . (inorg_fert_n2o, man_crop_n2o, awms_n2o, resid_n2o, man_past_n2o, som_n2o,
rice_bonus_n2o)
      ch4     . (rice_ch4, ent_ferm_ch4, awms_ch4)
co2_c . (crop_vegc, crop_litc, crop_soilc, past_vegc, past_litc, past_soilc,
forestry_vegc, forestry_litc, forestry_soilc, forest_vegc, forest_litc,
forest_soilc,urban_vegc, urban_litc, urban_soilc, other_vegc,
other_litc, other_soilc)
/

emis_co2_to_land(emis,land,c_pools)
/crop_vegc. (crop) . (vegc)
 crop_litc. (crop) . (litc)
crop_soilc . (crop) . (soilc)
 past_vegc. (past). (vegc)
past_litc . (past). (litc)
past_soilc . (past). (soilc)
forestry_vegc . (forestry) . (vegc)
 forestry_litc . (forestry) . (litc)
forestry_soilc . (forestry) . (soilc)
forest_vegc . (forest) . (vegc)
forest_litc . (forest) . (litc)
forest_soilc . (forest) . (soilc)
urban_vegc . (urban) . (vegc)
urban_litc . (urban) . (litc)
 urban_soilc . (urban) . (soilc)
 other_vegc. (other) . (vegc)
 other_litc . (other) . (litc)
 other_soilc. (other) . (soilc)
/

emis_co2_to_forestry(emis_co2_forestry,c_pools)
/forestry_vegc . (vegc)
forestry_litc . (litc)
 forestry_soilc . (soilc)
/

crp_kcr(crp,kcr)
/ cereals_r . (tece, maiz, trce)
rice_r . (rice_pro)
cer_rice_r . (tece, maiz, trce, rice_pro)
fieldoil_r . (soybean, rapeseed, groundnut, sunflower)
soybean_r . (soybean)
rapeseed_r . (rapeseed, sugr_beet)
sunflower_r. (sunflower)
groundnut_r. (groundnut)
```

```
oilpalm_r . (oilpalm)
puls_r. (puls_pro)
 potato_r. (potato)
cassava_r . (cassav_sp)
 sugr_cane_r. (sugr_cane)
 sugr_beet_r. (sugr_beet)
 others_r . (others)
 foddr_r. (foddr)
 fiber_r . (cottn_pro)
 begr_r. (begr)
 betr_r. (betr) /

;

*** EOF sets.gms ***
```

Declarations:

```
******************INTRODUCE CALCULATION PARAMETERS*****************************

parameters

*** Variable names:
* o_consrent_glo_k

****** Prefix:
* s parameter
* f data from files - influencing the optimization process without being influenced
itself
* i input -influencing without being influenced itself
* ic value within the current timestep (necessary for constraints)
* p processing - influencing and being influenced
* pc value within the current timestep (necessary for constraints)
* o output - only being influenced without influencing
* v variable
* q equations
* oq parameter containing levels and marginals of an equation
* ov parameter containing levels and marginals of a variable
* m an extension of the prefix with the letter "m" means, that this object is
*used by at least one module. So check all modules, if you intent to modify it
* ? an extension with another letter different to m and c means that this
* object belongs to a module. Hence, it should also only occur in modules
* without prefix - auxiliary parameters

****** Suffix
* no suffix: highest disaggregation scale available
* reg: regional aggregation
* glo: global aggregation
* k: aggregation over activities
* kve: can also be aggregated over a subset of k

pm_interest(i) real interest reate in each region
pm_annuity_due(i) Annuity-due annual cash flows over n years in each region
(vorschuessig)

*** Technical Parameters *******************************************************
o_modelstat(t) modelstat
im_years(t) years between previous and current time step(years)

****** Emissions and Nutrients
fcm_ghg_prices(i,ghg) current ghg prices
pm_nr_som(t,j) Nr released by soil organic matter loss (Tg Nr)
pm_nr_som_usable(t,j) Nr released by soil organic matter loss thatcan be
aquired by cropping activities (Tg Nr)

****** Land-Expansion
pm_land_start(j,land)landpools from initialization (mio.ha)
pm_land(t,j,land,si)area of different land types (mio. ha)
pcm_land(j,land,si) current area of different land types(mio. ha)
pcm_land_shift(j,land,si) current area of shifted land for different landtypes
(mio. ha)
********* SUPPLY ***************************************************************
****** Yields
im_yields(t,j,kve,w)               input yields (ton DM per ha)
p_yld(j,kcr,w)                     Yield (ton DM per ha)
p_tau(t,i)                         agricultural land use intensity tau (1)
pcm_tau(i)                         agricultural land use intensity tau of current time
```

```
step (1)

********* DEMAND ***************************************************************
*IW

****** Food
im_dem_food(t,i,k) regional food demand (10^6 ton DM)
i_food_ME_shr_new(t,i,k) updated food shares (1)
ic_dem_food(i,k) i_reg_dem_food for the actual time step (10^6ton DM)

****** Feed
im_feed_bask(t,i,kli,kbio)feed basket per animal type (Mt DM per Mt DM)

****** Others
im_dem_material(t,i,k)             regional material demand (10^6 ton DM)
i_mat_GE_shr_new(t,i,k) updated material shares (1)
ic_dem_material(i,k)i_reg_dem_material for the actual time step
(10^6 ton DM)
im_attributes_harvest(attributes,kve) attributes of harvested organs
(t DM WM Nr P KGJ per ton product)

i_carbon_density(t,j,land,c_pools) carbon density in vegetation soil andlitter
(tC per ha)
icm_carbon_density(j,land,c_pools) carbon density in vegetation soil andlitter of current
time step (tC per ha

********* CROP-ROTATIONAL CONSTRAINT *******************************************

********* WATER ****************************************************************

********* COSTS ****************************************************************

********* OTHER ****************************************************************

;

scalars
s_counter counter (-)
sm_years length of current time step (years)
sm_use_bioenergy switch to deactivate bioenergy use
(needed for presolve module)/ 1 /
;

variables
vm_cost_glo total costs of production (mio. US$)
vm_emissions_reg(i,ghg) endogenous emissions (Tg N2O-N CH4 and CO2-C)
vm_emission_costs(i) Costs for emission pollution rights (mio. US$)
 vm_btm_cell(j,emis_cell)annual emissions by emission source categories
(TgN2O-N CH4 and CO2-C per year)
vm_btm_reg(i,emis_reg) annual emissions by emission source categories
(TgN2O-N CH4 and CO2-C per year)
vm_exp_emis_affore(j,emis_co2_forestry)  total additional co2_c emissions beyond current
time step according to sm_invest_horizon) (Tg CO2-C)
;

positive variables

vm_cost_reg(i)regional costs (mio. US$)

vm_prod(j,k) production in each cell (mio. ton DM)
vm_prod_reg(i,k) regional aggregated production (mio. ton DM)
vm_area(j,kcr,w) production area (mio. ha)
vm_land(j,land,si)                areas of the different land types (mio.ha)

vm_yld(j,kcr,w)                   yields (variable because of technical change)
(ton DM per ha)
vm_tau(i)                         agricultural land use intensity tau (1)
vm_tech_cost(i)                   costs of technological change (mio. US$)

vm_cost_prod(i,k)                 factor costs (mio US$)
vm_cost_transp(j,k)               transportation costs (mio US$)
vm_cost_landcon(j,land)           landconversion costs (mio US$)

vm_supply(i,k)                    regional demand (mio ton DM)
vm_dem_feed(i,kli,kbio)           regional feed demand including byproducts (mio ton DM)
vm_dem_bioen(i,k)                 regional bioenergy demand (mio. ton DM)

```

```
vm_watdem(wat_dem,j)              amount of water needed in different sectors (mio. m^3)
vm_watavail(wat_src,j)            amount of water available from different sources
(mio. m^3)
vm_AEI(j)                         area equipped for irrigation in each gridcell (mio ha.)
vm_cost_AEI(i)                    irrigation expansion costs (mio. US$)

vm_maccs_costs(i)                 costs of technical mitigation of GHG emissions
(mio US$2004)
vm_nr_inorg_fert_costs(i)         inorganic fertilizer costs (module emissions)
vm_nr_impact_costs(i)             nitrogen impact costs (module nr_impacts) in mio US$
vm_dem_res_substitutes(i,kli,kcr) Demand for subsitutes of crop residues (when more crop
 residues are required than would be produced for crop
demand) (module residues)
vm_dem_convby_substitutes(i,kli,kcr) Demand for subsitutes of conversion byproducts(when
more crop residues are required than would be produced
                                  for crop demand) (module residues)
vm_prod_res_ag_reg(i,kve)         production of aboveground residues in each region
(mio. ton DM)
vm_prod_res_bg_reg(i,kve)         production of belowground residues in each region
(mio. ton DM)
vm_res_supply(i,res_use,kve)      use of residues for different purposes (1)
vm_res_use_feed(i,kli,attributes) residues used for feed distinguished by kli
(Mtattributes)
vm_convby_feed(i,kli,attributes)  nutrients in conversion byproducts fed to livestock by
kli (Mt attributes))

vm_cost_trade(i)                  transport costs and taxes for the bilateral trade
(Mio US$)

vm_carbon_stock(j,land,c_pools)   carbon in vegetation soil and litter for different land
types (Mio tC)
vm_cost_past(i) pasture costs (Mio US$)

vm_prod_wood(j,ws,tp) wood production (mio. m3 DM)
vm_cost_fore(i,ws) total forestry costs (Mio US$)
;

equations

q_cost_glo objective function
q_trade_glo(k) Global production >demand constraint
q_trade_reg(i,k_notrade) regional production >demand constraint for non traded
commodities
q_cost_reg(i) regional cost constraint

q_yield(j,kcr,w)yields
q_prod(j,kcr) production constraint for vegetal products

q_cropland(j)                    crop conversion constraint
q_land(j,si)                     land conversion constraint

q_supply(i,k)                    regional demand
q_prod_reg(i,k)                  regional production

q_rotation_max(j,crp,w)          local rotational constraints
q_rotation_min(j,crp,w)          local rotational constraints (minimum)

q_water(j)                       local seasonal water constraints
q_area_irrig(j)                  irrigation area constraint

;

*#################### R SECTION START (OUTPUT DECLARATIONS) ####################

parameters

ov_cost_glo(t,type)              total costs of production (mio. US$)
ov_emissions_reg(t,i,ghg,type)   endogenous emissions (Tg N2O-N CH4 and CO2-C)
ov_emission_costs(t,i,type)      Costs for emission pollution rights (mio. US$)
ov_btm_cell(t,j,emis_cell,type)  annual emissions by emission source categories
(Tg N2O-N CH4 and CO2-C per year)
ov_btm_reg(t,i,emis_reg,type)    annual emissions by emission source categories
(Tg N2O-N CH4 and CO2-C per year)
ov_exp_emis_affore(t,j,emis_co2_forestry,type)     total additional co2_c emissions beyond
                                 current time step according to sm_invest_horizon)
(Tg CO2-C)
ov_cost_reg(t,i,type)            regional costs (mio. US$)
```

```
ov_prod(t,j,k,type)              production in each cell (mio. ton DM)
ov_prod_reg(t,i,k,type)          regional aggregated production (mio. ton DM)
ov_area(t,j,kcr,w,type)          production area (mio. ha)
ov_land(t,j,land,si,type)        areas of the different land types (mio.ha)
ov_yld(t,j,kcr,w,type)           yields (variable because of technical change)
(ton DM per ha)
ov_tau(t,i,type)                 agricultural land use intensity tau (1)
ov_tech_cost(t,i,type)           costs of technological change (mio. US$)
ov_cost_prod(t,i,k,type)         factor costs (mio US$)
ov_cost_transp(t,j,k,type)       transportation costs (mio US$)
ov_cost_landcon(t,j,land,type)   landconversion costs (mio US$)
ov_supply(t,i,k,type) regional demand (mio ton DM)
ov_dem_feed(t,i,kli,kbio,type)   regional feed demand including byproducts
(mio ton DM)
ov_dem_bioen(t,i,k,type)         regional bioenergy demand (mio. ton DM)
ov_watdem(t,wat_dem,j,type)      amount of water needed in different sectors (mio. m^3)
ov_watavail(t,wat_src,j,type)    amount of water available from different sources
(mio. m^3)
ov_AEI(t,j,type)                 area equipped for irrigation in each gridcell
(mio ha.)
ov_cost_AEI(t,i,type)            irrigation expansion costs (mio. US$)
ov_maccs_costs(t,i,type)         costs of technical mitigation of GHG emissions
(mio US$2004)
ov_nr_inorg_fert_costs(t,i,type) inorganic fertilizer costs (module emissions)
ov_nr_impact_costs(t,i,type)     nitrogen impact costs (module nr_impacts) in mio US$
ov_dem_res_substitutes(t,i,kli,kcr,type)      Demand for subsitutes of crop residues (when
                                 more crop residues are required than would be produced
for crop demand) (module residues)
ov_dem_convby_substitutes(t,i,kli,kcr,type)      Demand for subsitutes of conversion
                                 byproducts (when more crop residues are required than
                                 would be produced for crop demand) (module residues)
ov_prod_res_ag_reg(t,i,kve,type) production of aboveground residues in each region
(mio. ton DM)
ov_prod_res_bg_reg(t,i,kve,type) production of belowground residues in each region
(mio. ton DM)
ov_res_supply(t,i,res_use,kve,type)         use of residues for different purposes (1)
ov_res_use_feed(t,i,kli,attributes,type)    residues used for feed distinguished by kli
(Mt attributes)
ov_convby_feed(t,i,kli,attributes,type)     nutrients in conversion byproducts fed to
                                 livestock by kli (Mt attributes))
ov_cost_trade(t,i,type)          transport costs and taxes for the bilateral trade
(Mio US$)
ov_carbon_stock(t,j,land,c_pools,type)      carbon in vegetation soil and litter for
different land types (Mio tC)
ov_cost_past(t,i,type)           pasture costs (Mio US$)
ov_prod_wood(t,j,ws,tp,type)     wood production (mio. m3 DM)
ov_cost_fore(t,i,ws,type)        total forestry costs (Mio US$)
oq_cost_glo(t,type)              objective function
oq_trade_glo(t,k,type)           Global production >demand constraint
oq_trade_reg(t,i,k_notrade,type) regional production >demand constraint for non traded
commodities
oq_cost_reg(t,i,type)            regional cost constraint
oq_yield(t,j,kcr,w,type)         yields
oq_prod(t,j,kcr,type)            production constraint for vegetal products
oq_cropland(t,j,type)            crop conversion constraint
oq_land(t,j,si,type)             land conversion constraint
oq_supply(t,i,k,type)            regional demand
oq_prod_reg(t,i,k,type)          regional production
oq_rotation_max(t,j,crp,w,type)  local rotational constraints
oq_rotation_min(t,j,crp,w,type)  local rotational constraints (minimum)
oq_water(t,j,type)                local seasonal water constraints
oq_area_irrig(t,j,type)           irrigation area constraint
;

*##################### R SECTION END (OUTPUT DECLARATIONS) #####################

*** EOF declarations.gms ***
```

Input:

```
** Technical Parameters *******************************************************
*Output parameters about calculation quality and feasibility

******* Calibration factor
table f_yld_calib(i,kve) Calibration factor for the LPJ yields ()
$ondelim
$include "./input/regional/reg.calib_factor.csv"
```

```
$offdelim;


********* SUPPLY ***************************************************************

****** Production

parameter fm_DM_content(kbio)    Dry matter content (% fresh matter)   [Wirsenius]
/
$ondelim
$include "./input/regional/DM_content.csv"
$offdelim
/;

table fm_seed_shr(i,k)           seed share relative to production (1) [FAO - FBS]
$ondelim
$include "./input/regional/seed_shr.csv"
$offdelim;


table fm_prod_kli_1995(i,kli)    livestock product production for 1995 in Mt
$ondelim
$include "./input/regional/prod_kli_fao_1995.csv"
$offdelim ;

parameter fm_tau1995(i)          agricultural land use intensity tau in 1995 (1)
/
$ondelim
$include "./input/regional/tau_total_1995.csv"
$offdelim
/;

****** Nutritional Value

parameter fm_GE_content(kbio)    Gross energy content (GJ per ton DM) [Wirsenius] used in
emimodule
/
$ondelim
$include "./input/regional/GE_content.csv"
$offdelim
/;

table f_attributes_harvest_pure(attributes, kve) Nutrient content of harvested organ in t
                                 nutrient per t DM not corrected for different isabelles
different dm contents
$ondelim
$include "./input/regional/f_attributes_harvest.csv"
$offdelim ;

parameter fm_DM_correct(k)       Dry matter correction factor between Wirsenius
(currently used)and more detailed dm-estimate
(only used in nutrient-implementation)
/
$ondelim
$include "./input/regional/dm_correct.csv"
$offdelim
/ ;

table fm_attributes_residue_ag(attributes,kve) Nutrient content of abovegroudn crop
residues in t nutrient per t DM
$ondelim
$include "./input/regional/f_attributes_residue_ag.csv"
$offdelim;

********* DEMAND ***************************************************************

table fm_prod_cal(i,k)           Calibration of FBS production to ProdSTAT production (1)
[FAO - FBS]
$ondelim
$include "./input/regional/production_cal.csv"
$offdelim;


****** Food

table f_food_ME_shr_1995(i,k)    Food shares in regional food energy consumption (1)
[FAO -FBS]
```

```
$ondelim
$include "./input/regional/food_ME_shr.csv"
$offdelim;

table fm_human_ME_content(i,k)   Calculated human metabolizable energy content
(GJ per ton DM)[FAO - FBS]
$ondelim
$include "./input/regional/human_ME_content.csv"
$offdelim;


****** Feed

*!!!!!!!!!!!!!!!!
table fm_animal_en_content(sub,ener,kbio) different energy densities of k for livestock
subsystems (GJ per ton DM) [Wirsenius]
$ondelim
$include "./input/regional/animal_en_content.csv"
$offdelim;

****** Others

table f_mat_GE_shr(i,k)          Material shares in regional material gross energy
consumption (1)[FAO - FBS] [Wirsenius]
$ondelim
$include "./input/regional/mat_GE_shr.csv"
$offdelim;

********* CROP-ROTATIONAL CONSTRAINT *******************************************

parameter f_rotation_max_shr(crp) Max allowed shares for each crop demand type (1)
/
$ondelim
$include "./input/regional/rotation_max.csv"
$offdelim
/;

parameter f_rotation_min_shr(crp) Max allowed shares for each crop demand type (1)
/
$ondelim
$include "./input/regional/rotation_min.csv"
$offdelim
/;

********* TRADE ****************************************************************
*CS

table fm_self_suff_seedred_1995(i,k) Self Sufficiency rate (reduced by seed use) (1)
[FAO - FBS]
$ondelim
$include "./input/regional/self_suff_seedred.csv"
$offdelim;

table fm_exp_shr_1995(i,k)         regional and crop-specific export share (1)
$ondelim
$include "./input/regional/export_shr.csv"
$offdelim;


********* RENTS AND VALUES *****************************************************

table f_ghg_prices(t_all,i,ghg)      ghg certificate prices
(US$ 2004 per Tg N2O-N CH4 and CO2-C)
$ondelim
$include "./input/regional/ghg_prices.cs3"
$offdelim
;

**************************** Cellular Inputs ************************************

****** C Content Density
table f_carbon_density(t_all,j,land,c_pools) LPJ carbon density for land and carbon pools
(tC per ha)
$ondelim
$include "./input/cellular/lpj_carbon_stocks.cs3"
$offdelim ;
```

```
table f_yields(t_all,j,kve,w) LPJ potential yields per cell
(rainfed and irrigated) [ton drymatter per ha]
$ondelim
$include "./input/cellular/lpj_yields.cs3"
$offdelim
;

table f_land(j,land,si) Different land type areas (si0 and nsi0) [mio. ha]
$ondelim
$include "./input/cellular/avl_land.cs3"
$offdelim
;

parameters
fm_irrig(j) available area equipped for irrigation (million ha)
[AVL]
/
$ondelim
$include "./input/cellular/avl_irrig.cs2"
$offdelim
/
;
****** Year auxiliary parameter

parameter fm_years(t_all) file containing the years of the t_all set
/
$ondelim
$include "./input/regional/years.csv"
$offdelim
/;

*** EOF input.gms ***
```

Equations:

```
*********************************************************************************
*****************************OBJECTIVE FUNCTION*********************************

q_cost_glo .. vm_cost_glo
=e=
sum(i, vm_cost_reg(i));

q_cost_reg(i) .. vm_cost_reg(i)
=e=
sum(k, vm_cost_prod(i,k))
+ sum((cell(i,j),land), vm_cost_landcon(j,land))
+ sum((cell(i,j),k), vm_cost_transp(j,k))
+ vm_tech_cost(i)
+ vm_nr_inorg_fert_costs(i)
+ vm_emission_costs(i)
+ vm_maccs_costs(i)
+ vm_nr_impact_costs(i)
+ vm_cost_AEI(i)
+ vm_cost_trade(i)
+ sum(ws, vm_cost_fore(i,ws))
+ vm_cost_past(i)
;

*********************************************************************************
*********************************CONSTRAINTS************************************

*****************************GLOBAL CONSTRAINTS*********************************

*Sum over all supplies > Global demand

q_trade_glo(k).. sum(i ,vm_prod_reg(i,k))
=g=
sum(i, vm_supply(i,k));

*****************************REGIONAL CONSTRAINTS*******************************

q_trade_reg(i,k_notrade).. vm_prod_reg(i,k_notrade)
=g=
vm_supply(i,k_notrade);


q_supply(i,k) .. vm_supply(i,k)
```

```
=e=
ic_dem_food(i,k)
+ ic_dem_material(i,k)
                 + sum(kli, vm_dem_feed(i,kli,k))
                 + vm_dem_bioen(i,k)
+ vm_prod_reg(i,k) * fm_seed_shr(i,k);

****************************CELLULAR Aggregation CONSTRAINTS********************

q_prod_reg(i,k) .. vm_prod_reg(i,k)
=e=
                   sum(cell(i,j), vm_prod(j,k));

****************************CELLULAR CONSTRAINTS********************************

q_land(j,si) .. sum(land, vm_land(j,land,si))
=e=
                sum(land, pcm_land(j,land,si));

q_cropland(j) .. sum((kcr,w), vm_area(j,kcr,w))
=e=
vm_land(j,"crop","si0");

q_yield(j,kcr,w) .. vm_yld(j,kcr,w)
=e=
p_yld(j,kcr,w)*sum(cell(i,j),vm_tau(i)/pcm_tau(i));

q_prod(j,kcr) .. vm_prod(j,kcr)
=e=
sum(w, vm_area(j,kcr,w)*vm_yld(j,kcr,w));

*Rotational constraints:
q_rotation_max(j,crp,w) .. sum((crp_kcr(crp,kcr)), vm_area(j,kcr,w))
=l=
sum(kcr, vm_area(j,kcr,w))*f_rotation_max_shr(crp);

q_rotation_min(j,crp,w) .. sum((crp_kcr(crp,kcr)), vm_area(j,kcr,w))
=g=
sum(kcr, vm_area(j,kcr,w))*f_rotation_min_shr(crp);


q_water(j) .. sum(wat_dem,vm_watdem(wat_dem,j))
=l=
sum(wat_src,vm_watavail(wat_src,j)) ;

q_area_irrig(j) .. sum(kcr, vm_area(j,kcr,"irrigated"))
=l=
vm_AEI(j);

*** EOF constraints.gms ***
```

Calculations:

```
********************************************************************************
****************************PREPROCESSING START*********************************
*In this section everything is calculated that is not influenced by the
*optimization process. Hence these lines CAN INFLUENCE the optimization process
*but CANNOT BE INFLUENCED by it.


im_years("y1995") = 1;
im_years(t)$(ord(t)>1) = fm_years(t)-fm_years(t-1);

display im_years;



***WATER PREPROCESSING**********************************************************


***YIELDS PREPROCESSING*********************************************************

***YIELD CORRECTION FOR 2ND GENERATION BIOENERGY CROPS***************************
f_yields(t,j,"begr",w) = f_yields(t,j,"begr",w)*sum(cell(i,j),fm_tau1995(i))/fm_tau1995
("EUR");
f_yields(t,j,"betr",w) = f_yields(t,j,"betr",w)*sum(cell(i,j),fm_tau1995(i))/fm_tau1995
("EUR");
```

```
if((sm_with_climate = 1),
im_yields(t,j,kve,w) = f_yields(t,j,kve,w);
i_carbon_density(t,j,land,c_pools) = f_carbon_density(t,j,land,c_pools);
else
im_yields(t,j,kve,w) = f_yields("y1995",j,kve,w);
i_carbon_density(t,j,land,c_pools) = f_carbon_density("y1995",j,land,c_pools);
);

if((s_use_calib = 1),
     im_yields(t,j,kve,w)    = im_yields(t,j,kve,w)*sum(cell(i,j),f_yld_calib(i,kve));
);

pcm_tau(i)                   = fm_tau1995(i);
p_tau("y1995",i)             = fm_tau1995(i);

*** LAND ************************************************************************
* set initial value (required for compiler)
pm_nr_som(t,j)=0;
pm_nr_som_usable(t,j)        =0;

*** LAND ************************************************************************

pm_land_start(j,land)        = sum(si, f_land(j,land,si));
pcm_land(j,land,si)          = f_land(j,land,si);
pcm_land_shift(j,land,si)    = 0;

***DEMAND ***********************************************************************


******Consumption shares
*Changes in food consumption patterns
i_food_ME_shr_new(t,i,kve)
= f_food_ME_shr_1995(i,kve)*(1 - fm_livst_shr(t,i))/(1 - fm_livst_shr("y1995",i));
i_food_ME_shr_new(t,i,kli)
= f_food_ME_shr_1995(i,kli)*fm_livst_shr(t,i)/fm_livst_shr("y1995",i);

*Changes in material consumption patterns
i_mat_GE_shr_new(t,i,k) = f_mat_GE_shr(i,k);


******Calculate final demand
*regional demand (10^6 ton DM)
im_dem_food(t,i,k) = (fm_food_demand(t,i)
*i_food_ME_shr_new(t,i,k)/fm_human_ME_content(i,k))$(i_food_ME_shr_new(t,i,k) >0);
im_dem_material(t,i,k)      = (fm_material_demand(t,i)
*i_mat_GE_shr_new(t,i,k)/fm_GE_content(k))$(i_mat_GE_shr_new(t,i,k) >0) ;

* correct for differences between FAO FBS and prodstat
im_dem_food(t,i,k) = im_dem_food(t,i,k) * fm_prod_cal(i,k);
im_dem_material(t,i,k)      = im_dem_material(t,i,k) * fm_prod_cal(i,k);


*** Crop Attritbutes
* correct differences in DM content between Isabelles crop groups and mine

im_attributes_harvest(attributes,kve)      =f_attributes_harvest_pure(attributes,kve)
*fm_DM_correct(kve);

$batinclude "./modules/include.gms" preloop

*****************************PREPROCESSING END***********************************
*********************************************************************************

*create dummy file (this is necessary to be able to use put_utility and it has
*to be done here because a file declaration cannot be inside a loop
file dummy; dummy.pw=2000;put dummy;

*********************************************************************************
************************OPTIMIZATION PROCESS START*******************************
*This section contains only sourcecode that is directly connected to the
*optimization process. That means that everything on the following lines
*INFLUENCES and IS INFLUENCED by the optimization process (except the
*redefinition on preprocessed data).
*Hence one can describe this section together with the constraints section
*as "model-core".
```

```

***************************TIMESTEP LOOP START***********************************
loop (t,

*Shift land between land pools
pcm_land(j,land,si)           = pcm_land(j,land,si) + pcm_land_shift(j,land,si);
pm_land(t,j,land,si)          = pcm_land(j,land,si);
vm_land.l(j,land,si)          = pcm_land(j,land,si);
pcm_land_shift(j,land,si)     = 0;

* redefine preprocessed data using only the information for the current time step
* this is necessary because every parameter used in a constraint must not
* contain the time t explicitly (parameters are marked with "c" for "current").

ic_dem_food(i,k) = im_dem_food(t,i,k);
ic_dem_material(i,k)          = im_dem_material(t,i,k);

icm_carbon_density(j,land,c_pools) = i_carbon_density(t,j,land,c_pools);

fcm_ghg_prices(i,ghg) = f_ghg_prices(t,i,ghg);

sm_years = im_years(t);

if((ord(t) = 1),
p_yld(j,kcr,w) = im_yields(t,j,kcr,w);
else
p_yld(j,kcr,w) = im_yields(t,j,kcr,w)*sum(cell(i,j),pcm_tau(i)/fm_tau1995(i));
);

$batinclude "./modules/include.gms" presolve

*Loading gdx-files (sm_use_gdx>0)
if((sm_use_gdx >0),
$if exist "magpie_y1995.gdx" if(sameas(t,"y1995"),Execute_Loadpoint "magpie_y1995.gdx"; );
);

if((sm_use_gdx = 2),
$if exist "magpie_y2000.gdx" if(sameas(t,"y2000"),Execute_Loadpoint "magpie_y2000.gdx"; );
$if exist "magpie_y2005.gdx" if(sameas(t,"y2005"),Execute_Loadpoint "magpie_y2005.gdx"; );
$if exist "magpie_y2010.gdx" if(sameas(t,"y2010"),Execute_Loadpoint "magpie_y2010.gdx"; );
$if exist "magpie_y2015.gdx" if(sameas(t,"y2015"),Execute_Loadpoint "magpie_y2015.gdx"; );
$if exist "magpie_y2020.gdx" if(sameas(t,"y2020"),Execute_Loadpoint "magpie_y2020.gdx"; );
$if exist "magpie_y2025.gdx" if(sameas(t,"y2025"),Execute_Loadpoint "magpie_y2025.gdx"; );
$if exist "magpie_y2030.gdx" if(sameas(t,"y2030"),Execute_Loadpoint "magpie_y2030.gdx"; );
$if exist "magpie_y2035.gdx" if(sameas(t,"y2035"),Execute_Loadpoint "magpie_y2035.gdx"; );
$if exist "magpie_y2040.gdx" if(sameas(t,"y2040"),Execute_Loadpoint "magpie_y2040.gdx"; );
$if exist "magpie_y2045.gdx" if(sameas(t,"y2045"),Execute_Loadpoint "magpie_y2045.gdx"; );
$if exist "magpie_y2050.gdx" if(sameas(t,"y2050"),Execute_Loadpoint "magpie_y2050.gdx"; );
$if exist "magpie_y2055.gdx" if(sameas(t,"y2055"),Execute_Loadpoint "magpie_y2055.gdx"; );
$if exist "magpie_y2060.gdx" if(sameas(t,"y2060"),Execute_Loadpoint "magpie_y2060.gdx"; );
$if exist "magpie_y2065.gdx" if(sameas(t,"y2065"),Execute_Loadpoint "magpie_y2065.gdx"; );
$if exist "magpie_y2070.gdx" if(sameas(t,"y2070"),Execute_Loadpoint "magpie_y2070.gdx"; );
$if exist "magpie_y2075.gdx" if(sameas(t,"y2075"),Execute_Loadpoint "magpie_y2075.gdx"; );
$if exist "magpie_y2080.gdx" if(sameas(t,"y2080"),Execute_Loadpoint "magpie_y2080.gdx"; );
$if exist "magpie_y2085.gdx" if(sameas(t,"y2085"),Execute_Loadpoint "magpie_y2085.gdx"; );
$if exist "magpie_y2090.gdx" if(sameas(t,"y2090"),Execute_Loadpoint "magpie_y2090.gdx"; );
$if exist "magpie_y2095.gdx" if(sameas(t,"y2095"),Execute_Loadpoint "magpie_y2095.gdx"; );
$if exist "magpie_y2100.gdx" if(sameas(t,"y2100"),Execute_Loadpoint "magpie_y2100.gdx"; );
$if exist "magpie_y2105.gdx" if(sameas(t,"y2105"),Execute_Loadpoint "magpie_y2105.gdx"; );
$if exist "magpie_y2110.gdx" if(sameas(t,"y2110"),Execute_Loadpoint "magpie_y2110.gdx"; );
$if exist "magpie_y2115.gdx" if(sameas(t,"y2115"),Execute_Loadpoint "magpie_y2115.gdx"; );
$if exist "magpie_y2120.gdx" if(sameas(t,"y2120"),Execute_Loadpoint "magpie_y2120.gdx"; );
$if exist "magpie_y2125.gdx" if(sameas(t,"y2125"),Execute_Loadpoint "magpie_y2125.gdx"; );
$if exist "magpie_y2130.gdx" if(sameas(t,"y2130"),Execute_Loadpoint "magpie_y2130.gdx"; );
$if exist "magpie_y2135.gdx" if(sameas(t,"y2135"),Execute_Loadpoint "magpie_y2135.gdx"; );
$if exist "magpie_y2140.gdx" if(sameas(t,"y2140"),Execute_Loadpoint "magpie_y2140.gdx"; );
$if exist "magpie_y2145.gdx" if(sameas(t,"y2145"),Execute_Loadpoint "magpie_y2145.gdx"; );
$if exist "magpie_y2150.gdx" if(sameas(t,"y2150"),Execute_Loadpoint "magpie_y2150.gdx"; );
);

* use_GDX -1:
if ((sm_use_gdx = -1),
if((ord(t)=1),
vm_area.l(j,kcr,"irrigated") = fm_irrig(j)/card(kcr);
          vm_area.l(j,kcr,"rainfed") = (pcm_land(j,"crop","si0") - fm_irrig(j))/card(kcr);

vm_tau.l(i) = 1.6;
```

```

);
);

vm_tech_cost.up(i)                 = 10e9;

vm_area.fx(j,"begr","irrigated")   =0;
vm_area.fx(j,"betr","irrigated")   =0;

s_counter = 0;

*************************** SOLVE STATEMENT ************************************

while((s_counter <sm_maxiter),
      solve magpie USING nlp MINIMIZING vm_cost_glo ;
o_modelstat(t) = magpie.modelstat;
if((magpie.modelstat <3),
s_counter = 1000;
         put_utility 'shell' / 'Rscript --vanilla ./rename_gdx.R ' t.tl;
);
s_counter = s_counter + 1 ;
      if((s_counter = sm_maxiter-1 and magpie.modelstat
>2 and magpie.modelstat ne 7),magpie.solprint = 1);
);

if((magpie.modelstat >2 and magpie.modelstat ne 7),
Execute_Unload "fulldata.gdx";
      abort "no feasible solution found ",magpie.modelstat;
);

********************************************************************************

*** Land Patterns are transferred to next timestep

pcm_land(j,land,si)       = vm_land.l(j,land,si);
pm_land(t,j,land,si)      = pcm_land(j,land,si);

pcm_tau(i)                = vm_tau.l(i);
p_tau(t,i)                = vm_tau.l(i);

********************************************************************************
$batinclude "./modules/include.gms" postsolve

********************************************************************************
*shift land reset vm_land and vm_carbon_stock after reshuffling in 1st timestep
if ((ord(t) = 1),
         vm_land.l(j,land,si) = vm_land.l(j,land,si) + pcm_land_shift(j,land,si);
         pcm_land(j,land,si) = vm_land.l(j,land,si);
         pm_land(t,j,land,si) = pcm_land(j,land,si);
         pcm_land_shift(j,land,si) = 0;
);

*************************OPTIMIZATION PROCESS END*******************************
********************************************************************************
*The time step loop does not stop at this point because it is also used for
*postprocessing. Nevertheless everything following on the next lines does not
*have any influence on the optimization process!

*#################### R SECTION START (OUTPUT DEFINITIONS) #####################
ov_cost_glo(t,"marginal")                     = vm_cost_glo.m;
ov_emissions_reg(t,i,ghg,"marginal")          = vm_emissions_reg.m(i,ghg);
ov_emission_costs(t,i,"marginal")             = vm_emission_costs.m(i);
ov_btm_cell(t,j,emis_cell,"marginal")         = vm_btm_cell.m(j,emis_cell);
ov_btm_reg(t,i,emis_reg,"marginal")           = vm_btm_reg.m(i,emis_reg);
ov_exp_emis_affore(t,j,emis_co2_forestry,"marginal") = vm_exp_emis_affore.m(j,
emis_co2_forestry);
ov_cost_reg(t,i,"marginal")                   = vm_cost_reg.m(i);
ov_prod(t,j,k,"marginal")                     = vm_prod.m(j,k);
ov_prod_reg(t,i,k,"marginal")                 = vm_prod_reg.m(i,k);
ov_area(t,j,kcr,w,"marginal")                 = vm_area.m(j,kcr,w);
ov_land(t,j,land,si,"marginal")               = vm_land.m(j,land,si);
ov_yld(t,j,kcr,w,"marginal")                  = vm_yld.m(j,kcr,w);
ov_tau(t,i,"marginal")                        = vm_tau.m(i);
ov_tech_cost(t,i,"marginal")                  = vm_tech_cost.m(i);
ov_cost_prod(t,i,k,"marginal")                = vm_cost_prod.m(i,k);
ov_cost_transp(t,j,k,"marginal")              = vm_cost_transp.m(j,k);
ov_cost_landcon(t,j,land,"marginal")          = vm_cost_landcon.m(j,land);
```

```
ov_supply(t,i,k,"marginal")                   = vm_supply.m(i,k);
ov_dem_feed(t,i,kli,kbio,"marginal") = vm_dem_feed.m(i,kli,kbio);
ov_dem_bioen(t,i,k,"marginal") = vm_dem_bioen.m(i,k);
ov_watdem(t,wat_dem,j,"marginal")             = vm_watdem.m(wat_dem,j);
ov_watavail(t,wat_src,j,"marginal")           = vm_watavail.m(wat_src,j);
ov_AEI(t,j,"marginal")                        = vm_AEI.m(j);
ov_cost_AEI(t,i,"marginal")                   = vm_cost_AEI.m(i);
ov_maccs_costs(t,i,"marginal")                = vm_maccs_costs.m(i);
ov_nr_inorg_fert_costs(t,i,"marginal")        = vm_nr_inorg_fert_costs.m(i);
ov_nr_impact_costs(t,i,"marginal")            = vm_nr_impact_costs.m(i);
ov_dem_res_substitutes(t,i,kli,kcr,"marginal") = vm_dem_res_substitutes.m(i,kli,kcr);
ov_dem_convby_substitutes(t,i,kli,kcr,"marginal") = vm_dem_convby_substitutes.m
(i,kli,kcr);
ov_prod_res_ag_reg(t,i,kve,"marginal")        = vm_prod_res_ag_reg.m(i,kve);
ov_prod_res_bg_reg(t,i,kve,"marginal") = vm_prod_res_bg_reg.m(i,kve);
ov_res_supply(t,i,res_use,kve,"marginal") = vm_res_supply.m(i,res_use,kve);
ov_res_use_feed(t,i,kli,attributes,"marginal") = vm_res_use_feed.m(i,kli,attributes);
ov_convby_feed(t,i,kli,attributes,"marginal") = vm_convby_feed.m(i,kli,attributes);
ov_cost_trade(t,i,"marginal") = vm_cost_trade.m(i);
ov_carbon_stock(t,j,land,c_pools,"marginal") = vm_carbon_stock.m(j,land,c_pools);
ov_cost_past(t,i,"marginal") = vm_cost_past.m(i);
ov_prod_wood(t,j,ws,tp,"marginal") = vm_prod_wood.m(j,ws,tp);
ov_cost_fore(t,i,ws,"marginal") = vm_cost_fore.m(i,ws);
oq_cost_glo(t,"marginal") = q_cost_glo.m;
oq_trade_glo(t,k,"marginal") = q_trade_glo.m(k);
oq_trade_reg(t,i,k_notrade,"marginal") = q_trade_reg.m(i,k_notrade);
oq_cost_reg(t,i,"marginal") = q_cost_reg.m(i);
oq_yield(t,j,kcr,w,"marginal") = q_yield.m(j,kcr,w);
oq_prod(t,j,kcr,"marginal") = q_prod.m(j,kcr);
oq_cropland(t,j,"marginal") = q_cropland.m(j);
oq_land(t,j,si,"marginal") = q_land.m(j,si);
oq_supply(t,i,k,"marginal") = q_supply.m(i,k);
oq_prod_reg(t,i,k,"marginal") = q_prod_reg.m(i,k);
oq_rotation_max(t,j,crp,w,"marginal") = q_rotation_max.m(j,crp,w);
oq_rotation_min(t,j,crp,w,"marginal") = q_rotation_min.m(j,crp,w);
oq_water(t,j,"marginal") = q_water.m(j);
oq_area_irrig(t,j,"marginal") = q_area_irrig.m(j);
ov_cost_glo(t,"level") = vm_cost_glo.l;
ov_emissions_reg(t,i,ghg,"level") = vm_emissions_reg.l(i,ghg);
ov_emission_costs(t,i,"level") = vm_emission_costs.l(i);
ov_btm_cell(t,j,emis_cell,"level") = vm_btm_cell.l(j,emis_cell);
ov_btm_reg(t,i,emis_reg,"level") = vm_btm_reg.l(i,emis_reg);
ov_exp_emis_affore(t,j,emis_co2_forestry,"level") = vm_exp_emis_affore.l
(j,emis_co2_forestry);
ov_cost_reg(t,i,"level") = vm_cost_reg.l(i);
ov_prod(t,j,k,"level") = vm_prod.l(j,k);
ov_prod_reg(t,i,k,"level") = vm_prod_reg.l(i,k);
ov_area(t,j,kcr,w,"level") = vm_area.l(j,kcr,w);
ov_land(t,j,land,si,"level")                  = vm_land.l(j,land,si);
ov_yld(t,j,kcr,w,"level")                     = vm_yld.l(j,kcr,w);
ov_tau(t,i,"level") = vm_tau.l(i);
ov_tech_cost(t,i,"level") = vm_tech_cost.l(i);
ov_cost_prod(t,i,k,"level")                   = vm_cost_prod.l(i,k);
ov_cost_transp(t,j,k,"level")                 = vm_cost_transp.l(j,k);
ov_cost_landcon(t,j,land,"level")             = vm_cost_landcon.l(j,land);
ov_supply(t,i,k,"level")                      = vm_supply.l(i,k);
ov_dem_feed(t,i,kli,kbio,"level") = vm_dem_feed.l(i,kli,kbio);
ov_dem_bioen(t,i,k,"level")                   = vm_dem_bioen.l(i,k);
ov_watdem(t,wat_dem,j,"level")                = vm_watdem.l(wat_dem,j);
ov_watavail(t,wat_src,j,"level")              = vm_watavail.l(wat_src,j);
ov_AEI(t,j,"level")                           = vm_AEI.l(j);
ov_cost_AEI(t,i,"level")                      = vm_cost_AEI.l(i);
ov_maccs_costs(t,i,"level")                   = vm_maccs_costs.l(i);
ov_nr_inorg_fert_costs(t,i,"level")           = vm_nr_inorg_fert_costs.l(i);
ov_nr_impact_costs(t,i,"level")               = vm_nr_impact_costs.l(i);
ov_dem_res_substitutes(t,i,kli,kcr,"level") = vm_dem_res_substitutes.l(i,kli,kcr);
ov_dem_convby_substitutes(t,i,kli,kcr,"level") = vm_dem_convby_substitutes.l
(i,kli,kcr);
ov_prod_res_ag_reg(t,i,kve,"level") = vm_prod_res_ag_reg.l(i,kve);
ov_prod_res_bg_reg(t,i,kve,"level")           = vm_prod_res_bg_reg.l(i,kve);
ov_res_supply(t,i,res_use,kve,"level")        = vm_res_supply.l(i,res_use,kve);
ov_res_use_feed(t,i,kli,attributes,"level")   = vm_res_use_feed.l(i,kli,attributes);
ov_convby_feed(t,i,kli,attributes,"level")    = vm_convby_feed.l(i,kli,attributes);
ov_cost_trade(t,i,"level")                    = vm_cost_trade.l(i);
ov_carbon_stock(t,j,land,c_pools,"level") = vm_carbon_stock.l(j,land,c_pools);
ov_cost_past(t,i,"level") = vm_cost_past.l(i);
ov_prod_wood(t,j,ws,tp,"level") = vm_prod_wood.l(j,ws,tp);
```

```
ov_cost_fore(t,i,ws,"level") = vm_cost_fore.l(i,ws);
oq_cost_glo(t,"level") = q_cost_glo.l;
oq_trade_glo(t,k,"level") = q_trade_glo.l(k);
oq_trade_reg(t,i,k_notrade,"level") = q_trade_reg.l(i,k_notrade);
oq_cost_reg(t,i,"level") = q_cost_reg.l(i);
oq_yield(t,j,kcr,w,"level") = q_yield.l(j,kcr,w);
oq_prod(t,j,kcr,"level") = q_prod.l(j,kcr);
oq_cropland(t,j,"level") = q_cropland.l(j);
oq_land(t,j,si,"level") = q_land.l(j,si);
oq_supply(t,i,k,"level") = q_supply.l(i,k);
oq_prod_reg(t,i,k,"level") = q_prod_reg.l(i,k);
oq_rotation_max(t,j,crp,w,"level") = q_rotation_max.l(j,crp,w);
oq_rotation_min(t,j,crp,w,"level") = q_rotation_min.l(j,crp,w);
oq_water(t,j,"level") = q_water.l(j);
oq_area_irrig(t,j,"level") = q_area_irrig.l(j);
ov_cost_glo(t,"upper") = vm_cost_glo.up;
ov_emissions_reg(t,i,ghg,"upper") = vm_emissions_reg.up(i,ghg);
ov_emission_costs(t,i,"upper") = vm_emission_costs.up(i);
ov_btm_cell(t,j,emis_cell,"upper") = vm_btm_cell.up(j,emis_cell);
ov_btm_reg(t,i,emis_reg,"upper") = vm_btm_reg.up(i,emis_reg);
ov_exp_emis_affore(t,j,emis_co2_forestry,"upper") = vm_exp_emis_affore.up(j,
emis_co2_forestry);
ov_cost_reg(t,i,"upper") = vm_cost_reg.up(i);
ov_prod(t,j,k,"upper") = vm_prod.up(j,k);
ov_prod_reg(t,i,k,"upper") = vm_prod_reg.up(i,k);
ov_area(t,j,kcr,w,"upper") = vm_area.up(j,kcr,w);
ov_land(t,j,land,si,"upper")                  = vm_land.up(j,land,si);
ov_yld(t,j,kcr,w,"upper")                     = vm_yld.up(j,kcr,w);
ov_tau(t,i,"upper") = vm_tau.up(i);
ov_tech_cost(t,i,"upper") = vm_tech_cost.up(i);
ov_cost_prod(t,i,k,"upper")                   = vm_cost_prod.up(i,k);
ov_cost_transp(t,j,k,"upper")                 = vm_cost_transp.up(j,k);
ov_cost_landcon(t,j,land,"upper")             = vm_cost_landcon.up(j,land);
ov_supply(t,i,k,"upper")                      = vm_supply.up(i,k);
ov_dem_feed(t,i,kli,kbio,"upper")             = vm_dem_feed.up(i,kli,kbio);
ov_dem_bioen(t,i,k,"upper")                   = vm_dem_bioen.up(i,k);
ov_watdem(t,wat_dem,j,"upper")                = vm_watdem.up(wat_dem,j);
ov_watavail(t,wat_src,j,"upper")              = vm_watavail.up(wat_src,j);
ov_AEI(t,j,"upper")                           = vm_AEI.up(j);
ov_cost_AEI(t,i,"upper")                      = vm_cost_AEI.up(i);
ov_maccs_costs(t,i,"upper")                   = vm_maccs_costs.up(i);
ov_nr_inorg_fert_costs(t,i,"upper")           = vm_nr_inorg_fert_costs.up(i);
ov_nr_impact_costs(t,i,"upper")               = vm_nr_impact_costs.up(i);
ov_dem_res_substitutes(t,i,kli,kcr,"upper") = vm_dem_res_substitutes.up(i,kli,kcr);
ov_dem_convby_substitutes(t,i,kli,kcr,"upper") = vm_dem_convby_substitutes.up
(i,kli,kcr);
ov_prod_res_ag_reg(t,i,kve,"upper") = vm_prod_res_ag_reg.up(i,kve);
ov_prod_res_bg_reg(t,i,kve,"upper")           = vm_prod_res_bg_reg.up(i,kve);
ov_res_supply(t,i,res_use,kve,"upper")        = vm_res_supply.up(i,res_use,kve);
ov_res_use_feed(t,i,kli,attributes,"upper")   = vm_res_use_feed.up
(i,kli,attributes);
ov_convby_feed(t,i,kli,attributes,"upper")    = vm_convby_feed.up(i,kli,attributes);
ov_cost_trade(t,i,"upper")                    = vm_cost_trade.up(i);
ov_carbon_stock(t,j,land,c_pools,"upper") = vm_carbon_stock.up(j,land,c_pools);
ov_cost_past(t,i,"upper") = vm_cost_past.up(i);
ov_prod_wood(t,j,ws,tp,"upper") = vm_prod_wood.up(j,ws,tp);
ov_cost_fore(t,i,ws,"upper") = vm_cost_fore.up(i,ws);
oq_cost_glo(t,"upper") = q_cost_glo.up;
oq_trade_glo(t,k,"upper") = q_trade_glo.up(k);
oq_trade_reg(t,i,k_notrade,"upper") = q_trade_reg.up(i,k_notrade);
oq_cost_reg(t,i,"upper") = q_cost_reg.up(i);
oq_yield(t,j,kcr,w,"upper") = q_yield.up(j,kcr,w);
oq_prod(t,j,kcr,"upper") = q_prod.up(j,kcr);
oq_cropland(t,j,"upper") = q_cropland.up(j);
oq_land(t,j,si,"upper")                       = q_land.up(j,si);
oq_supply(t,i,k,"upper") = q_supply.up(i,k);
oq_prod_reg(t,i,k,"upper") = q_prod_reg.up(i,k);
oq_rotation_max(t,j,crp,w,"upper") = q_rotation_max.up(j,crp,w);
oq_rotation_min(t,j,crp,w,"upper") = q_rotation_min.up(j,crp,w);
oq_water(t,j,"upper") = q_water.up(j);
oq_area_irrig(t,j,"upper") = q_area_irrig.up(j);
ov_cost_glo(t,"lower") = vm_cost_glo.lo;
ov_emissions_reg(t,i,ghg,"lower") = vm_emissions_reg.lo(i,ghg);
ov_emission_costs(t,i,"lower") = vm_emission_costs.lo(i);
ov_btm_cell(t,j,emis_cell,"lower") = vm_btm_cell.lo(j,emis_cell);
ov_btm_reg(t,i,emis_reg,"lower") = vm_btm_reg.lo(i,emis_reg);
ov_exp_emis_affore(t,j,emis_co2_forestry,"lower") = vm_exp_emis_affore.lo(j,
```

```
emis_co2_forestry);
ov_cost_reg(t,i,"lower") = vm_cost_reg.lo(i);
ov_prod(t,j,k,"lower") = vm_prod.lo(j,k);
ov_prod_reg(t,i,k,"lower") = vm_prod_reg.lo(i,k);
ov_area(t,j,kcr,w,"lower") = vm_area.lo(j,kcr,w);
ov_land(t,j,land,si,"lower")                  = vm_land.lo(j,land,si);
ov_yld(t,j,kcr,w,"lower")                     = vm_yld.lo(j,kcr,w);
ov_tau(t,i,"lower")                           = vm_tau.lo(i);
ov_tech_cost(t,i,"lower")                     = vm_tech_cost.lo(i);
ov_cost_prod(t,i,k,"lower")                   = vm_cost_prod.lo(i,k);
ov_cost_transp(t,j,k,"lower")                 = vm_cost_transp.lo(j,k);
ov_cost_landcon(t,j,land,"lower")             = vm_cost_landcon.lo(j,land);
ov_supply(t,i,k,"lower")                      = vm_supply.lo(i,k);
ov_dem_feed(t,i,kli,kbio,"lower") = vm_dem_feed.lo(i,kli,kbio);
ov_dem_bioen(t,i,k,"lower")                   = vm_dem_bioen.lo(i,k);
ov_watdem(t,wat_dem,j,"lower")                = vm_watdem.lo(wat_dem,j);
ov_watavail(t,wat_src,j,"lower")              = vm_watavail.lo(wat_src,j);
ov_AEI(t,j,"lower") = vm_AEI.lo(j);
ov_cost_AEI(t,i,"lower")                      = vm_cost_AEI.lo(i);
ov_maccs_costs(t,i,"lower")                   = vm_maccs_costs.lo(i);
ov_nr_inorg_fert_costs(t,i,"lower")           = vm_nr_inorg_fert_costs.lo(i);
ov_nr_impact_costs(t,i,"lower")               = vm_nr_impact_costs.lo(i);
ov_dem_res_substitutes(t,i,kli,kcr,"lower") = vm_dem_res_substitutes.lo(i,kli,kcr);
ov_dem_convby_substitutes(t,i,kli,kcr,"lower") = vm_dem_convby_substitutes.lo (i,kli,kcr);
ov_prod_res_ag_reg(t,i,kve,"lower") = vm_prod_res_ag_reg.lo(i,kve);
ov_prod_res_bg_reg(t,i,kve,"lower")           = vm_prod_res_bg_reg.lo(i,kve);
ov_res_supply(t,i,res_use,kve,"lower")        = vm_res_supply.lo(i,res_use,kve);
ov_res_use_feed(t,i,kli,attributes,"lower")   = vm_res_use_feed.lo (i,kli,attributes);
ov_convby_feed(t,i,kli,attributes,"lower")    = vm_convby_feed.lo(i,kli,attributes);
ov_cost_trade(t,i,"lower")                    = vm_cost_trade.lo(i);
ov_carbon_stock(t,j,land,c_pools,"lower")     = vm_carbon_stock.lo(j,land,c_pools);
ov_cost_past(t,i,"lower")                     = vm_cost_past.lo(i);
ov_prod_wood(t,j,ws,tp,"lower")               = vm_prod_wood.lo(j,ws,tp);
ov_cost_fore(t,i,ws,"lower")                  = vm_cost_fore.lo(i,ws);
oq_cost_glo(t,"lower")                        = q_cost_glo.lo;
oq_trade_glo(t,k,"lower")                     = q_trade_glo.lo(k);
oq_trade_reg(t,i,k_notrade,"lower")           = q_trade_reg.lo(i,k_notrade);
oq_cost_reg(t,i,"lower") = q_cost_reg.lo(i);
oq_yield(t,j,kcr,w,"lower") = q_yield.lo(j,kcr,w);
oq_prod(t,j,kcr,"lower") = q_prod.lo(j,kcr);
oq_cropland(t,j,"lower") = q_cropland.lo(j);
oq_land(t,j,si,"lower") = q_land.lo(j,si);
oq_supply(t,i,k,"lower") = q_supply.lo(i,k);
oq_prod_reg(t,i,k,"lower") = q_prod_reg.lo(i,k);
oq_rotation_max(t,j,crp,w,"lower") = q_rotation_max.lo(j,crp,w);
oq_rotation_min(t,j,crp,w,"lower") = q_rotation_min.lo(j,crp,w);
oq_water(t,j,"lower") = q_water.lo(j);
oq_area_irrig(t,j,"lower") = q_area_irrig.lo(j);
*##################### R SECTION END (OUTPUT DEFINITIONS) ######################

**********************WRITE ALL DATA IN 1 GDX FILE*****************************
Execute_Unload "fulldata.gdx";

);
*******************************************************************************
****************************TIMESTEP LOOP END**********************************

****************************POSTPROCESSING END*********************************
*******************************************************************************

*** EOF calculations.gms ***
```

Appendix 2: Mathematical model description – Phosphorus modul

Sets:

```
* Here you can define module-specific sets

sets

wbe(kcr)           vegetal production activities without bioenegry crops
                   /tece,maiz,trce,rice_pro,soybean,rapeseed,groundnut,sunflower,Oilpalm,
puls_pro,potato,cassav_sp,sugr_cane,sugr_beet,others,foddr,cottn_pro/

***EMISSIONS***

n_flows nitrogen flows
                   / n_i_res_ag, n_i_res_bg, n_i_fix, n_i_man_c, n_i_man_p, n_i_dep,
n_i_fert,n_i_som, n_losses, n_w_harv, n_w_res_ag, n_w_res_bg /
n_with(n_flows)    nitrogen withdrawals
/ n_w_harv, n_w_res_ag, n_w_res_bg/
n_inp_exfp(n_flows) nitrogen inputs excluding industrial fertilizer and n on pastureland
                   / n_i_res_ag, n_i_res_bg, n_i_fix, n_i_man_c, n_i_dep/
emis_way emission categories
/direct,leach,volat/
emis_uncertainty   different estimates for emission parameters
/best,low, high/
npk(attributes) plant nutrients
/nr,p,k/
fixation Fixation of Nr
                   / i_fix_production, i_fix_area/
awms animal waste management systems
                   / grazing_pasture, grazing_cropland, fuel, confinement /
awms_prp(awms)     animal waste management systems pasture range and paddock
/ grazing_pasture, grazing_cropland /
awms_conf          animal waste management systems in confinements
                   / lagoon, liquid, solid, drylot, daily_spread, digest, other, pit_shrt,
pit_long,chick/
lvst detailed livestock categories
                   / asses, meat_buffalo, dairy_buffalo, dairy_camel, meat_camel,
dairy_ctl, meat_ctl, lay_chick, meat_chick, dairy_goat, meat_goat,
horse, mule, pig, dairy_sheep, meat_sheep/
ipcc_ef ipcc emission factors
                   / frac_gasf,frac_gasm,frac_leach,frac_leach_h,ef_1,ef_1fr,ef_2,ef_4,
ef_5/

$ontext

flows material flows
/
*** Field***
soil ,
crop ,
harvest ,
residues ,
bgresidue ,
loss ,
soilinputs ,
soilwithdrawals ,

*** Pasture***
pasturesoil ,
pastureharvest ,
pastureloss ,

*** Food use***
food ,
material ,
convby ,
feed ,

*** Consumption
intake ,
```

```
hhwaste ,

*** Livestock
slaughter ,
                    manure ,

food_to_noneatenfood ,
food_to_intake ,
noneatenfood_to_waste ,
noneatenfood_to_feed ,
livestock_to_slaughter ,
slaughter_to_livstproduct,
slaughter_to_waste ,
livstproduct ,
livstproduct_to_fooduse ,
livstproduct_to_material ,
livstproduct_to_feed ,
livstproduct_to_seed ,
livestock_to_manure ,
manure_to_pasture ,
manure_to_soil ,
manure_to_conf ,
manure_to_fuel ,
conf_to_soil ,
conf_to_pasture ,
conf_to_loss ,
conf_to_directn2o ,
conf_to_gas ,
feed_to_livestock ,
pasture_to_feed ,
pasture_to_loss ,
pasture_to_directn2o ,
pasture_to_gas ,
pasture_to_leach ,
harvest_to_feed ,
harvest_to_material ,
harvest_to_bioenergy ,
harvest_to_fooduse ,
harvest_to_seed ,
fooduse_to_food ,
fooduse_to_convby ,
harvest_to_convby_feedsubst ,
harvest_to_residue_feedsubst ,
processing_to_convby ,
residues_to_feed ,
residues_to_soil ,
residues_to_bioenergy ,
residues_to_resburn ,
residues_to_other ,
convby_to_feed ,
convby_to_waste ,
convby_to_other ,
crop_to_harvest ,
crop_to_residue ,
crop_to_bgresidue ,
soil_to_crop ,
soil_to_loss ,
soil_to_directn2o ,
soil_to_gas ,
soil_to_leach ,
bgresidue_to_soil ,
resburn_to_soil ,
resburn_to_loss ,
fert_to_soil ,
fert_to_pasture ,
seed_to_crop ,
fix_to_crop ,
fix_to_harvest ,
fix_to_residue ,
fix_to_bgresidue ,
fixarea_to_pasture ,
fixarea_to_soil ,
dep_to_soil ,
dep_to_pasture ,
loss_to_dep ,
som_to_soil ,
trade_crops ,
```

```
trade_convby ,
trade_livst ,
gas_to_n2o ,
leach_to_n2o
/

$offtext

* natveg_c_pools(c_pools) natural vegetation carbon pools
* /natvegc,soilc,litc/
* crop_c_pools(c_pools) crop carbon pools
* /crop_c,crop_soil_c/

***RELATIONSHIPS BETWEEN DIFFERENT SETS***

n2o_to_n(emis_n2o,n_flows)
/ resid_n2o .(n_i_res_ag, n_i_res_bg)
man_crop_n2o .(n_i_man_c)
man_past_n2o .(n_i_man_p)
inorg_fert_n2o.(n_i_fert)
som_n2o .(n_i_som) /

lvst_to_kli(kli, lvst)
/ livst_rum .(meat_buffalo, meat_ctl, meat_goat, meat_sheep)
livst_pig .(asses, meat_camel, horse, mule, pig)
livst_chick .(meat_chick)
livst_egg .(lay_chick)
livst_milk  .(dairy_buffalo, dairy_camel, dairy_ctl, dairy_goat,dairy_sheep)/

;
```

Declarations:

```
Scalars

ic54_years time between previous and current time step (years)
sc54_t current timestep

*********Parameter für Transport zwischen Bodenphosphorpools*******

s54_adsorption_share adsoption of p to stable soil pool / 0.2 /
s54_desorption_share activation of p from stable soil pool / 0.2 /

*********Parameter für Aufteilung von P-Input auf Bodenphosphorpools*********

s54_inputs_to_labile_shr share of p inputs that go into labile pool /0.2/

;

parameters

*********Bodenphosphorpools***********

p54_labile_p_pre(i)labile soil phosphorus pool presolve
*p54_stable_p_pre(t,i) stable soil phosphorus pool presolve
p54_stable_p(t,i) stable soil phosphorus pool actual
p54_labile_p(t,i) labile soil phosphorus pool actual

*********P Flows***********

*M54_Pmin_from Rock             Phosphorus mineralization from Rock to stablepool
*L54_Pleach_to_water Phosphorus leaching to groundwater

********* N Flows*********

i54_only_nr(attributes) array to select only nr (1 0)
i54_attributes_products_isabelle(i,dm_ge_nr,k) attributes of final products (attributes)
i54_n_eff(t,i) selected scenario values for nr
efficiency (1)

********* Livestock systems******

i54_n_content_kli(kli) nitrogen content of animal products (used
                              for feed ask isabelle) (1)
i54_heads_per_kli(t,i,kli,lvst)                  animal heads per livestock unit (heads
                                                 per ton)
i54_nex(t,i,lvst) nitrogen excretion per livestock type
```

```
                                                (ton per head)
i54_heads_per_kli_1995(i,kli,lvst)animal heads per livestock unit in 1995
                                                (heads per ton)
i54_nex_1995(i,lvst) nitrogen excretion per livestock type in
                                                 1995(ton per head)
i54_recycl_conf(t,i,npk,kli) share of nutrients in confinement
                                                 returned to field (1)
ic54_recycl_conf(i,npk,kli)                      timesteps share of nutrients in
confinement returned to field (1)
i54_nutrients_frac_gas_ms(npk,lvst,awms_conf)    share of nutrients lost as effect of
volatilisation (1)
i54_animal_shr_awms(t,i,kli,awms)                share of animals managed under a specific
awms  (1)
ic54_animal_shr_awms(i,kli,awms)                 timesteps share of animals managed under
a specific awms  (1)
i54_manure_fuel_shr(t,i,kli)                     share of manure on pasture collected for
household fuel  (1)
ic54_manure_fuel_shr(i,kli)                      timesteps share of manure on pasture
collected for household fuel  (1)
i54_conf_to_cropl_shr(t,i)                       share of manure-N in confinements applied
to croplands  (1)
i54_feedres_to_cropl_shr(t,i)                    Share of cropland residues used as feed
eaten on croplands (as opposed to eaten
in confinement)(1)
ic54_feedres_to_cropl_shr(i)                     Share of cropland residues used as feed
eaten on croplands (as opposed to eaten
in confinement)(1)
ic54_conf_to_cropl_shr(i)                        share of manure-N in confinements applied
to croplands  (1)
i54_ipcc_ms_awms_conf_scenario(t_all,i,lvst,awms_conf)  fraction of livestock type managed
under which waste management system
i54_manure_conf_distribution(t,i,kli,awms_conf)  share of confined manure distributed to
different awms_conf  (1))
i54_ipcc_ms_awms(t,i,lvst,awms)                  fraction of livestock type managed under
which feeding system  (1)
i54_conf_direct_emis(t,i,kli)                    share of direct emissions in the form of
N2O-N  (1)
ic54_conf_direct_emis(i,kli)                     share of direct emissions in the form of
N2O-N  (1)
i54_conf_loss_gas(t,i,npk,kli)                   share of nutrients volatilized per kli(1)
ic54_conf_loss_gas(i,npk,kli)                    share of nutrients volatilized per kli(1)

$ontext
o54_flows_reg(t,i,attributes,flows,k)            mass flows (attributes)
o54_flows_cell(t,j,attributes,flows)             cellular disaggregated mass flows
(attributes)
$offtext

;

variables

* should be positive, but may lead to unwanted errors due to pasture

v54_nutrient_manure(i, kli, awms) calculation of manure excreted in awms
without pasture (Tg nutrient)
;

positive variables

********** nutrient balances*********

v54_inorg_fert_reg(i,npk)                        inorganic fertilizer application (Tg
Nutrients)

;

equations

********** Phosphorus balances*********

q54_phosphorus_bal_crp(i) cropland phosphorus inputs have toequal
                                                 withdrawals and losses
q54_phosphorus_bal_manure_confinement(i,kli) phosphorus balance for manure in
                                                 confinement
q54_phosphorus_bal_manure_grazing_pasture(i,kli) phosphorus balance for manure ofgrazing
                                                 animals on pastures
```

```
q54_phosphorus_bal_manure_grazing_cropland(i,kli) phosphorus balance for manure of
                                                  grazing animals on cropland
q54_phosphorus_bal_manure_fuel(i,kli)             phosphorus balance for manure ofgrazing
                                                  animals on pasture whose excreate are
                                                  collected for household fuel
* q54_cost_fert(i) inorganic fertilizer costs (fortaxation)

;

******* EOF declarations.gms ******

*#################### R SECTION START (OUTPUT DECLARATIONS) ####################

parameters

ov54_nutrient_manure(t,i,kli,awms,type)           calculation of manure excreted inawms
                                                  without pasture (Tg nutrient)
ov54_inorg_fert_reg(t,i,npk,type)                 inorganic fertilizer application(Tg
                                                  Nutrients)
oq54_phosphorus_bal_crp(t,i,type)                 cropland phosphorus inputs haveto equal
                                                  withdrawals and losses
oq54_phosphorus_bal_manure_confinement(t,i,kli,type) phosphorus balance for manure in
                                                  confinement
oq54_phosphorus_bal_manure_grazing_pasture(t,i,kli,type) phosphorus balance for manure of
                                                  grazing animals on pastures
oq54_phosphorus_bal_manure_grazing_cropland(t,i,kli,type) phosphorus balance for manure
                                                  of grazing animals on cropland
oq54_phosphorus_bal_manure_fuel(t,i,kli,type)     phosphorus balance for manure of grazing
                                                  animals on pasture whose excreate are
                                                  collected for household fuel
;
*##################### R SECTION END (OUTPUT DECLARATIONS) #####################
```

Input:

```
* Here you can load additional inputs from external files*

**** GENERAL PARAMETERS****

parameter f54_slaughter_factor(kli) ratio of DM in product to DM in slaughtered weight
/
$ondelim
$include "./modules/54_phosphorus/normal_developer/input/slaughter_factor.csv"
$offdelim
/
;

parameter f54_intake_shr_dm(i) DM-Share of Food intake of available food from
Wirsenius (1)
/
$ondelim
$include "./modules/54_phosphorus/normal_developer/input/intake_shr_dm.csv"
$offdelim
/
;

table f54_attributes_living_animals(attributes,kli) attributes of living animals
(attributes per ton DM)
$ondelim
$include "./modules/54_phosphorus/normal_developer/input/nutrients/
attributes_living_animals.csv"
$offdelim ;

table f54_attributes_livstproducts(attributes,kli)      attributes of livestocj products
(attributes per ton DM)
$ondelim
$include "./modules/54_phosphorus/normal_developer/input/nutrients/
attributes_livstproducts.csv"
30 $offdelim ;


*** LIVESTOCK SYSTEMS ***

parameter f54_feedres_to_cropl_shr(i)    Share of cropland residues used as feed eaten on
                                         croplands (as opposed to eaten in confinement)(1)
/
$ondelim
```

```
$include "./modules/54_phosphorus/normal_developer/input/feedres_to_cropl_shr.csv"
$offdelim
/
;

table f54_heads_lvst_1995(i,lvst) heads of livestock population for 1995 in 1000 animals
$ondelim
$include "./modules/54_phosphorus/normal_developer/input/heads_lvst_fao_1995.csv"
$offdelim ;

table f54_ipcc_tam(i,lvst) total animal mass of livestock type in kg per animal
$ondelim
$include "./modules/54_phosphorus/normal_developer/input/ch10_tam.csv"
$offdelim ;

table f54_ipcc_ms_awms(i,lvst,awms)        fraction of livestock type managed under which
feedingsystem
$ondelim
$include "./modules/54_phosphorus/normal_developer/input/ch10_ms_awms.csv"
$offdelim ;

table f54_ipcc_ms_awms_conf_scenario_a1(t_all,i,lvst,awms_conf) fraction of livestock type
                                         managed under which waste management system
$ondelim
$include "./modules/54_phosphorus/normal_developer/input/scenarios/
            ch10_ms_awms_conf_scenario_a1.csv"
$offdelim ;

table f54_ipcc_ms_awms_conf_scenario_a2(t_all,i,lvst,awms_conf) fraction of livestock type
                                         managed under which waste management system
$ondelim
$include "./modules/54_phosphorus/normal_developer/input/scenarios/
            ch10_ms_awms_conf_scenario_a2.csv"
$offdelim ;

table f54_ipcc_ms_awms_conf_scenario_b1(t_all,i,lvst,awms_conf) fraction of livestock type
                                         managed under which waste management system
$ondelim
$include "./modules/54_phosphorus/normal_developer/input/scenarios/
ch10_ms_awms_conf_scenario_b1.csv"
$offdelim ;

table f54_ipcc_ms_awms_conf_scenario_b2(t_all,i,lvst,awms_conf) fraction of livestock type
                                         managed under which waste management system
$ondelim
$include "./modules/54_phosphorus/normal_developer/input/scenarios/
ch10_ms_awms_conf_scenario_b2.csv"
$offdelim ;

*** NUTRIENTS ***

table f54_inorg_fert_reg_1995(i,npk)     input of inorganic industrial fertilizer in 1995
(MtNutrient)
$ondelim
$include "./modules/54_phosphorus/normal_developer/input/nutrients/
inorg_fert_reg_1995.csv"
$offdelim ;

table f54_inorg_fert_costs_1995(i,npk)   input of inorganic industrial fertilizer in 1995
(Mt Nutrient)
$ondelim
$include "./modules/54_phosphorus/normal_developer/input/nutrients/inorg_fert_costs.csv"
$offdelim ;

parameter f54_res_combust_eff(kve)       Combustion efficiency of residue burning (1)
/
$ondelim
$include "./modules/54_phosphorus/normal_developer/input/res_combust_eff.csv"
$offdelim
/ ;
table f54_ipcc_n_rate(i,lvst)            rate of Nr excretion in kg N per t weight per day
$ondelim
$include "./modules/54_phosphorus/normal_developer/input/nutrients/ch10_n_rate.csv"
$offdelim ;

table f54_ipcc_frac_loss_ms(lvst,awms_conf) fraction of manure managed which is lost and
not recycled to agricultural soils
```

```
$ondelim
$include "./modules/54_phosphorus/normal_developer/input/ch10_Frac_LossMS.csv"
$offdelim ;

table f54_ipcc_frac_gas_ms(lvst,awms_conf) fraction of nitrogen in awms lost to the
                                          environment in the form of NOx and NHx
$ondelim
$include "./modules/54_phosphorus/normal_developer/input/ch10_Frac_GasMS.csv"
$offdelim ;

parameter f54_conf_to_cropl_shr(i)       share of manure-N in confinements applied to
croplands(1)
/
$ondelim
$include "./modules/54_phosphorus/normal_developer/input/conf_to_cropl_shr.csv"
$offdelim
/;

******* Input Initial labil P Contents **********

parameter f54_labile_p_1995(i)           Initial P-Contents in lablile soil pool(1)

/
$ondelim
$include "./modules/54_phosphorus/normal_developer/input/labile_p_1995.csv"
$offdelim
/
;

parameter f54_stable_p_1995(i)           Initial P-Contents in lablile soil pool(1)

/
$ondelim
$include "./modules/54_phosphorus/normal_developer/input/stable_p_1995.csv"
$offdelim
/
;

*** ATTRIBUTES ***

table f54_human_protein_content(i,k) Calculated protein content (ton protein per ton
DM)[FAO - FBS]
$ondelim
$include "./modules/54_phosphorus/normal_developer/input/nutrients/
human_protein_content.csv"
$offdelim ;

parameter f54_protein_content(k) Protein content (ton protein per ton DM)

/
$ondelim
$include "./modules/54_phosphorus/normal_developer/input/nutrients/protein_content.csv"
$offdelim
/
;

parameter f54_protein_N_ratio(k) t       Proteins per t nitrogen (N:P ratio)
/
$ondelim
$include "./modules/54_phosphorus/normal_developer/input/nutrients/protein_n_ratio.csv"
$offdelim
/
;

parameter f54_n_eff_scenario_a1(t_all,i) Nutrient efficiency scenarios. please choose file
for scenario
/
$ondelim
$include "./modules/54_phosphorus/normal_developer/input/scenarios/n_eff_a1.csv"
$offdelim
/;

parameter f54_n_eff_scenario_a2(t_all,i) Nutrient efficiency scenarios. please choose file
for scenario
/
$ondelim
$include "./modules/54_phosphorus/normal_developer/input/scenarios/n_eff_a2.csv"
```

```
$offdelim
/;

parameter f54_n_eff_scenario_b1(t_all,i) Nutrient efficiency scenarios. please choose file
for scenario
/
$ondelim
$include "./modules/54_phosphorus/normal_developer/input/scenarios/n_eff_b1.csv"
$offdelim
/;

parameter f54_n_eff_scenario_b2(t_all,i) Nutrient efficiency scenarios. please choose file
for scenario
/
$ondelim
$include "./modules/54_phosphorus/normal_developer/input/scenarios/n_eff_b2.csv"
$offdelim
/;

parameter f54_n_eff_scenario_boundary(t_all,i) Nutrient efficiency scenarios. please
choose file for scenario
/
$ondelim
$include "./modules/54_phosphorus/normal_developer/input/scenarios/
n_eff_planetary_boundary.csv"
$offdelim
/
;
```

Equations:

```
***** OBJECTIVE FUNCTION***********
$ontext
q54_cost_fert(i) ..
vm_inorg_fert_costs(i)
=e=
sum("p",v54_inorg_fert_reg(i,"p")
*                  * f54_inorg_fert_costs_1995(i,"p"))
)* 1
;
* almost free inorganic fertilizer, to avoid distortions in the initial timestep.
* current prices are much higher, with about 640$
* work on this is needed in the future!

$offtext

*******P-Balances Croplands********

   q54_phosphorus_bal_crp(i) ..
s54_inputs_to_labile_shr*
(
sum(kcr,vm_res_supply(i,"recycle",kcr)*
fm_attributes_residue_ag("p",kcr))
+ sum(kcr, vm_res_supply(i,"burn",kcr)*
                         fm_attributes_residue_ag("p",kcr))
+ sum(kli, v54_nutrient_manure(i, kli, "grazing_cropland"))
+ sum(kli, v54_nutrient_manure(i, kli, "confinement")*
ic54_recycl_conf(i,kli)*ic54_conf_to_cropl_shr(i))
+ v54_p_fert_reg(i)
*                  + pc54_nr_som_usable(i) * i54_only_nr("p")
*                  + v54_n_dep_crop(i) * i54_only_nr("p")
)
+ v54_p_pool_pre(i) / s54_pool_release_time
=e=
sum(kcr,
vm_prod_reg(i,kcr)* im_attributes_harvest("p",kcr)
+ vm_prod_res_ag_reg(i,kcr)*fm_attributes_residue_ag("p",kcr)
- vm_prod_reg(i,kcr) * fm_seed_shr(i,kcr) * im_attributes_harvest
("p",kcr)
)
;

q54_phosphorus_bal_manure_grazing_pasture(i,kli) ..
           v54_nutrient_manure(i, kli, "grazing_pasture")
=e=
(vm_dem_feed(i,kli,"pasture")+ vm_dem_feed(i,kli,"scavenging"))
            * im_attributes_harvest("p","pasture")
```

```
            *(1-ic54_manure_fuel_shr(i,kli))
- vm_prod_reg(i,kli)
            * ic54_animal_shr_awms(i,kli,"grazing_pasture")
*f54_slaughter_factor(kli)
            *f54_attributes_living_animals("p",kli)
;

q54_phosphorus_bal_manure_fuel(i,kli) ..
v54_nutrient_manure(i, kli, "fuel")
=e=
(vm_dem_feed(i,kli,"pasture")+vm_dem_feed(i,kli,"scavenging"))
             *im_attributes_harvest("p","pasture")
             *ic54_manure_fuel_shr(i,kli)
- vm_prod_reg(i,kli)
             *ic54_animal_shr_awms(i,kli,"fuel")
*f54_slaughter_factor(kli)
             *f54_attributes_living_animals("p",kli)
;

q54_phosphorus_bal_manure_grazing_cropland(i,kli) ..
v54_nutrient_manure(i, kli, "grazing_cropland")
=e=
vm_res_use_feed(i,kli,"p")
* ic54_feedres_to_cropl_shr(i)
**        for simplification, nr in animal products is only subtracted in confinement
** - v_prod_reg(i,kli)
**        * ic_animal_shr_awms(i,kli,"grazing_cropland")
**        *f_slaughter_factor(kli)
**        *f_attributes_living_animals("p",kli)
;

q54_phosphorus_bal_manure_confinement(i,kli) ..
v54_nutrient_manure(i, kli, "confinement")
=e=
sum(kcr,vm_dem_feed(i,kli,kcr)
* im_attributes_harvest("p",kcr))
*        +sum(kli2, vm_dem_feed(i,kli,kli2)
*                  * i54_n_content_kli(kli2))
+ vm_convby_feed(i, kli, "p")
+ vm_res_use_feed(i,kli,"p")
                   * (1-ic54_feedres_to_cropl_shr(i))
- vm_prod_reg(i,kli) * (ic54_animal_shr_awms(i,kli,"confinement")
                                 +ic54_animal_shr_awms(i,kli,"grazing_cropland"))
* f54_slaughter_factor(kli)
                              * f54_attributes_living_animals("p",kli)
;

*** EOF constraints.gms ***
```

Preloop:

```
***** NUTRIENTS PREPROCESSING *****

*nutrients of final products
i54_attributes_products_isabelle(i,"dm",k)  =  1/fm_prod_cal(i,k);
i54_attributes_products_isabelle(i,"nr",k)  =  (f54_human_protein_content(i,k)
                                                /f54_protein_N_ratio(k))/fm_prod_cal(i,k);
i54_attributes_products_isabelle(i,"ge",k)  =  fm_human_ME_content(i,k)/fm_prod_cal(i,k);

* Calculate initial feeding parameters in 1995

i54_heads_per_kli_1995(i,lvst_to_kli(kli,lvst)) = (f54_heads_lvst_1995(i,lvst)/1000)
/fm_prod_kli_1995(i,kli);

* aggregation from lvst to kli

*i54_nex_mms(i,kli,awms)   =   sum(lvst_to_kli(kli,lvst),
*                                   i54_heads_per_kli(i,lvst_to_kli)*f54_ipcc_tam(i,lvst)*
*                                   f54_ipcc_N_rate(i,lvst)*365*10**(-6)*
*                                    f54_ipcc_ms_awms(i, lvst, awms));

i54_nex_1995(i,lvst)      =    (f54_heads_lvst_1995(i,lvst)/1000)*f54_ipcc_tam(i,lvst)
                                *f54_ipcc_N_rate(i,lvst)*365*10**(-6);


* Nitrogen efficiency scenario selection
```

```
* Management system for confined manure scenario selection

if ((sm_n_eff=1) ,
  i54_n_eff(t,i)=f54_n_eff_scenario_a1(t,i);
  i54_ipcc_ms_awms_conf_scenario(t,i,lvst,awms_conf) = f54_ipcc_ms_awms_conf_scenario_a1
                                                       (t,i,lvst,awms_conf);
Elseif (sm_n_eff=2),
  i54_n_eff(t,i)=f54_n_eff_scenario_a2(t,i);
  i54_ipcc_ms_awms_conf_scenario(t,i,lvst,awms_conf) = f54_ipcc_ms_awms_conf_scenario_a2
                                                       (t,i,lvst,awms_conf);
Elseif (sm_n_eff=3),
  i54_n_eff(t,i)=f54_n_eff_scenario_b1(t,i);
  i54_ipcc_ms_awms_conf_scenario(t,i,lvst,awms_conf) = f54_ipcc_ms_awms_conf_scenario_b1
                                                       (t,i,lvst,awms_conf);
Elseif (sm_n_eff=4),
  i54_n_eff(t,i)=f54_n_eff_scenario_b2(t,i);
  i54_ipcc_ms_awms_conf_scenario(t,i,lvst,awms_conf) = f54_ipcc_ms_awms_conf_scenario_b2
                                                       (t,i,lvst,awms_conf);
Elseif (sm_n_eff=5),
  i54_n_eff(t,i)=f54_n_eff_scenario_boundary(t,i);
  i54_ipcc_ms_awms_conf_scenario(t,i,lvst,awms_conf) = f54_ipcc_ms_awms_conf_scenario_a1
                                                       (t,i,lvst,awms_conf);
);

*** LIVESTOCK SYSTEM SCENARIOS ***
*** Convergence to EUROPE ********

* Mixing scenarios
i54_heads_per_kli(t,i,kli,lvst) = i54_heads_per_kli_1995(i,kli,lvst)
*(1 - fm_feeding_convergence(t))
+ i54_heads_per_kli_1995("EUR",kli,lvst)
*fm_feeding_convergence(t);
i54_nex(t,i,lvst) = i54_nex_1995(i,lvst)
                                        *(1 -fm_feeding_convergence(t))
+ i54_nex_1995("EUR",lvst)
*fm_feeding_convergence(t);
i54_conf_to_cropl_shr(t,i)         =  f54_conf_to_cropl_shr(i)
*(1-fm_feeding_convergence(t))
+ f54_conf_to_cropl_shr("EUR")
* fm_feeding_convergence(t);
i54_feedres_to_cropl_shr(t,i) = f54_feedres_to_cropl_shr(i)
*(1 - fm_feeding_convergence(t))
+ f54_feedres_to_cropl_shr("EUR")
* fm_feeding_convergence(t);
i54_ipcc_ms_awms(t,i,lvst,awms) = f54_ipcc_ms_awms(i,lvst,awms)
*(1 - fm_feeding_convergence(t))
+ f54_ipcc_ms_awms("EUR",lvst,awms)
*fm_feeding_convergence(t);

i54_n_content_kli(kli)             =f54_protein_content(kli)/f54_protein_N_ratio(kli);
i54_nutrients_frac_gas_ms("p",lvst,awms_conf)=0;
i54_nutrients_frac_gas_ms("nr",lvst,awms_conf)=f54_ipcc_frac_gas_ms(lvst,awms_conf);

*** Livestock systems

i54_manure_conf_distribution(t,i,kli,awms_conf)=sum((lvst_to_kli(kli,lvst)),
i54_nex(t,i,lvst)
*i54_ipcc_ms_awms(t,i, lvst, "confinement")
                                      *i54_ipcc_ms_awms_conf_scenario(t,i,lvst,awms_conf))
/sum(lvst_to_kli(kli,lvst), i54_nex(t,i,lvst)
*i54_ipcc_ms_awms(t,i, lvst, "confinement"));

i54_recycl_conf(t,i,"p",kli)=sum((awms_conf,lvst_to_kli(kli,lvst)),i54_nex(t,i,lvst)
*i54_ipcc_ms_awms(t,i, lvst, "confinement")
*i54_ipcc_ms_awms_conf_scenario(t,i,lvst,awms_conf)
*(1 - f54_ipcc_frac_loss_ms(lvst,awms_conf)))
/sum(lvst_to_kli(kli,lvst), i54_nex(t,i,lvst)
*i54_ipcc_ms_awms(t, i, lvst, "confinement"));

i54_conf_loss_gas(t,i,"p",kli)=sum((awms_conf,lvst_to_kli(kli,lvst)),i54_nex(t,i,lvst)
* i54_ipcc_ms_awms(t, i, lvst, "confinement")
*i54_ipcc_ms_awms_conf_scenario(t,i,lvst,awms_conf)
* i54_nutrients_frac_gas_ms("p",lvst,awms_conf))
                                       /sum(lvst_to_kli(kli,lvst), i54_nex(t,i,lvst)
                                       *i54_ipcc_ms_awms(t, i, lvst, "confinement"));

i54_animal_shr_awms(t,i,kli,awms) =  sum(lvst_to_kli(kli,lvst),
```

```
i54_heads_per_kli(t,i,lvst_to_kli)
                                       *i54_ipcc_ms_awms(t,i,lvst,awms))
/sum(lvst_to_kli(kli,lvst),
                                        i54_heads_per_kli(t,i,lvst_to_kli));

i54_manure_fuel_shr(t,i,kli)   =   sum(lvst_to_kli(kli,lvst), i54_nex(t,i,lvst)
                                       *i54_ipcc_ms_awms(t, i, lvst, "fuel"))
/sum(lvst_to_kli(kli,lvst),i54_nex(t,i,lvst)
                                       *(i54_ipcc_ms_awms(t, i, lvst, "fuel")
                                       +i54_ipcc_ms_awms(t,i, lvst, "grazing_pasture")));


p54_stable_p(t,i)=0;
p54_stable_p("y1995",i)=f54_stable_p_1995(i);

p54_labile_p(t,i)=0;
p54_labile_p("y1995",i)=f54_labile_p_1995(i);

*** EOF pre.gms ***
```

Presolve:

```
**** Here you can put your code that should be executed within the ****
****       timestep loop, but BEFORE the solve statement           ****

*** Currents

sc54_t=ord(t);

ic54_animal_shr_awms(i,kli,awms)    =     i54_animal_shr_awms(t,i,kli,awms);
ic54_manure_fuel_shr(i,kli)         =     i54_manure_fuel_shr(t,i,kli);
ic54_recycl_conf(i,"p",kli)         =     i54_recycl_conf(t,i,"p",kli);
ic54_conf_to_cropl_shr(i)           =     i54_conf_to_cropl_shr(t,i);
ic54_feedres_to_cropl_shr(i)        =     i54_feedres_to_cropl_shr(t,i);

*****Phosphorus Pool*****

p54_labile_p_pre(i)                 =     (p54_stable_p(t,i)*s54_desorption_share)
                                         -(p54_labile_p(t,i)*s54_adsorption_share)
                                         + p54_labile_p(t,i);

***   +m54_pmin_from rock-l54_Pleach_to_water  -- not yet modeled   ***

*** EOF solve.gms ***
```

Postsolve:

```
**** Here you put your code, that should be executed within ***
****    the timestep loop, but AFTER the solve statement    ***

p54_stable_p(t,i)   =
                      p54_stable_p(t-1,i)
+(1-s54_inputs_to_labile_shr)*
(     sum   (kcr, m_res_supply.l(i,"recycle",kcr)
                                                *fm_attributes_residue_ag("p",kcr))
                         +sum(kcr, vm_res_supply.l(i,"burn",kcr)
                                                *fm_attributes_residue_ag("p",kcr))
+sum(kli, v54_nutrient_manure.l(i, kli, "grazing_cropland"))
+sum(kli, v54_nutrient_manure.l(i, kli, "confinement")
                                   *ic54_recycl_conf(i,"p",kli)*ic54_conf_to_cropl_shr(i))
+ v54_inorg_fert_reg.l(i,"p")
)
;

*** EOF post.gms ***

*#################### R SECTION START (OUTPUT DEFINITIONS) #####################

*##################### R SECTION END (OUTPUT DEFINITIONS) ######################
```

Appendix 3: r-skript for the analysis of the model output and data export

```
################################################
###*******************************************###
### Export von Ergebnissen via Latex als pdf ###
###*******************************************###
################################################

outfile<-"Ergebnisse.pdf"

### Libraries ###
setwd("C:/Users/Veikko Heintz/Documents/R/library")

library(ludata)
library(faodata)
library(magpie)
library(gdx)
library(gdxrrw)
library(lubase)
library(luscale)
library(luplot)
library(lucode)
library(lusweave)

options(error=function()traceback(2))

### Setzen des working directories ###

getwd()
setwd("C:/Users/Veikko Heintz/Documents/Masterarbeit/Ergebnisse_april_2014/2014_06_11")

gdx<-readGDX("fulldata_def.gdx")   #gdx file in workspace imortieren
fulldata<-gdx           #Umbenennnung in "fulldata"

######################
### Neue Funktionen ###
######################

### gdx-input ###

inp <- function (gdx, name, ..., react = "warning", as.magpie = FALSE)
{
  allnames <- c(name, c(...))
  if (!is.list(gdx)) {
    gdx <- readGDX(gdx, name = c(name, ...))
  }
  assigned = FALSE

  for (n in allnames) {
    if (n %in% names(gdx)) {
      x <- gdx[[n]]
      assigned = TRUE
      if (n != name & react != "silent")
        warning(name, " not found in GDX file! ", n,
                " returned")
      break
    }
  }

  if (assigned == FALSE) {
    if (react == "warning")
      warning("No element of ", allnames, " found in GDX file! NULL returned")
    if (react == "error")
```

```
      stop("No element of ", allnames, " found in GDX file!")
    return(NULL)
  }
  if (as.magpie) {
    require(magclass)
    x <- as.magpie(x)
  }
  return(x)
}

### Fertilizer use ###

fertilizer<-function(fulldata, nutrient="p") {
  if(nutrient=="nr"){
    out<-as.magpie(inp(fulldata, name="ov51_nr_inorg_fert_reg")[,,"level"])
  } else if(nutrient=="p")
    out<-as.magpie(inp(fulldata, name="ov54_p_fert_reg")[,,"level"])
  else {stop("only nr fertlizer parametrized in fertilizer()")}
  return(out)
}

### Harvest ###

harvest<-function(fulldata, nutrient="p") {

  nutrient_content<-inp(fulldata, name="im_attributes_harvest")[nutrient,]
  out<-as.magpie(production(fulldata, level="reg", crop_aggr=FALSE,water="sum")) * as.magpie(nutrient_content[-which(names(nutrient_content)=="pasture")])
  return(out)
}

### Aboveground residues ###

ag_res<-function(fulldata, nutrient="p") {
  kcr<-inp(fulldata,"kcr")
  dm<-inp(fulldata, name="ov_prod_res_ag_reg")[,,kcr,"level"]
  nr<-inp(fulldata, name="fm_attributes_residue_ag")[nutrient,kcr]
  out<-as.magpie(dm)*as.magpie(nr)
  return(out)
}

### Use of aboveground residues ###

ag_res_use<-function(fulldata, nutrient="p") {
  dm<-inp(fulldata, name="ov_res_supply")[,,,,"level"]
  nr<-inp(fulldata, name="fm_attributes_residue_ag")[nutrient,]
  out<-as.magpie(dm)*as.magpie(nr)
  return(out)
}

### manure ###

manure<-function(fulldata,nutrient="p"){
  if (nutrient=="p") {
    out<-as.magpie(inp(fulldata,name="ov54_nutrient_manure")[,,,,"level"])
  } else {stop("not parametrized for other nutrients")}
  return(out)
}

### Use ###

use<-function(fulldata, nutrient="p"){
  k=inp(gdx=fulldata,name="k")
  food=inp(gdx=fulldata, name="im_dem_food",as.magpie=TRUE)
  material=inp(gdx=fulldata, name="im_dem_material",as.magpie=TRUE)
```

```
  feed=dimSums(as.magpie(inp(gdx=fulldata,
name="ov_dem_feed")[,,,k,"level"]),dim=3)
  bioenergy=as.magpie(inp(gdx=fulldata, name="ov_dem_bioen")[,,,"level"])
  seed=as.magpie(inp(gdx=fulldata,
name="ov_prod_reg")[,,,"level"])*inp(gdx=fulldata,
name="fm_seed_shr",as.magpie=TRUE)
  dimnames(food)[[3]]<-paste("food",dimnames(food)[[3]],sep=".")
  dimnames(material)[[3]]<-paste("material",dimnames(material)[[3]],sep=".")
  dimnames(feed)[[3]]<-paste("feed",dimnames(feed)[[3]],sep=".")
  dimnames(bioenergy)[[3]]<-
paste("bioenergy",dimnames(bioenergy)[[3]],sep=".")
  dimnames(seed)[[3]]<-paste("seed",dimnames(seed)[[3]],sep=".")
  out<-combine.chunks(bioenergy,seed)
  out<-combine.chunks(feed,out)
  out<-combine.chunks(material,out)
  out<-combine.chunks(food,out)
  out<-as.magpie(out)
  names(dimnames(out))[[3]]<-"dem.k"
  if (nutrient=="dm_model") {nutrient_content<-as.magpie(1)
  } else if (nutrient=="p") {
    nutrient_content<-as.magpie(c(
      inp(fulldata, name="im_attributes_harvest")["p",],
      inp(fulldata, name="f54_attributes_livstproducts")["p",]
    ))[,,k]
  } else {
    nutrient_content<-as.magpie(c(
      inp(fulldata, name="im_attributes_harvest")[nutrient,],
      inp(fulldata, name="f51_attributes_livstproducts")[nutrient,]
    ))[,,k]
  }
  out<-out*nutrient_content
  return(out)
}

### livestock products ###

livestock_products<-function(fulldata,nutrient="p") {
  kli=inp(gdx=fulldata,name="kli")
  out            = dim-
Sums(use(fulldata,nutrient="p")[,,kli][,,"food"],dims=3)
  return(out)
}


### vegetal products ###

vegetal_products<-function(fulldata,nutrient="p") {
  kve=inp(gdx=fulldata,name="kve")
  out            = dim-
Sums(use(fulldata,nutrient="p")[,,kve][,,"food"],dims=3)
  return(out)
}

### slaughtered animals ###

slaughtered_animals<-function(fulldata,nutrient="p") {
  kli=inp(gdx=fulldata,name="kli")
  use_reg            = use(fulldata,nutrient="dm_model")[,,kli]
  animal_shr         = inp(gdx=fulldata,
name="i54_animal_shr_awms",as.magpie=TRUE)[,,kli]
  slaughter_factor   = inp(gdx=fulldata,
name="f54_slaughter_factor",as.magpie=TRUE)[,,kli]
  attributes_animals = as.magpie(inp(gdx=fulldata,
name="f54_attributes_living_animals")[nutrient,])[,,kli]
```

```
  out<-use_reg*slaughter_factor*attributes_animals*as.magpie(aperm(unwrap(animal_shr),c(1,2,4,3)))
  return(out)
}

### manure recycling on croplands ###

manure_recycl_cropl<-function(fulldata,nutrient="p"){
  if (nutrient=="nr") {

    recycl_conf       <- inp(fulldata,name="i51_recycl_conf",as.magpie=TRUE)
    conf_to_cropl_shr <- inp(fulldata,name="i51_conf_to_cropl_shr",as.magpie=TRUE)

  } else if (nutrient=="p") {
    recycl_conf       <- inp(fulldata,name="i54_recycl_conf",as.magpie=TRUE)
    conf_to_cropl_shr <- inp(fulldata,name="i54_conf_to_cropl_shr",as.magpie=TRUE)


  } else {stop("not parametrized for other nutrients yet")}
  manure         <- manure(fulldata,nutrient=nutrient)
  out <-  (
    setNames(dimSums(manure[,,"grazing_cropland"],dim=3),NULL)
    + setNames(dimSums(manure[,,"confinement"]*recycl_conf*conf_to_cropl_shr,dim=3),NULL)
  )
  return(setNames(out,"manure_recycl_cropl"))
}

### manure-p recycling on pasture ###

manure_recycl_past<-function(fulldata,nutrient="p"){
  if (nutrient=="nr") {

    recycl_conf       <- inp(fulldata,name="i51_recycl_conf",as.magpie=TRUE)
    conf_to_cropl_shr <- inp(fulldata,name="i51_conf_to_cropl_shr",as.magpie=TRUE)


  } else if (nutrient=="p") {

    recycl_conf       <- inp(fulldata,name="i54_recycl_conf",as.magpie=TRUE)
    conf_to_cropl_shr <- inp(fulldata,name="i54_conf_to_cropl_shr",as.magpie=TRUE)


  } else {stop("not parametrized for other nutrients yet")}
  manure         <- manure(fulldata,nutrient=nutrient)
  out <-  (
    setNames(dimSums(manure[,,"confinement"]*recycl_conf*(1-conf_to_cropl_shr),dim=3),NULL)
  )
  return(setNames(out,"manure_recycl_past"))

}

### recycling ag_residues ###

ag_res_recycle<-function(fulldata,nutrient ="p") {
  if (nutrient=="dm_model") {
    out<-setNames(dimSums(ag_res_use(fulldata,nutrient=nutrient)[,,"recycle"],dim=4),
```

```
NULL)+setNames(dimSums(ag_res_use(fulldata,nutrient=nutrient)[,,"burn"]*as.magpie(1-inp(fulldata,
"f51_res_combust_eff")),dim=4),NULL)
  }else if (nutrient=="p") {
    out<-setNames(dimSums(ag_res_use(fulldata,nutrient=nutrient)[,,"recycle"],dim=4),
NULL)+setNames(dimSums(ag_res_use(fulldata,nutrient=nutrient)[,,"burn"],dim=4),NULL)
  }else if (nutrient=="nr") {
    out<-setNames(dimSums(ag_res_use(fulldata,nutrient=nutrient)[,,"recycle"],dim=4),
NULL)+setNames(dimSums(ag_res_use(fulldata,nutrient=nutrient)[,,"burn"],dim=4),NULL)
  }
  return(out)
}

### slaughter waste ###

slaughter_waste<-function(fulldata,nutrient="p"){
  kli<-inp(gdx,"kli")
  out<-dimSums(slaughtered_animals(fulldata,nutrient=nutrient),dim=c(3,5)) - dimSums(use(fulldata,nutrient="p")[,,kli],dims=3)
  return(out)
}

### convby_use ###

convby_use<-function(fulldata,nutrient="p"){
  out<-as.magpie(inp(fulldata,"ov20_convby_use")[,,,nutrient,"level"])
  return(out)
}

### convby_supply ###

convby_supply<-function(fulldata,nutrient="p"){
  out<-as.magpie(inp(fulldata,"ov20_convby_supply")[,,nutrient,"level"])
  return(out)
}

### convby_prood ###

convby_prod<-function(fulldata,nutrient="p"){
  out<-as.magpie(inp(fulldata,"i20_convby_prod")[,,nutrient])
  return(out)
}

### plant products ###

plant_products<-function(fulldata,nutrient="p"){
  kcr<-inp(fulldata,"kcr")
  fooduse<-use(fulldata=fulldata,nutrient=nutrient)[,,"food"][,,kcr]
  #foodmatuse<-use(fulldata=fulldata,nutrient=nutrient)[,,c("food","material")][,,kcr]
  convby<-convby_prod(fulldata=fulldata,nutrient=nutrient)
  #  convby_food_shr=dimSums(fooduse,dim=c(3,4))/dimSums(foodmatuse,dim=c(3,4))
  #  out<-setNames(dimSums(fooduse,dim=c(3,4))-convby*convby_food_shr,"plant_products")
  out<-setNames(dimSums(fooduse,dim=c(3,4))-convby,"plant_products")
  return(out)
}
```

```

### feed ###

feed<-function(fulldata,nutrient="p"){
  kcr<-inp(fulldata,"kcr")
  kcr<-kcr[-which(kcr=="foddr")]    #### ??? kcr=kcr ??? ####
  kli<-inp(fulldata,"kli")          ####     klären      ####

  if (nutrient=="nr") {

    concentrate_feed  <- setNames(dimSums(use(fulldata=fulldata,nutrient="nr")[,,"feed"][,,kcr],dims=c(3,4)),"concentrate")
    fodder_feed       <- setNames(dimSums(use(fulldata=fulldata,nutrient="nr")[,,"feed"][,,"foddr"],dims=c(3,4)),"fodder")
    pasture_feed      <-setNames(dimSums(as.magpie(inp(fulldata, "ov_dem_feed")[,,,"pasture","level"]),dims=c(3))*inp(fulldata, name="im_attributes_harvest")[nutrient,"pasture"],"pasture")
    residues_feed     <- setNames(dimSums(ag_res_use(fulldata=fulldata,nutrient=nutrient)[,,"feed"],dims=c(3,4)),"residues")
    convby_feed       <- setNames(dimSums(convby_use(fulldata=fulldata,nutrient=nutrient)[,,"feed"],dims=c(3)),"convby")
    animal_feed       <- setNames(dimSums(use(fulldata=fulldata,nutrient="nr")[,,"feed"][,,kli],dims=c(3,4)),"animal_feed")
    scavenging_feed   <- setNames(dimSums(as.magpie(inp(fulldata,"ov_dem_feed")[,,,"scavenging","level"]),dims=3)*inp(fulldata, name="im_attributes_harvest")[nutrient,"pasture"],"scavenging")
    out<- mbind(concentrate_feed,fodder_feed,pasture_feed,residues_feed,convby_feed,animal_feed,scavenging_feed)
  } else if (nutrient=="p") {

    concentrate_feed  <- setNames(dimSums(use(fulldata=fulldata,nutrient="p")[,,"feed"][,,kcr],dims=c(3,4)),"concentrate")
    fodder_feed       <- setNames(dimSums(use(fulldata=fulldata,nutrient="p")[,,"feed"][,,"foddr"],dims=c(3,4)),"fodder")
    pasture_feed      <-setNames(dimSums(as.magpie(inp(fulldata, "ov_dem_feed")[,,,"pasture","level"]),dims=c(3))*inp(fulldata, name="im_attributes_harvest")[nutrient,"pasture"],"pasture")
    residues_feed     <- setNames(dimSums(ag_res_use(fulldata=fulldata,nutrient=nutrient)[,,"feed"],dims=c(3,4)),"residues")
    convby_feed       <- setNames(dimSums(convby_use(fulldata=fulldata,nutrient=nutrient)[,,"feed"],dims=c(3)),"convby")
    scavenging_feed   <- setNames(dimSums(as.magpie(inp(fulldata,"ov_dem_feed")[,,,"scavenging","level"]
```

```
),dims=3)*inp(fulldata,
name="im_attributes_harvest")[nutrient,"pasture"],"scavenging")
    out<-
mbind(concentrate_feed,fodder_feed,pasture_feed,residues_feed,convby_feed,sc
avenging_feed)
  } else {stop("losses_material so far only parametized for nr and p")}


  return(out)

}

### out_2_p_pool ###

out_2_pp<-function(fulldata, nutrient="p") {
  ag_res_recl       <-ag_res_recycle(fulldata, nutrient="p")
  man_rec_crpl      <-manure_recycl_cropl(fulldata, nutrient="p")
  p_fert            <-as.magpie(inp(fulldata,
name="ov54_p_fert_reg")[,,"level"])
  inp_2_l_shr       <-
inp(fulldata,name="s54_inputs_to_labile_shr",as.magpie=TRUE)
  out<-       setNames((ag_res_recl+man_rec_crpl+p_fert)*(1-
inp_2_l_shr),NULL)
  return(out)
}

### in_from_p_pool ###

in_from_pp<-function(fulldata, nutrient="p") {
  pp_pre            <-inp(fulldata,
name="ov54_p_pool_pre",as.magpie=TRUE)[,,"level"]
  pp_rel_tm         <-inp(fulldata,
name="s54_pool_release_time",as.magpie=TRUE)
  out           <-setNames(pp_pre/pp_rel_tm,NULL)
  return(out)
}

# Berechnung der Cropland Bilanzen #

cropland_budget<-function(fulldata,nutrient="p"){
  kcr               <-inp(fulldata,"kcr")
  rename_it         <-function(x,name){
    if (is.null(dimnames(x)[[3]])) {
      dimnames(x)[[3]]<-name
    } else {
      dimnames(x)[[3]]<-paste(name,dimnames(x)[[3]],sep=".")
    }
    x<-unwrap(x)
    return(x)
  }
  outharvest  <-   -
(re-
name_it(x=dimSums(harvest(fulldata,nutrient=nutrient),dim=3),name="harvest")
)
  outresidues <-   -
(re-
name_it(x=dimSums(ag_res(fulldata,nutrient=nutrient),dim=3),name="ag_residue
s"))


  NA_object <- setNames(as.magpie(outharvest),NULL)
  NA_object[,,]<-NA
  out_2_p_pool   <-   -
(rename_it(x=out_2_pp(fulldata,nutrient=nutrient),name="out_2_p_pool"))
  in_from_p_pool <-   (rename_it(x=in_from_pp(fulldata, nutrient=nutrient),
name="in_from_p_pool"))
```

```


  inseeds     <-   (rename_it(x=setNames(dimSums(use(fulldata, nutri-
ent=nutrient)[,,"seed"][,,kcr],dim=4),NULL),name="seed"))
  inagres     <-   (rename_it(x=setNames(ag_res_recycle(fulldata, nutri-
ent=nutrient),NULL),name="ag_residues_rec"))
  infertilizer<-   (rename_it(x=fertilizer(fulldata, nutri-
ent=nutrient),name="fix_fertilizer"))
  inmanure    <-   (rename_it(x=dimSums(manure_recycl_cropl(fulldata, nutri-
ent=nutrient)),name="manure"))


  out<-combine.chunks(outharvest,outresidues)
  out<-combine.chunks(out,out_2_p_pool)
  out<-combine.chunks(out,in_from_p_pool)
  out<-combine.chunks(out,infertilizer)
  out<-combine.chunks(out,inmanure)
  out<-combine.chunks(out,inagres)
  out<-combine.chunks(out,inseeds)
  out<-as.magpie(out)
  return(out)
}


#### Berechnung losses_field ###

#losses_field<-function(fulldata,nutrient="p"){
#  if (nutrient=="nr") {
#
#    budget <- cropland_budget(fulldata, "nr")
#    budget_out<- -
dimSums(budget[,,c("harvest","ag_residues","seed")],dim=3)
#    budget_in<-dimSums(budget[,,c("fix_fertilizer","manure",
#                                  "ag_residues_rec")],dim=3)
#
#  } else if (nutrient=="p") {
#    #
#    budget <- cropland_budget(fulldata,"p")
#    budget_out<- -
dimSums(budget[,,c("harvest","ag_residues","out_2_p_pool","seed")],dim=3)
#    budget_in<-
dimSums(budget[,,c("fix_fertilizer","manure","in_from_p_pool",
#                                  "ag_residues_rec")],dim=3)
#
#  } else {stop("losses_awms so far only parametized for nr and p")}
#
#  out<-budget_in-budget_out
#  return(setNames(out,"losses_field"))
#
#}
##
### Berechnung losses_awms ###

losses_awms<-function(fulldata,nutrient="p"){
  if (nutrient=="nr") {

    nutrient_manure   <-
inp(fulldata,"ov51_nr_manure")[,,,"confinement","level"]
    recycl_conf       <- inp(fulldata,"i51_recycl_conf",as.magpie=TRUE)


  } else if (nutrient=="p") {

    nutrient_manure   <-
inp(fulldata,"ov54_nutrient_manure")[,,,"confinement","level"]
    recycl_conf       <- inp(fulldata,"i54_recycl_conf",as.magpie=TRUE)
```

```

  } else {stop("losses_awms so far only parametized for nr and p")}

  out<-dimSums(as.magpie(nutrient_manure)*(1-recycl_conf),dims=c(3))
  return(setNames(out,"losses_awms"))

}


losses_material<-function(fulldata,nutrient="p"){
  kli<-inp(gdx=fulldata,"kli")
  if (nutrient=="nr") {

    nut_use_mat  <- dimSums(use(fulldata=fulldata,nutrient="nr")[,,"material"],dim=c(3,4))
    # livestock "seed" is so far not recycled, grouped together with bioenergy to losses_material in order to clear the balance
    nut_use_seed <- dimSums(use(fulldata=fulldata,nutrient="nr")[,,c("seed","bioenergy")][,,kli],dim=c(3,4))

  } else if (nutrient=="p") {

    nut_use_mat  <- dimSums(use(fulldata=fulldata,nutrient="p")[,,"material"],dim=c(3,4))
    # livestock "seed" is so far not recycled, grouped together with bioenergy to losses_material in order to clear the balance
    nut_use_seed <- dimSums(use(fulldata=fulldata,nutrient="p")[,,c("seed","bioenergy")][,,kli],dim=c(3,4))

  } else {stop("losses_material so far only parametized for nr and p")}

  out<-nut_use_mat+nut_use_seed
  return(setNames(out,"losses_material"))

}


losses_bioenergy<-function(fulldata,nutrient="p"){
  kcr<-inp(fulldata,"kcr")
  if (nutrient=="nr") {

    nut_use_bioen    <- dimSums(use(fulldata=fulldata,nutrient="nr")[,,"bioenergy"][,,kcr],dim=c(3,4))
    ag_res_use_bioen <-dimSums(ag_res_use(fulldata)[,,"bioenergy"],dim=4)

  } else if (nutrient=="p") {

    nut_use_bioen    <- dimSums(use(fulldata=fulldata,nutrient="p")[,,"bioenergy"][,,kcr],dim=c(3,4))
    ag_res_use_bioen <-dimSums(ag_res_use(fulldata)[,,"bioenergy"],dim=4)

  } else {stop("losses_material so far only parametized for nr and p")}

  return(setNames(nut_use_bioen+setNames( ag_res_use_bioen,NULL),"losses_bioenergy"))
}


losses_slwaste<-function(fulldata,nutrient="p"){

```

```
  if (nutrient=="nr") {

    out<-dimSums(slaughter_waste(fulldata, "nr"),dims=3)

  } else if (nutrient=="p") {

    out<-dimSums(slaughter_waste(fulldata, "p"),dims=3)

  } else {stop("losses_material so far only parametized for nr and p")}

  return(setNames(out,"losses_slwaste"))
}

#losses_resburn<-function(fulldata,nutrient="p"){
#
#  if (nutrient=="nr") {
#
#    out<-setNames(dimSums(ag_res_use(fulldata, "nr")[,,"burn"]*as.magpie(inp(fulldata,name="f51_res_combust_eff")),dim=4),NULL)#
#
#  } else if (nutrient=="p") {
#
#    out<-setNames(dimSums(ag_res_use(fulldata, "p")[,,"burn"]*0,dim=4),NULL)
#
#  } else {stop("losses_material so far only parametized for nr and p")}
#
#  return(setNames(out,"losses_resburn"))
#}
#
losses_resother<-function(fulldata,nutrient="p"){

  if (nutrient=="nr") {

    out<-setNames(dimSums(ag_res_use(fulldata, "nr")[,,"other"],dim=4),NULL)

  } else if (nutrient=="p") {

    out<-setNames(dimSums(ag_res_use(fulldata, "p")[,,"other"],dim=4),NULL)

  } else {stop("losses_resother so far only parametized for nr and p")}

  return(setNames(out,"losses_resotherbioenergy"))
}
#
#losses_convby<-function(fulldata){
#  out<-dimSums(convby_use(fulldata)[,,c("other_util","food","processing","waste")],dim=3)
#  return(setNames(out,"losses_convby"))
#}

losses_convby<-function(fulldata,nutrient="p"){

  if (nutrient=="nr") {

    out<-dimSums(convby_use(fulldata, "nr")[,,c("other_util","food","processing","waste")],dim=3)

  } else if (nutrient=="p") {

    out<-dimSums(convby_use(fulldata, "p")[,,c("other_util","food","processing","waste")],dim=3)

```

```
  } else {stop("losses_convby so far only parametized for nr and p")}

  return(setNames(out,"losses_convby"))
}

losses<-function(fulldata,nutrient="p"){

  if (nutrient=="nr") {

    out<-losses_material(fulldata,"nr")
   # out<-combine.chunks(manure_recycl_past(fulldata,"nr"),out)
    out<-combine.chunks(losses_convby(fulldata,"nr"),out)
    out<-combine.chunks(losses_bioenergy(fulldata,"nr"),out)
    out<-combine.chunks(losses_resother(fulldata,"nr"),out)
    #out<-combine.chunks(losses_resburn(fulldata,"nr"),out)
    out<-combine.chunks(losses_slwaste(fulldata,"nr"),out)
    out<-combine.chunks(losses_awms(fulldata,"nr"),out)
    #out<-combine.chunks(losses_field(fulldata,"nr"),out)
    out<-as.magpie(out)

  } else if (nutrient=="p") {

    foood<-setNames(plant_products(fulldata, nutrient="p")+dimSums(livestock_products(fulldata, nutrient="p"), dim=3),"Food products")

    out<-losses_material(fulldata,"p")
   # out<-combine.chunks(manure_recycl_past(fulldata,"p"),out)
    out<-combine.chunks(losses_convby(fulldata,"p"),out)
    out<-combine.chunks(losses_bioenergy(fulldata,"p"),out)
    out<-combine.chunks(losses_resother(fulldata,"p"),out)
    #out<-combine.chunks(losses_resburn(fulldata,"p"),out)
    out<-combine.chunks(foood,out)
    out<-combine.chunks(losses_slwaste(fulldata,"p"),out)
    out<-combine.chunks(setNames(manure(fulldata,nutrient=nutrient)[,,"fuel"],"manure_fuel"),out)
    out<-combine.chunks(losses_awms(fulldata,"p"),out)
    #out<-combine.chunks(losses_field(fulldata,"p"),out)
    out<-as.magpie(out)

  } else {stop("losses_convby so far only parametized for nr and p")}

  return(out)

}


livestock_budget<-function(fulldata, nutrient="p"){

  out<-combine.chunks(feed(fulldata,nutrient=nutrient),-losses_awms(fulldata,nutrient))

  out<-combine.chunks(out,setNames(-dimSums(manure(fulldata,nutrient=nutrient)[,,"fuel"],dims=3),"manure_fuel"))

  out<-combine.chunks(out,setNames(-dimSums(manure(fulldata,nutrient=nutrient)[,,"grazing_pasture"],dims=3),"manure_grazing"))
  out<-combine.chunks(out,-manure_recycl_cropl(fulldata,nutrient=nutrient))
  out<-combine.chunks(out,-manure_recycl_past(fulldata,nutrient=nutrient))

  out<-combine.chunks(out,-set-
```

```
Names(dimSums(slaughtered_animals(fulldata,nutrient=nutrient),dims=c(3,4,5)),"slaughtered_animals"))
  out<-combine.chunks(out, setNames(dimSums(as.magpie(out),dims=c(3)),"sum"))
  return(as.magpie(out))
}


##################################
### PDF output file erstellen ###
##################################

swout<-swopen(outfile=outfile,folder="C:/Users/Veikko Heintz/Documents/Masterarbeit/ERgebnisse_april_2014/2014_06_11/Ergebnisse")

### Introduction ###

swlatex(swout,"\\huge")
swlatex(swout,"\\textbf{Integrated Assesment of Phosphorus Use}\\newline")
swlatex(swout,"\\textbf{and Depletion}\\newline")
swlatex(swout,"\\newline")
swlatex(swout,"\\textbf{Output (second Run - Default)}\\newline")
swlatex(swout,"\\normalsize")
swlatex(swout,"\\newline")
swlatex(swout,"\\tableofcontents")
swlatex(swout,"\\setcounter{tocdepth}{1}")
swlatex(swout,"\\newpage")
### Fertilizer Use ###

# regional #

swlatex(swout,"\\section{P Fertilizer Use}")
swlatex(swout,"\\subsection{Tables}")
p_fert<-inp(gdx,"ov54_p_fert_reg",as.magpie=T)[,,1]
getNames(p_fert)<-"P-fertilizer (TgP)"
swtable(swout,p_fert,caption="p_fertilizer",transpose=FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,p_fert,legend=TRUE,add=FALSE, fig.orientation="landscape",tex_caption="fert_fig")
swlatex(swout,"\\newpage")

# global #

swlatex(swout,"\\section{P Fertilizer Use global}")
swlatex(swout,"\\subsection{Tables}")
p_fert_glo<-dimSums(inp(gdx,"ov54_p_fert_reg",as.magpie=T)[,,1], dims=1)
getNames(p_fert_glo)<-"p_fert_glo"
swtable(swout,p_fert_glo,caption="p_fertilizer_glo",transpose=FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,p_fert,legend=TRUE,add=TRUE, fig.orientation="landscape",tex_caption="global fertilizer use")
swlatex(swout,"\\newpage")

### Harvest ###

# global #

swlatex(swout,"\\section{P in Harvest (global)}")
swlatex(swout,"\\subsection{Tables}")
p_in_harvest_glo<-dimSums(harvest(fulldata, nutrient="p"),dims=c(1,3))
getNames(p_in_harvest_glo)<-"p_in_harvest_glo"
swtable(swout,p_in_harvest_glo,caption="p_in_harvest_glo",transpose=FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,p_in_harvest_glo,legend=TRUE, fig.orientation="landscape",tex_caption="p_in_harvest")
swlatex(swout,"\\newpage")
```

```

# regional #

swlatex(swout,"\\section{P in Harvest (regions)}")
swlatex(swout,"\\subsection{Tables}")
p_in_harvest_reg<-dimSums(harvest(fulldata, nutrient="p"),dims=3)
getNames(p_in_harvest_reg)<-"p_in_harvest_reg"
swtable(swout,p_in_harvest_reg,caption="p_in_harvets_reg",transpose=FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,p_in_harvest_reg,legend=TRUE,
fig.orientation="landscape",tex_caption="p_in_harvest_reg")
swlatex(swout,"\\newpage")

### Different Use (Food, Feed, Bioenergy, Material, Seed) ###

#  Use global sum #

swlatex(swout,"\\section{P in use total (global)}")
swlatex(swout,"\\subsection{Tables}")
kcr<-inp(gdx,"kcr")
p_in_use_glo_tot<-dimSums(use(fulldata, nutrient="p")[,,kcr],dims=c(1,3,4))
getNames(p_in_use_glo_tot)<-"p_in_use_glo_tot"
swtable(swout,p_in_use_glo_tot,caption="p_in_use_glo_tot",transpose=FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,p_in_use_glo_tot,legend=TRUE,
fig.orientation="landscape",tex_caption="p_in_use_glo_tot")
swlatex(swout,"\\newpage")

# use global #

swlatex(swout,"\\section{P in Use (global)}")
swlatex(swout,"\\subsection{Tables}")
p_in_use_glo<-dimSums(use(fulldata, nutrient="p")[,,kcr],dims=c(1,4))
swtable(swout,p_in_use_glo,caption="p_in_use_glo",transpose=TRUE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,p_in_use_glo,legend=TRUE,
fig.orientation="landscape",tex_caption="p_in_use_glo")
swlatex(swout,"\\newpage")

# Use regional sum #

swlatex(swout,"\\section{P in Use (regional)}")
swlatex(swout,"\\subsection{Tables}")
p_in_use_reg<-dimSums(use(fulldata, nutrient="p")[,,kcr],dims=c(3,4))
p_in_use_reg<-setNames(p_in_use_reg,"Use regional")
swtable(swout,p_in_use_reg,caption="p_in_use_reg",transpose=FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,p_in_use_reg,legend=TRUE,
fig.orientation="landscape",tex_caption="p_in_use_reg")
swlatex(swout,"\\newpage")

### Feed ###

# global supply #

swlatex(swout,"\\section{Feed Total (global supply)}")
swlatex(swout,"\\subsection{Tables}")
feed_glo_supply<-dimSums(feed(fulldata, "p"),dim=1)
swtable(swout,feed_glo_supply,caption="Feed_supply",transpose=TRUE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,feed_glo_supply,legend=TRUE,
fig.orientation="landscape",tex_caption="Feed_supply")
swlatex(swout,"\\newpage")

# global sum#

```

```
swlatex(swout,"\\section{Feed Total (global)}")
swlatex(swout,"\\subsection{Tables}")
feed_glo<-dimSums(feed(fulldata, "p"),dim=c(1,3))
feed_glo<-setNames(feed_glo,"feed_glo")
swtable(swout,feed_glo,caption="Feed",transpose=FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,feed_glo,legend=TRUE, fig.orientation="landscape",tex_caption="Feed")
swlatex(swout,"\\newpage")

# regional sum#

swlatex(swout,"\\section{Feed Total (regional)}")
swlatex(swout,"\\subsection{Tables}")
feed_reg<-dimSums(feed(fulldata, "p"),dim=3)
feed_reg<-setNames(feed_reg,"Feed_reg")
swtable(swout,feed_reg,caption="Feed_reg",transpose=TRUE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,feed_reg,legend=TRUE, fig.orientation="landscape",tex_caption="Feed_reg")
swlatex(swout,"\\newpage")

### Aboveground residues ###

# global #

swlatex(swout,"\\section{P in aboveground residues (global)}")
swlatex(swout,"\\subsection{Tables}")
p_in_ag_res_glo<-dimSums(ag_res(fulldata, nutrient="p"),dims=c(1,3))
p_in_ag_res_glo<-setNames(p_in_ag_res_glo,"p_in_ag_res_glo")
swtable(swout,p_in_ag_res_glo,caption="p_in_ag_res_glo",transpose=FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,p_in_ag_res_glo,legend=TRUE, fig.orientation="landscape",tex_caption="p_in_ag_res_glo")
swlatex(swout,"\\newpage")

# regional #

swlatex(swout,"\\section{P in aboveground residues (regions)}")
swlatex(swout,"\\subsection{Tables}")
p_in_ag_res_reg<-dimSums(ag_res(fulldata, nutrient="p"),dims=3)
p_in_ag_res_reg<-setNames(p_in_ag_res_reg,"p_in_ag_res_reg")
swtable(swout,p_in_ag_res_reg,caption="p_in_ag_res_reg",transpose=FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,p_in_ag_res_reg,legend=TRUE, fig.orientation="landscape",tex_caption="p_in_ag_res_reg")
swlatex(swout,"\\newpage")

### Use aboveground residues ###

# global Use #

swlatex(swout,"\\section{P in Ag_res_Use nach Verwendungen (global)}")
swlatex(swout,"\\subsection{Tables}")
p_in_ag_res_use_glo<-dimSums(ag_res_use(fulldata, nutrient="p"),dims=c(1,4))
swtable(swout,p_in_ag_res_use_glo,caption="p_in_ag_res_use_glo",transpose=TRUE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,p_in_ag_res_use_glo,legend=TRUE, fig.orientation="landscape",tex_caption="p_in_ag_res_use_glo")
swlatex(swout,"\\newpage")

### conversion byproducts ###

# convby_use (feed, waste, processing, food, other) #

```

```
# convby_use global sum #

swlatex(swout,"\\section{P in Convby Use Total (global)}")
swlatex(swout,"\\subsection{Tables}")
p_in_convby_use_glo_ges<-dimSums(convby_use(fulldata, "p"), dims =c(1,3))
p_in_convby_use_glo_ges<-setNames(p_in_convby_use_glo_ges,"p_in_convby_use_glo_ges")
swtable(swout,p_in_convby_use_glo_ges,caption="p_in_convby_use_glo_ges",transpose=FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,p_in_convby_use_glo_ges,legend=TRUE, fig.orientation="landscape",tex_caption="p_in_convby_use_glo_ges")
swlatex(swout,"\\newpage")

# convby_use regional sum #

swlatex(swout,"\\section{P in Convby Use Total (regional)}")
swlatex(swout,"\\subsection{Tables}")
p_in_convby_use_reg_ges<-dimSums(convby_use(fulldata, "p"), dims = 3)
p_in_convby_use_reg_ges<-setNames(p_in_convby_use_reg_ges,"p_in_convby_use_reg_ges")
swtable(swout,p_in_convby_use_reg_ges,caption="p_in_convby_use_reg_ges",transpose=FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,p_in_convby_use_reg_ges,legend=TRUE, fig.orientation="landscape",tex_caption="p_in_convby_use_reg_ges")
swlatex(swout,"\\newpage")

# convby_use global #

swlatex(swout,"\\section{P in Convby Use nach Verwendungen (global)}")
swlatex(swout,"\\subsection{Tables}")
p_in_convby_use_glo<-dimSums(convby_use(fulldata, "p"), dims = 1)
swtable(swout,p_in_convby_use_glo,caption="p_in_convby_use_glo",transpose=TRUE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,p_in_convby_use_glo,legend=TRUE, fig.orientation="landscape",tex_caption="p_in_convby_use_glo")
swlatex(swout,"\\newpage")

# conv_by supply #

swlatex(swout,"\\section{P in Convby Use Total (regional)}")
swlatex(swout,"\\subsection{Tables}")
p_in_convby_supply<-convby_supply(fulldata, "p")
p_in_convby_supply<-setNames(p_in_convby_supply,"p_in_convby_supply")
swtable(swout,p_in_convby_supply,caption="p_in_convby_supply",transpose=FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,p_in_convby_supply,legend=TRUE, fig.orientation="landscape",tex_caption="p_in_convby_supply")
swlatex(swout,"\\newpage")

# convby_products #       #################################
                          ###   Unterschied zu Use und  ###
                          ###    supply wegenen Trade   ###
                          #################################

# convby_prod global und gesamt #

swlatex(swout,"\\section{P in produzierten Convby_products (global)}")
swlatex(swout,"\\subsection{Tables}")
p_in_convby_prod_glo<-colSums(convby_prod(fulldata, "p"))
p_in_convby_prod_glo<-setNames(p_in_convby_prod_glo,"p_in_convby_prod_glo")
swtable(swout,p_in_convby_prod_glo,caption="p_in_convby_prod_glo",transpose=FALSE)
```

```
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,p_in_convby_prod_glo,legend=TRUE, fig.orientation="landscape",tex_caption="p_in_convby_prod_glo")
swlatex(swout,"\\newpage")

# convby_prod regional und gesamt #

swlatex(swout,"\\section{P in produzierten Convby_products (regional)}")
swlatex(swout,"\\subsection{Tables}")
p_in_convby_prod_reg<-convby_prod(fulldata, "p")
p_in_convby_prod_reg<-setNames(p_in_convby_prod_reg,"p_in_convby_prod_reg")
swtable(swout,p_in_convby_prod_reg,caption="p_in_convby_prod_reg",transpose=FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,p_in_convby_prod_reg,legend=TRUE, fig.orientation="landscape",tex_caption="p_in_convby_prod_reg")
swlatex(swout,"\\newpage")

##################################
### livestock slaughter weight ###
##################################

#################################
### slaughter waste and other ###
#################################

############
### Food ###
############

### vegetal products ###

# vegetal prdoucts global sum #

swlatex(swout,"\\section{P in vegetal products total (gobal)}")
swlatex(swout,"\\subsection{Tables}")
p_in_vegt_prod_glo_tot<-dimSums(vegetal_products(fulldata, nutrient="p"),dims=c(1,3))
getNames(p_in_vegt_prod_glo_tot)<-"p_in_vegt_prod_glo_tot"
swtable(swout,p_in_vegt_prod_glo_tot,caption="p_in_vegt_prod_glo_tot",transpose=FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,p_in_vegt_prod_glo_tot,legend=TRUE, fig.orientation="landscape",tex_caption="p_in_vegt_prod_glo_tot")
swlatex(swout,"\\newpage")

# vegetal products regional sum #

swlatex(swout,"\\section{P in vegetal products total (regional)}")
swlatex(swout,"\\subsection{Tables}")
p_in_vegt_prod_reg<-dimSums(vegetal_products(fulldata, nutrient="p"),dims=3)
p_in_vegt_prod_reg<-setNames(p_in_vegt_prod_reg,"p_in_vegt_prod_reg")
swtable(swout,p_in_vegt_prod_reg,caption="p_in_vegt_prod_reg",transpose=FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,p_in_vegt_prod_reg,legend=TRUE, fig.orientation="landscape",tex_caption="p_in_vegt_prod_reg")
swlatex(swout,"\\newpage")

### livestock products ###

# global sum #

swlatex(swout,"\\section{P in Livestock products total (gobal)}")
swlatex(swout,"\\subsection{Tables}")
```

```
p_in_livst_prod_glo_tot<-dimSums(livestock_products(fulldata, nutrient="p"),dims=c(1,3))
p_in_livst_prod_glo_tot<-setNames(p_in_livst_prod_glo_tot,"p_in_livst_prod_glo_tot")
swtable(swout,p_in_livst_prod_glo_tot,caption="p_in_livst_prod_glo_tot",transpose=FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,p_in_livst_prod_glo_tot,legend=TRUE, fig.orientation="landscape",tex_caption="p_in_livst_prod_glo_tot")
swlatex(swout,"\\newpage")

# regional sum #

swlatex(swout,"\\section{P in livestock products total (regional)}")
swlatex(swout,"\\subsection{Tables}")
p_in_livst_prod_reg<-dimSums(livestock_products(fulldata, nutrient="p"),dims=3)
p_in_livst_prod_reg<-setNames(p_in_livst_prod_reg,"p_in_livst_prod_reg")
swtable(swout,p_in_livst_prod_reg,caption="p_in_livst_prod_reg",transpose=FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,p_in_livst_prod_reg,legend=TRUE, fig.orientation="landscape",tex_caption="p_in_livst_prod_reg")
swlatex(swout,"\\newpage")

### plant products ###

# global sum #

swlatex(swout,"\\section{P in plant products total (gobal)}")
swlatex(swout,"\\subsection{Tables}")
p_in_plant_prod_glo_tot<-dimSums(plant_products(fulldata, nutrient="p"),dims=c(1,3))
p_in_plant_prod_glo_tot<-setNames(p_in_plant_prod_glo_tot,"p_in_plant_prod_glo_tot")
swtable(swout,p_in_plant_prod_glo_tot,caption="p_in_plant_prod_glo_tot",transpose=FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,p_in_plant_prod_glo_tot,legend=TRUE,fig.orientation="landscape",tex_caption="p_in_plant_prod_glo_tot")
swlatex(swout,"\\newpage")

# regional sum #

swlatex(swout,"\\section{P in plant products total (regional)}")
swlatex(swout,"\\subsection{Tables}")
p_in_plant_prod_reg<-dimSums(plant_products(fulldata, nutrient="p"),dims=3)
p_in_plant_prod_reg<-setNames(p_in_plant_prod_reg,"p_in_plant_prod_reg")
swtable(swout,p_in_plant_prod_reg,caption="p_in_plant_prod_reg",transpose=FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,p_in_plant_prod_reg,legend=TRUE, fig.orientation="landscape",tex_caption="p_in_plant_prod_reg")
swlatex(swout,"\\newpage")


###################
###    manure    ###
###################

# global sum #

swlatex(swout,"\\section{P in Manure Total (global)}")
swlatex(swout,"\\subsection{Tables}")
p_in_manure_glo_tot<-dimSums(manure(fulldata, nutrient="p"),dims=c(1,3,4))
```

```
p_in_manure_glo_tot<-setNames(p_in_manure_glo_tot,"p_in_manure_glo_tot")
swtable(swout,p_in_manure_glo_tot,caption="p_in_manure_glo_tot",transpose=FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,p_in_manure_glo_tot,legend=TRUE, fig.orientation="landscape",tex_caption="p_in_manure_glo_tot")
swlatex(swout,"\\newpage")

# manure use #

swlatex(swout,"\\section{P in Manure in different use (global)}")
swlatex(swout,"\\subsection{Tables}")
p_in_manure_glo<-dimSums(manure(fulldata, nutrient="p"),dims=c(1,3))
swtable(swout,p_in_manure_glo,caption="p_in_manure_glo",transpose=TRUE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,p_in_manure_glo,legend=TRUE, fig.orientation="landscape",tex_caption="p_in_manure_glo")
swlatex(swout,"\\newpage")

# regional sum #

swlatex(swout,"\\section{P in manure (regions)}")
swlatex(swout,"\\subsection{Tables}")
p_in_manure_reg<-dimSums(manure(fulldata, nutrient="p"),dims=c(3,4))
p_in_manure_reg<-setNames(p_in_manure_reg,"p_in_manure_reg")
swtable(swout,p_in_manure_reg,caption="p_in_manure_reg",transpose=FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,p_in_manure_reg,legend=TRUE, fig.orientation="landscape",tex_caption="p_in_manure_reg")
swlatex(swout,"\\newpage")

### P in slaughter weight ###

# P in sl_animals global sum #

swlatex(swout,"\\section{P in Schlachtkörpern total (global)}")
swlatex(swout,"\\subsection{Tables}")
p_in_sl_anim_glo_tot<-dimSums(slaughtered_animals(fulldata, nutrient="p"),dims=c(1,3,4,5))
p_in_sl_anim_glo_tot<-setNames(p_in_sl_anim_glo_tot,"p_in_sl_anim_glo_tot")
swtable(swout,p_in_sl_anim_glo_tot,caption="p_in_sl_anim_glo_tot",transpose=FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,p_in_sl_anim_glo_tot,legend=TRUE, fig.orientation="landscape",tex_caption="p_in_sl_anim_glo_tot")
swlatex(swout,"\\newpage")

#P in sl_animals global #

swlatex(swout,"\\section{P in Schlachtkörpern nach Verwendung (global)}")
swlatex(swout,"\\subsection{Tables}")
p_in_sl_anim_glo<-dimSums(slaughtered_animals(fulldata, nutrient="p"),dims=c(1,3,5))
swtable(swout,p_in_sl_anim_glo,caption="p_in_sl_anim_glo",transpose=TRUE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,p_in_sl_anim_glo,legend=TRUE, fig.orientation="landscape",tex_caption="p_in_sl_anim_glo")
swlatex(swout,"\\newpage")

# P in sl_animals regional sum #

swlatex(swout,"\\section{P in Schlachtkörpern total (regional)}")
swlatex(swout,"\\subsection{Tables}")
p_in_sl_anim_reg_tot<-dimSums(slaughtered_animals(fulldata, nutrient="p"),dims=c(3,4,5))
p_in_sl_anim_reg_tot<-setNames(p_in_sl_anim_reg_tot,"p_in_sl_anim_reg_tot")
```

```
swtable(swout,p_in_sl_anim_reg_tot,caption="p_in_sl_anim_reg_tot",transpose=
FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,p_in_sl_anim_reg_tot,legend=TRUE,
fig.orientation="landscape",tex_caption="p_in_sl_anim_reg_tot")
swlatex(swout,"\\newpage")

### Manure-P recycling on croplands ###

# Manure Recycling on croplands (global) #

swlatex(swout,"\\section{P Recycling on cropland (global)}")
swlatex(swout,"\\subsection{Tables}")
p_recycl_on_crpl_glo<-colSums(manure_recycl_cropl(fulldata, nutrient="p"))
swtable(swout,p_recycl_on_crpl_glo,caption="p_recycl_on_crpl_glo",transpose=
FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,p_recycl_on_crpl_glo,legend=TRUE,
fig.orientation="landscape",tex_caption="p_recycl_on_crpl_glo")
swlatex(swout,"\\newpage")

# Manure Recycling on croplands (regional) #

swlatex(swout,"\\section{P Recycling on croplands (regional)}")
swlatex(swout,"\\subsection{Tables}")
p_recycl_on_crpl_reg<-manure_recycl_cropl(fulldata, nutrient="p")
swtable(swout,p_recycl_on_crpl_reg,caption="p_recycl_on_crpl_reg",transpose=
FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,p_recycl_on_crpl_reg,legend=TRUE,
fig.orientation="landscape",tex_caption="p_recycl_on_crpl_reg")
swlatex(swout,"\\newpage")

### Manure-P recycling on pasture ###

# Manure P Recycling on pasture (global) #

swlatex(swout,"\\section{P Recycling on Pasture (global)}")
swlatex(swout,"\\subsection{Tables}")
p_recycl_on_past_glo<-colSums(manure_recycl_past(fulldata, nutrient="p"))
swtable(swout,p_recycl_on_past_glo,caption="p_recycl_on_past_glo",transpose=
FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,p_recycl_on_past_glo,legend=TRUE,
fig.orientation="landscape",tex_caption="p_recycl_on_past_glo")
swlatex(swout,"\\newpage")

# Manure P Recycling on Pasture (regional) #

swlatex(swout,"\\section{P Recycling on Pasture (regional)}")
swlatex(swout,"\\subsection{Tables}")
p_recycl_on_past_reg<-manure_recycl_past(fulldata, nutrient="p")
swtable(swout,p_recycl_on_past_reg,caption="p_recycl_on_past_reg",transpose=
FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,p_recycl_on_past_reg,legend=TRUE,
fig.orientation="landscape",tex_caption="p_recycl_on_past_reg")
swlatex(swout,"\\newpage")
#swclose(swout,clean_output=FALSE) # erhält alle zwischendateien

### Recycling aboveground residues ###

# ag_residues recycling (global) #

swlatex(swout,"\\section{AG_res Recycling (global)}")
swlatex(swout,"\\subsection{Tables}")
```

```
p_recycl_ag_res_glo<-colSums(ag_res_recycle(fulldata, nutrient="p"))
getNames(p_recycl_ag_res_glo)<-"p_recycl_ag_res_glo"
swtable(swout,p_recycl_ag_res_glo,caption="p_recycl_ag_res_glo",transpose=FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,p_recycl_ag_res_glo,legend=TRUE, fig.orientation="landscape",tex_caption="p_recycl_ag_res_glo")
swlatex(swout,"\\newpage")

# ag_residues recycling (regional) #

swlatex(swout,"\\section{AG_res Recycling (regional)}")
swlatex(swout,"\\subsection{Tables}")
p_recycl_ag_res_reg<-ag_res_recycle(fulldata, nutrient="p")
p_recycl_ag_res_reg<-setNames(p_recycl_ag_res_reg,"p_recycl_ag_res_reg")
swtable(swout,p_recycl_ag_res_reg,caption="p_recycl_ag_res_reg",transpose=FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,p_recycl_ag_res_reg,legend=TRUE, fig.orientation="landscape",tex_caption="p_recycl_ag_res_reg")
swlatex(swout,"\\newpage")

### Slaughter waste ###

# P in sl_waste (Global) #

swlatex(swout,"\\section{P in slaughter waste (Global)}")
swlatex(swout,"\\subsection{Tables}")
p_in_sl_waste_glo<-dimSums(slaughter_waste(fulldata, nutrient="p"),dims=c(1,3))
p_in_sl_waste_glo<-setNames(p_in_sl_waste_glo,"p_in_sl_waste_glo")
swtable(swout,p_in_sl_waste_glo,caption="p_in_sl_waste_glo",transpose=FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,p_in_sl_waste_glo,legend=TRUE, fig.orientation="landscape",tex_caption="p_in_sl_waste_glo")
swlatex(swout,"\\newpage")

# P in sl_waste (regional) #

swlatex(swout,"\\section{P in Slaughter waste (regional)}")
swlatex(swout,"\\subsection{Tables}")
p_in_sl_waste_reg<-dimSums(slaughter_waste(fulldata, nutrient="p"),dims=3)
p_in_sl_waste_reg<-setNames(p_in_sl_waste_reg,"p_in_sl_waste_reg")
swtable(swout,p_in_sl_waste_reg,caption="p_in_sl_waste_reg",transpose=FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,p_in_sl_waste_reg,legend=TRUE, fig.orientation="landscape",tex_caption="p_in_sl_waste_reg")
swlatex(swout,"\\newpage")

### plant products ###

# plant_prod_food global #

swlatex(swout,"\\section{P in plant products for fooduse (global)}")
swlatex(swout,"\\subsection{Tables}")
p_in_plant_prod_glo<-colSums(plant_products(fulldata, "p"))
swtable(swout,p_in_plant_prod_glo,caption="p_in_plant_prod_glo",transpose=FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,p_in_plant_prod_glo,legend=TRUE, fig.orientation="landscape",tex_caption="p_in_plant_prod_glo")
swlatex(swout,"\\newpage")

# plant_prod regional #

swlatex(swout,"\\section{P in plant products for fooduse (regional)}")
```

```
swlatex(swout,"\\subsection{Tables}")
p_in_plant_prod_reg<-plant_products(fulldata, "p")
swtable(swout,p_in_plant_prod_reg,caption="p_in_plant_prod_reg",transpose=FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,p_in_plant_prod_reg,legend=TRUE, fig.orientation="landscape",tex_caption="p_in_plant_prod_reg")
swlatex(swout,"\\newpage")

### P Pools ###

# p pool regional #

swlatex(swout,"\\section{P Pool}")
swlatex(swout,"\\subsection{Tables}")
p_pool<-inp(gdx,"p54_p_pool",as.magpie=T)
p_pool<-setNames(p_pool,"p_pool")
swtable(swout,p_pool,caption="p_pool",transpose=FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,p_pool,legend=TRUE,fig.orientation="landscape", tex_caption="p_pool")
swlatex(swout,"\\subsection{tables}")
swlatex(swout,"\\newpage")

### P Pool global ###

swlatex(swout,"\\section{P Pool global}")
swlatex(swout,"\\subsection{Tables}")
p_pool_glo<-dimSums(inp(gdx,"p54_p_pool",as.magpie=T),dims=1)
p_pool_glo<-setNames(p_pool_glo,"p_pool_glo")
swtable(swout,p_pool_glo,caption="p_pool_glo",transpose=FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,p_pool,legend=TRUE,add=TRUE, fig.orientation="landscape",tex_caption="p_pool")
swlatex(swout,"\\subsection{tables}")
swlatex(swout,"\\newpage")

# Out_2_p_pool #

swlatex(swout,"\\section{Out to P_pool (regional)}")
swlatex(swout,"\\subsection{Tables}")
out_2_p_pool<-out_2_pp(fulldata, "p")
out_2_p_pool<-setNames(out_2_p_pool,"out_2_p_pool")
swtable(swout,out_2_p_pool,caption="out_2_p_pool",transpose=FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,out_2_p_pool,legend=TRUE,fig.orientation="landscape", tex_caption="out_2_p_pool")
swlatex(swout,"\\newpage")

# Out_2_p_pool global#

swlatex(swout,"\\section{Out to P_pool (global)}")
swlatex(swout,"\\subsection{Tables}")
out_2_p_pool_glo<-dimSums(out_2_pp(fulldata, "p"), dims=1)
#getNames(out_2_p_pool_glo)<-"out_2_p_pool_glo"
out_2_p_pool_glo<-setNames(out_2_p_pool_glo,"out_2_p_pool_glo")
swtable(swout,out_2_p_pool_glo,caption="out_2_p_pool_glo",transpose=FALSE)
swlatex(swout,"\\subsection{Figures}")
#swfigure(swout,scratch_plot,out_2_p_pool_glo,legend=TRUE,fig.orientation="landscape",tex_caption="out_2_p_pool_glo")
swfigure(swout,scratch_plot,out_2_p_pool,legend=TRUE, add=TRUE,fig.orientation="landscape",tex_caption="out_2_p_pool")
swlatex(swout,"\\newpage")

```

```
### in_from_p_pool ###

# regional #

swlatex(swout,"\\section{n from P_pool (regional)}")
swlatex(swout,"\\subsection{Tables}")
in_from_p_pool<-in_from_pp(fulldata, "p")
in_from_p_pool<-setNames(in_from_p_pool,"in_from_p_pool")
swtable(swout,in_from_p_pool,caption="in_from_p_pool",transpose=FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,in_from_p_pool,legend=TRUE,fig.orientation="landscape",tex_caption="in_from_p_pool")
swlatex(swout,"\\newpage")

# global #

swlatex(swout,"\\section{n from P_pool (global)}")
swlatex(swout,"\\subsection{Tables}")
in_from_p_pool_glo<-dimSums(in_from_pp(fulldata, "p"), dims=1)
in_from_p_pool_glo<-setNames(in_from_p_pool_glo,"in_from_p_pool_glo")
swtable(swout,in_from_p_pool_glo,caption="in_from_p_pool_glo",transpose=FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,in_from_p_pool,legend=TRUE, add=TRUE,fig.orientation="landscape",tex_caption="in_from_p_pool")
swlatex(swout,"\\newpage")

#################################
### !!! Cropland Bilanzen !!! ###
#################################

Harvest<-dimSums(cropland_budget(fulldata, "p"), na.rm = TRUE, dims=1)[,,"harvest"]
AG_residues<-dimSums(cropland_budget(fulldata, "p"), na.rm = TRUE, dims=1)[,,"ag_residues"]
Out_to_p_pool<-dimSums(cropland_budget(fulldata, "p"), na.rm = TRUE, dims=1)[,,"out_2_p_pool"]
In_from_p_pool<-dimSums(cropland_budget(fulldata, "p"), na.rm = TRUE, dims=1)[,,"in_from_p_pool"]
Fertilizer<-dimSums(cropland_budget(fulldata, "p"), na.rm = TRUE, dims=1)[,,"fix_fertilizer"]
Manure<-dimSums(cropland_budget(fulldata, "p"), na.rm = TRUE, dims=1)[,,"manure"]
AG_res_Recycling<-dimSums(cropland_budget(fulldata, "p"), na.rm = TRUE, dims=1)[,,"ag_residues_rec"]
Seeds<-dimSums(cropland_budget(fulldata, "p"), na.rm = TRUE, dims=1)[,,"seed"]
Sum<-dimSums(cropland_budget(fulldata, "p"), na.rm = TRUE, dims=c(1,3))
getNames(Sum)<-"SUM"

crplbdgt<-mbind(Harvest,AG_residues,Out_to_p_pool,In_from_p_pool,Fertilizer,Manure, AG_res_Recycling,Seeds,Sum)

swlatex(swout,"\\section{Cropland Budgets}")
swlatex(swout,"\\subsection{Tables}")
swtable(swout,crplbdgt,caption="Cropland Budget",transpose=TRUE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,crplbdgt,legend=TRUE,fig.orientation="landscape", tex_caption="Cropland Budget")
swlatex(swout,"\\newpage")

# cropland dynamics #

```

```
Harvest<--(dimSums(cropland_budget(fulldata, "p"), na.rm = TRUE, dims=1)[,,"harvest"])
AG_residues<--(dimSums(cropland_budget(fulldata, "p"), na.rm = TRUE, dims=1)[,,"ag_residues"])
Fixation<--(dimSums(cropland_budget(fulldata, "p"), na.rm = TRUE, dims=1)[,,"out_2_p_pool"])
Release<-dimSums(cropland_budget(fulldata, "p"), na.rm = TRUE, dims=1)[,,"in_from_p_pool"]
Fertilizer<-dimSums(cropland_budget(fulldata, "p"), na.rm = TRUE, dims=1)[,,"fix_fertilizer"]
Manure<-dimSums(cropland_budget(fulldata, "p"), na.rm = TRUE, dims=1)[,,"manure"]
AG_res_Recycling<-dimSums(cropland_budget(fulldata, "p"), na.rm = TRUE, dims=1)[,,"ag_residues_rec"]

crpldyn<-mbind(Harvest,AG_residues,Fixation,Release,Fertilizer,Manure)

swlatex(swout,"\\section{Cropland Dynamics}")
swlatex(swout,"\\subsection{Tables}")
swtable(swout,crpldyn,caption="Cropland Dynamics",transpose=TRUE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,crpldyn,legend=TRUE,fig.orientation="landscape",tex_caption="Cropland Dynamics")
swlatex(swout,"\\newpage")

################################
### Bestimmung von Verlusten ###
################################

swlatex(swout,"\\section{Losses AWMS (regional)}")
swlatex(swout,"\\subsection{Tables}")
loss_awms<-losses_awms(fulldata, "p")
getNames(loss_awms)<-"loss_awms"
swtable(swout,loss_awms,caption="loss_awms",transpose=FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,loss_awms,legend=TRUE,fig.orientation="landscape", tex_caption="loss_awms")
swlatex(swout,"\\newpage")

### Berechnung losses_material ###

swlatex(swout,"\\section{Losses material (regional)}")
swlatex(swout,"\\subsection{Tables}")
loss_mat<-losses_material(fulldata,"p")
getNames(loss_mat)<-"loss_mat"
swtable(swout,loss_mat,caption="loss_mat",transpose=FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,loss_mat,legend=TRUE,fig.orientation="landscape",tex_caption="loss_mat")
swlatex(swout,"\\newpage")

### Berechnung losses bioenergy ####

swlatex(swout,"\\section{Losses bioenergy (regional)}")
swlatex(swout,"\\subsection{Tables}")
loss_bioen<-losses_bioenergy(fulldata,"p")
getNames(loss_bioen)<-"loss_bioen"
swtable(swout,loss_bioen,caption="loss_bioen",transpose=FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,loss_bioen,legend=TRUE,fig.orientation="landscape",tex_caption="loss_bioen")
swlatex(swout,"\\newpage")
```

```

### Berechnung losses slaughterwaste ###

swlatex(swout,"\\section{Losses Slaughterwaste (regional)}")
swlatex(swout,"\\subsection{Tables}")
loss_slw<-losses_slwaste(fulldata, "p")
getNames(loss_slw)<-"loss_slw"
swtable(swout,loss_slw,caption="loss_slw",transpose=FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,loss_slw,legend=TRUE,fig.orientation="landscape",tex_caption="loss_slw")
swlatex(swout,"\\newpage")

swclose(swout,clean_output=FALSE) # erhält alle zwischendateien

# Berechnung Losses Conversion Byproducts #

swlatex(swout,"\\section{Losses Convby (regional)}")
swlatex(swout,"\\subsection{Tables}")
loss_Convby<-losses_convby(fulldata, "p")
getNames(loss_Convby)<-"loss_Convby"
swtable(swout,loss_Convby,caption="loss_Convby",transpose=FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,loss_Convby,legend=TRUE,fig.orientation="landscape",tex_caption="loss_Convby")
swlatex(swout,"\\newpage")

swclose(swout,clean_output=FALSE) # erhält alle zwischendateien

# Berechnung losses Gesamt #

# losses sum #

swlatex(swout,"\\section{Losses Total (regional)}")
swlatex(swout,"\\subsection{Tables}")
loss_ges<-dimSums(losses(fulldata,"p"),dim=1)
getNames(loss_ges)<-"Losses Gesamt"
swtable(swout,loss_ges,caption="Losses Gesamt",transpose=TRUE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,loss_ges,legend=TRUE,fig.orientation="landscape",tex_caption="Losses Gesamt")
swlatex(swout,"\\newpage")

# losses total sum #

swlatex(swout,"\\section{Losses Total sum (global)}")
swlatex(swout,"\\subsection{Tables}")
loss_ges_sum<-dimSums(losses(fulldata,"p"),dim=c(1,3))
getNames(loss_ges_sum)<-"Losses Gesamt Sum"
swtable(swout,loss_ges_sum,caption="Losses Gesamt Sum",transpose=FALSE)
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,loss_ges_sum,legend=TRUE,fig.orientation="landscape",tex_caption="Losses Gesamt Sum")
swlatex(swout,"\\newpage")

# Berechnung der Animal Bilanzen #

animbdgt<-livestock_budget(gdx)

swlatex(swout,"\\section{Animal Budgets}")
swlatex(swout,"\\subsection{Tables}")
animbudget_sum<-dimSums(livestock_budget(fulldata,"p"),dim=1)
swtable(swout,animbudget_sum,caption="Animal Budget",transpose=TRUE)
```

```
swlatex(swout,"\\subsection{Figures}")
swfigure(swout,scratch_plot,animbudget_sum,legend=TRUE,
fig.orientation="landscape",tex_caption="Animal Budget")
swlatex(swout,"\\newpage")

### pdf export schließen ###

swclose(swout,clean_output=FALSE) # erhält alle zwischendateien
```

Appendix 4: Model output – Integrated Assessment of Phosphorus Use and Depletion

Integrated Assesment of Phosphorus Use and Depletion

Output (second Run - Default)

Contents

1 P Fertilizer Use

1.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
AFR.1	0.27	1.05	2.31	3.32	6.88	3.98	6.16	7.13
CPA.2	4.03	5.62	4.45	5.26	7.97	4.38	10.09	2.42
EUR.3	2.14	2.46	2.04	2.03	1.79	1.29	1.73	1.55
FSU.4	0.33	0.05	0.82	0.76	1.06	0.18	0.84	0.62
LAM.5	1.10	2.14	2.05	2.99	7.25	1.52	2.12	3.29
MEA.6	0.47	0.69	0.55	0.76	0.99	0.51	0.85	0.31
NAM.7	2.08	3.70	3.45	3.75	3.34	2.15	2.87	2.90
PAO.8	0.87	0.76	0.32	0.31	0.41	0.25	0.19	0.33
PAS.9	0.62	0.85	0.82	0.76	1.09	0.62	0.22	0.59
SAS.10	1.60	2.74	2.89	3.67	5.86	2.84	4.51	4.02

Table 1: p_fertilizer

1.2 Figures

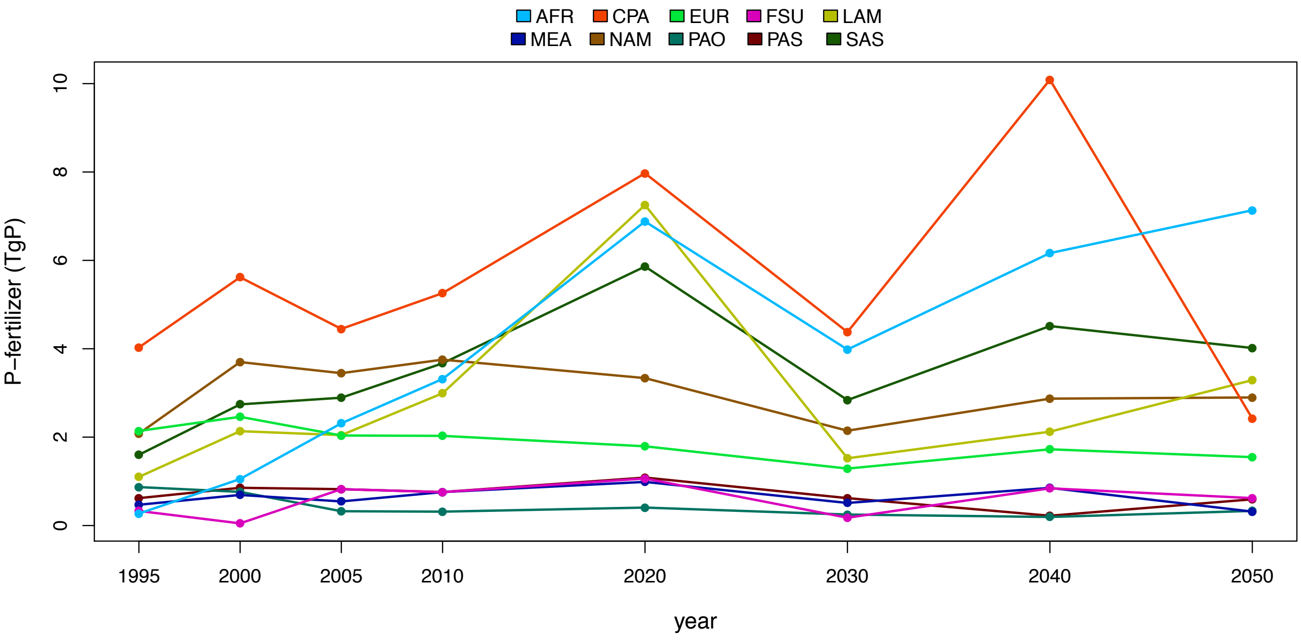

Figure 1: fert_fig

2 P Fertilizer Use global

2.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
GLO.1	13.51	20.06	19.70	23.60	36.64	17.71	29.59	23.17

Table 2: p_fertilizer_glo

2.2 Figures

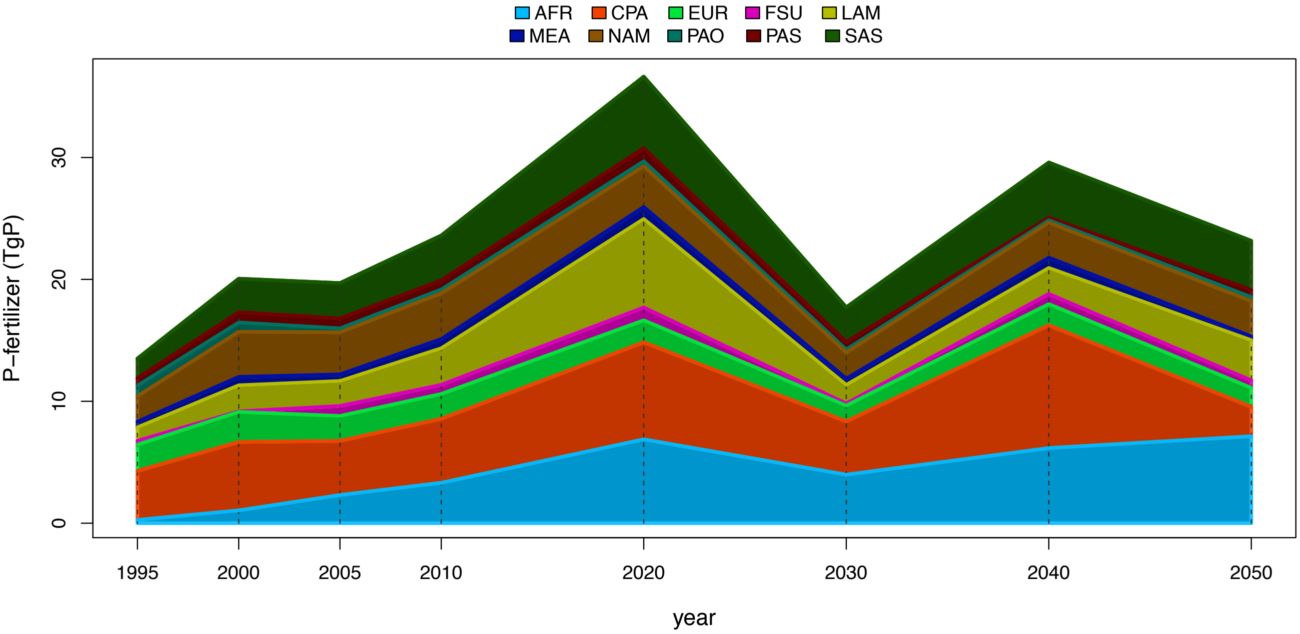

Figure 2: global fertilizer use

3 P in Harvest (global)

3.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
GLO.1	13.05	14.26	15.60	17.40	20.72	23.61	26.36	28.89

Table 3: p_in_harvest_glo

3.2 Figures

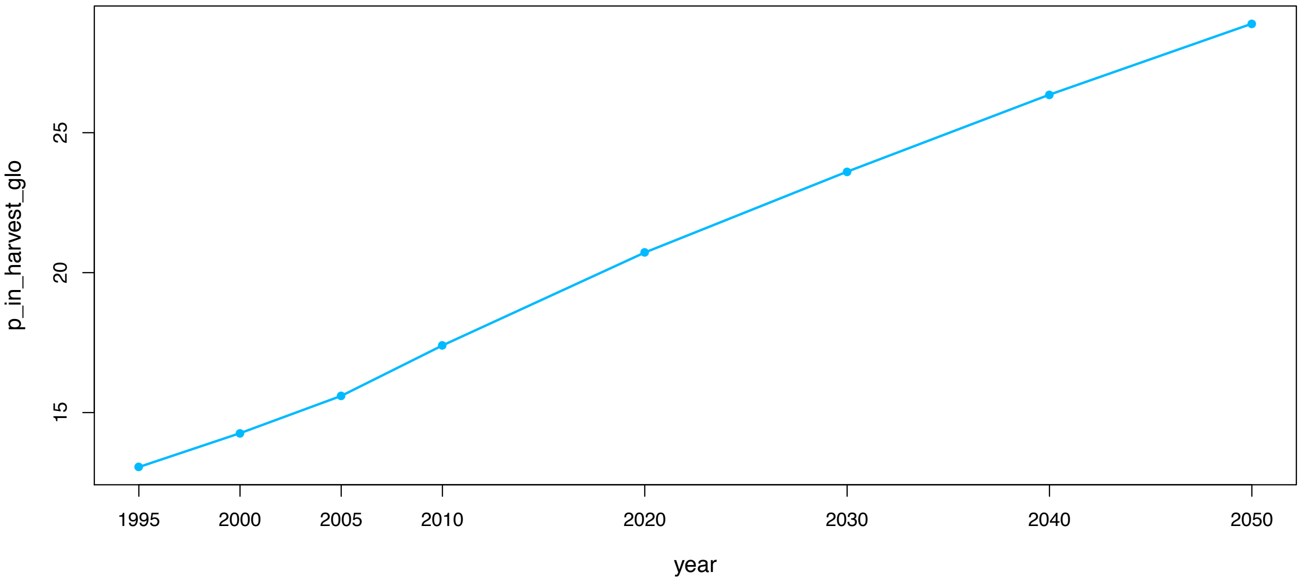

Figure 3: p_in_harvest

4 P in Harvest (regions)

4.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
AFR.1	0.61	0.72	0.95	1.27	2.04	2.85	3.65	4.70
CPA.2	2.34	2.68	2.99	3.46	4.37	5.17	6.34	6.67
EUR.3	2.16	2.24	2.31	2.39	2.42	2.41	2.43	2.41
FSU.4	1.05	1.00	1.08	1.13	1.23	1.23	1.23	1.25
LAM.5	1.16	1.33	1.47	1.69	2.28	2.85	3.24	3.90
MEA.6	0.38	0.43	0.48	0.57	0.68	0.80	0.92	0.97
NAM.7	2.78	3.06	3.27	3.49	3.57	3.56	3.53	3.55
PAO.8	0.42	0.42	0.43	0.45	0.48	0.51	0.50	0.50
PAS.9	0.53	0.58	0.63	0.67	0.77	0.87	0.84	0.85
SAS.10	1.62	1.80	1.98	2.28	2.86	3.36	3.69	4.08

Table 4: p_in_harvets_reg

4.2 Figures

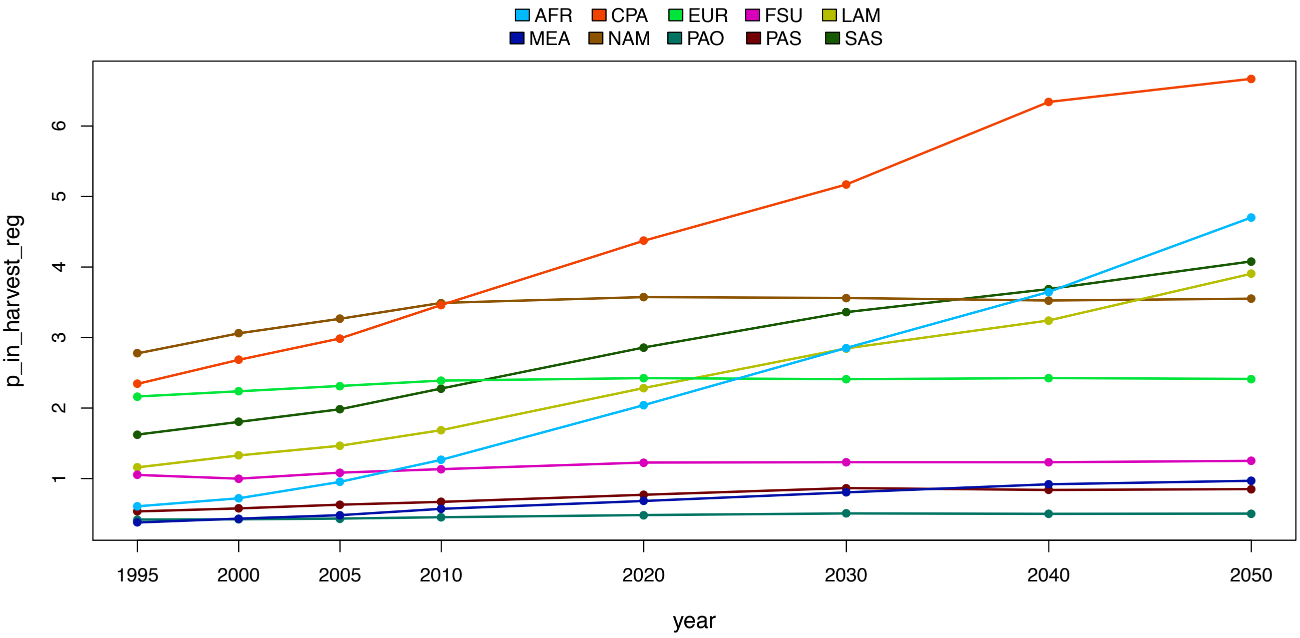

Figure 4: p_in_harvest_reg

5 P in use total (global)

5.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
GLO.1	13.04	14.26	15.59	17.40	20.72	23.61	26.36	28.89

Table 5: p_in_use_glo_tot

5.2 Figures

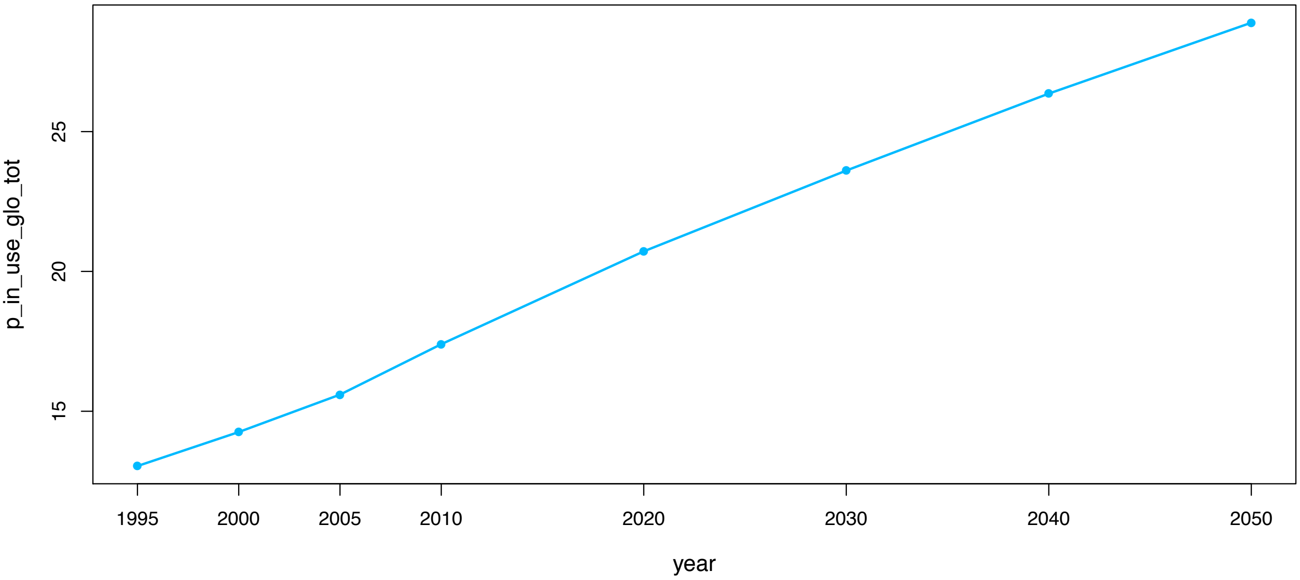

Figure 5: p_in_use_glo_tot

6 P in Use (global)

6.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
food	6.27	6.79	7.30	7.76	8.69	9.56	10.33	10.97
material	1.44	1.57	1.70	1.83	2.09	2.33	2.51	2.66
feed	4.90	5.33	5.84	6.81	8.85	10.77	12.40	13.63
bioenergy	0.01	0.13	0.27	0.45	0.42	0.18	0.25	0.69
seed	0.42	0.45	0.49	0.55	0.67	0.77	0.86	0.94

Table 6: p_in_use_glo

6.2 Figures

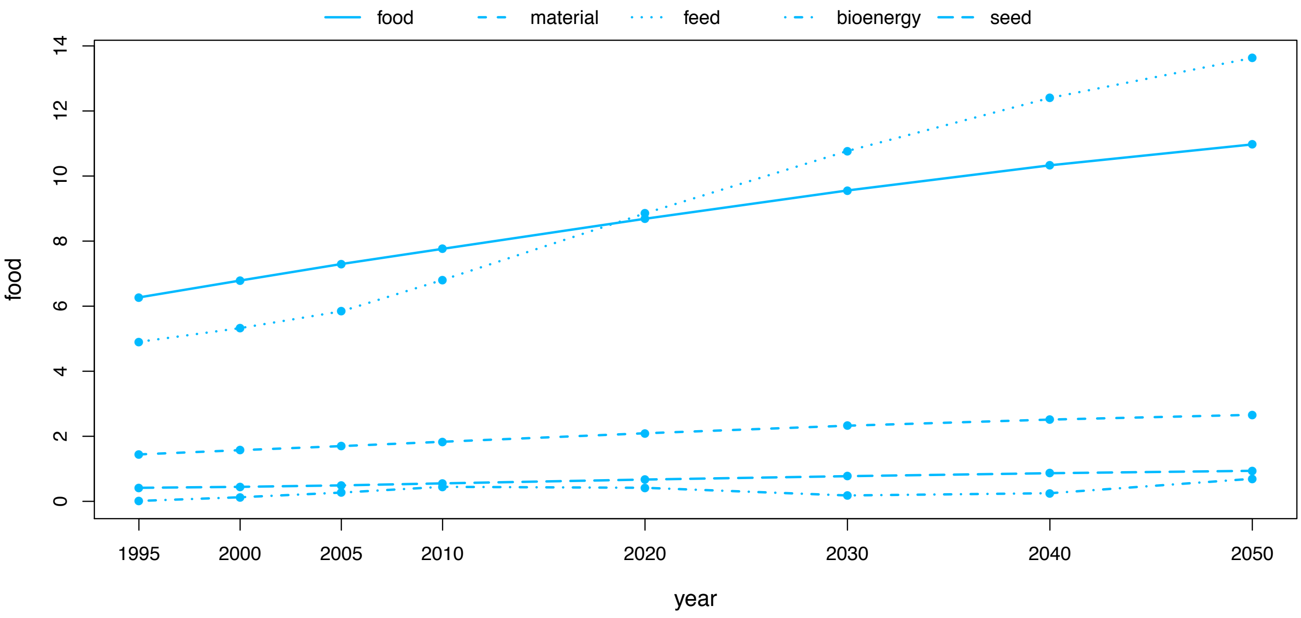

Figure 6: p_in_use_glo

7 P in Use (regional)

7.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
AFR.1	0.66	0.77	0.93	1.12	1.60	2.21	2.93	3.85
CPA.2	2.44	2.80	3.13	3.70	4.77	5.40	6.00	6.38
EUR.3	2.18	2.27	2.36	2.45	2.49	2.42	2.46	2.38
FSU.4	1.17	1.06	1.16	1.20	1.27	1.30	1.27	1.18
LAM.5	1.07	1.23	1.37	1.57	2.14	2.81	3.46	4.03
MEA.6	0.68	0.78	0.87	1.02	1.22	1.46	1.66	1.83
NAM.7	2.05	2.30	2.45	2.58	2.51	2.33	2.31	2.28
PAO.8	0.50	0.50	0.51	0.53	0.55	0.57	0.56	0.56
PAS.9	0.64	0.70	0.78	0.87	1.14	1.44	1.46	1.63
SAS.10	1.65	1.84	2.04	2.38	3.03	3.68	4.25	4.79

Table 7: p_in_use_reg

7.2 Figures

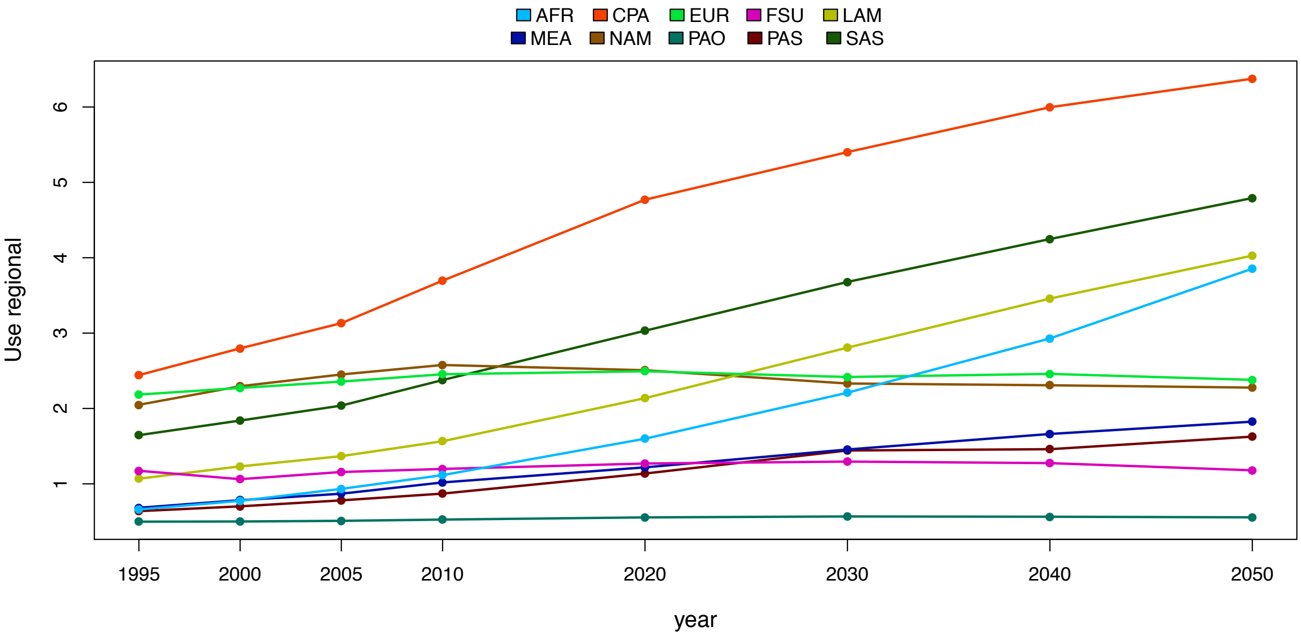

Figure 7: p_in_use_reg

8 Feed Total (global supply)

8.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
concentrate	2.83	3.18	3.58	4.41	6.15	7.70	8.95	9.72
fodder	2.08	2.14	2.26	2.40	2.70	3.07	3.45	3.91
pasture	12.33	13.68	14.88	16.65	19.36	21.30	22.18	22.40
residues	1.76	1.98	2.21	2.55	2.98	3.30	3.59	3.53
convby	2.07	2.29	2.49	2.67	3.03	3.36	3.64	3.86
scavenging	1.27	1.56	1.87	2.43	3.02	3.17	3.00	2.74

Table 8: Feed_supply

8.2 Figures

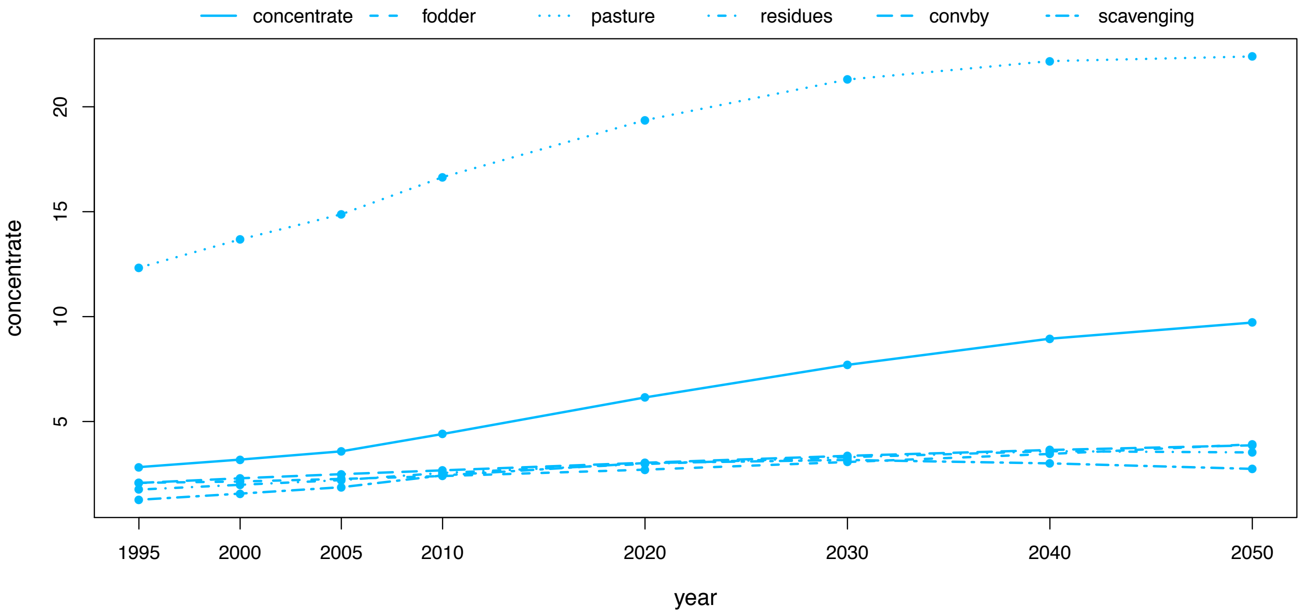

Figure 8: Feed_supply

9 Feed Total (global)

9.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
GLO.1	22.33	24.84	27.28	31.10	37.24	41.90	44.81	46.16

Table 9: Feed

9.2 Figures

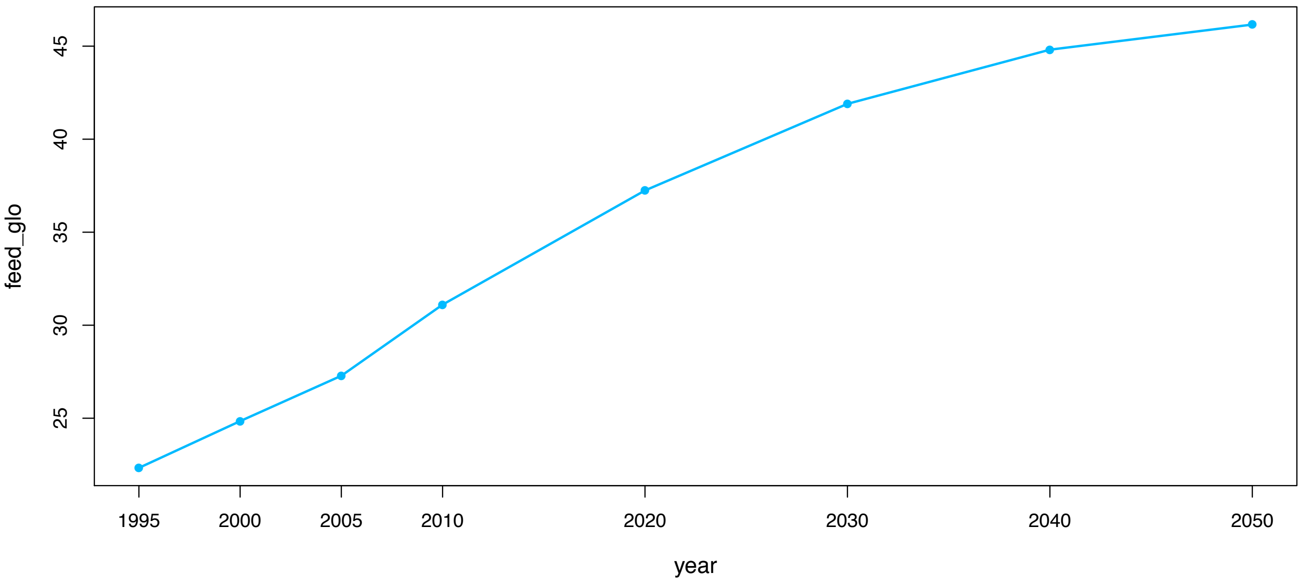

Figure 9: Feed

10 Feed Total (regional)

10.1 Tables

	AFR.1	CPA.2	EUR.3	FSU.4	LAM.5	MEA.6	NAM.7	PAO.8	PAS.9	SAS.10
y1995	2.25	2.24	2.93	1.57	4.60	0.63	2.26	0.98	0.57	4.29
y2000	2.50	2.83	2.97	1.37	5.15	0.74	2.42	0.98	0.62	5.26
y2005	2.87	3.27	2.99	1.48	5.34	0.82	2.53	0.99	0.68	6.30
y2010	3.24	4.16	3.01	1.52	5.72	0.96	2.52	1.01	0.77	8.20
y2020	4.09	5.59	3.01	1.61	6.60	1.14	2.39	1.02	1.06	10.72
y2030	5.21	6.11	2.95	1.64	7.79	1.36	2.25	1.01	1.38	12.19
y2040	6.45	6.39	2.79	1.62	8.66	1.54	2.03	0.97	1.35	13.01
y2050	7.48	6.70	2.58	1.44	8.61	1.65	1.80	0.92	1.49	13.50

Table 10: Feed_reg

10.2 Figures

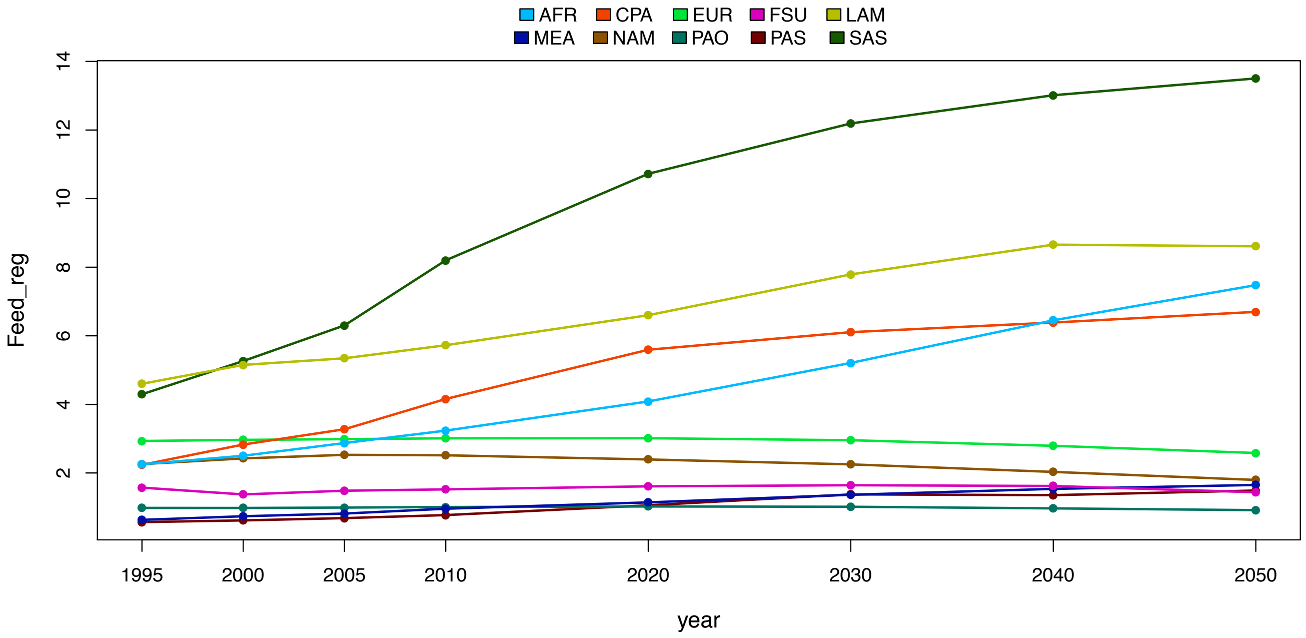

Figure 10: Feed_reg

11 P in aboveground residues (global)

11.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
GLO.1	6.60	7.05	7.58	8.38	10.31	11.69	12.23	12.54

Table 11: p_in_ag_res_glo

11.2 Figures

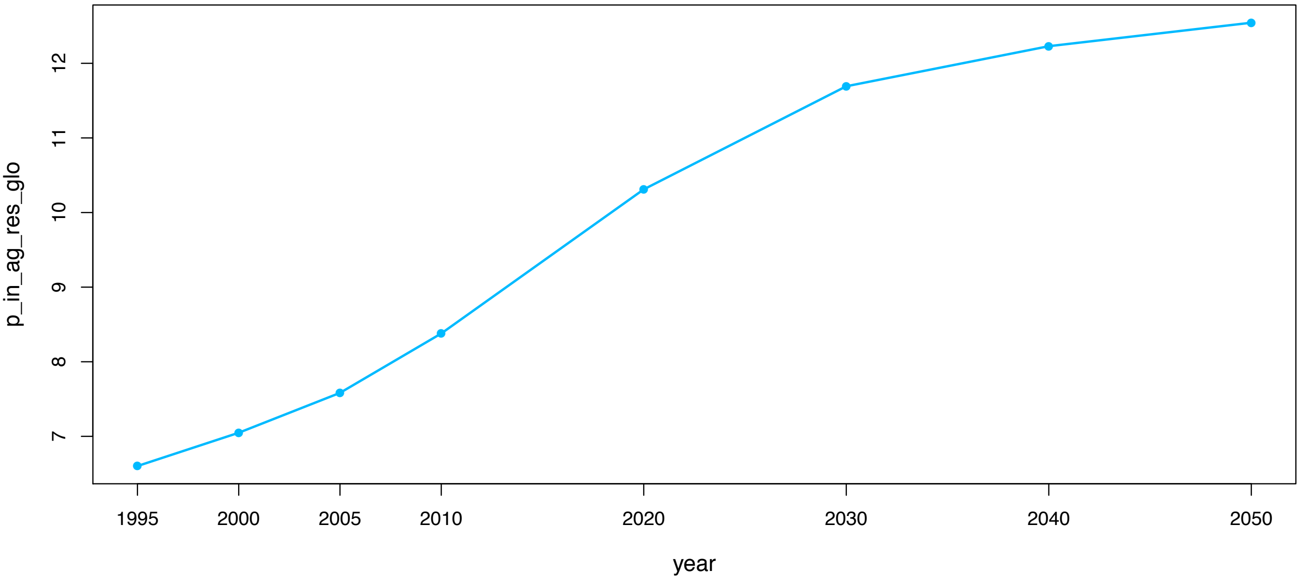

Figure 11: p_in_ag_res_glo

12 P in aboveground residues (regions)

12.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
AFR.1	0.50	0.56	0.68	0.86	1.29	1.73	2.00	2.33
CPA.2	1.03	1.13	1.22	1.35	1.62	1.94	2.43	2.58
EUR.3	0.86	0.89	0.92	0.95	0.96	0.96	0.94	0.94
FSU.4	0.49	0.46	0.49	0.50	0.53	0.51	0.52	0.52
LAM.5	0.89	0.98	1.06	1.27	2.06	2.42	2.09	1.75
MEA.6	0.18	0.19	0.20	0.23	0.27	0.30	0.33	0.34
NAM.7	1.03	1.12	1.19	1.27	1.34	1.38	1.39	1.42
PAO.8	0.17	0.17	0.18	0.18	0.20	0.21	0.21	0.22
PAS.9	0.37	0.39	0.40	0.42	0.45	0.49	0.48	0.48
SAS.10	1.08	1.17	1.24	1.34	1.59	1.73	1.85	1.97

Table 12: p_in_ag_res_reg

12.2 Figures

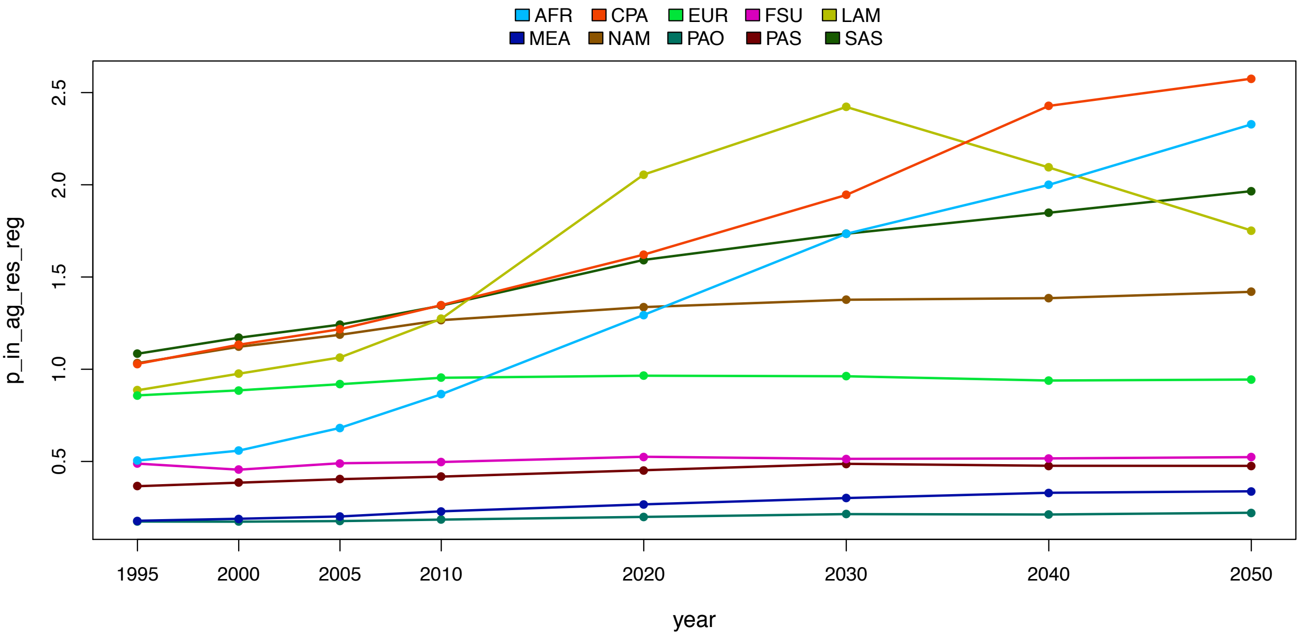

Figure 12: p_in_ag_res_reg

13 P in Ag_res_Use nach Verwendungen (global)

13.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
other	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
recycle	3.05	3.17	3.37	3.68	4.83	5.73	6.05	6.53
feed	1.76	1.98	2.21	2.55	2.98	3.30	3.59	3.53
burn	1.40	1.48	1.57	1.70	2.02	2.21	2.22	2.18
bioenergy	0.40	0.42	0.43	0.44	0.48	0.45	0.38	0.30

Table 13: p_in_ag_res_use_glo

13.2 Figures

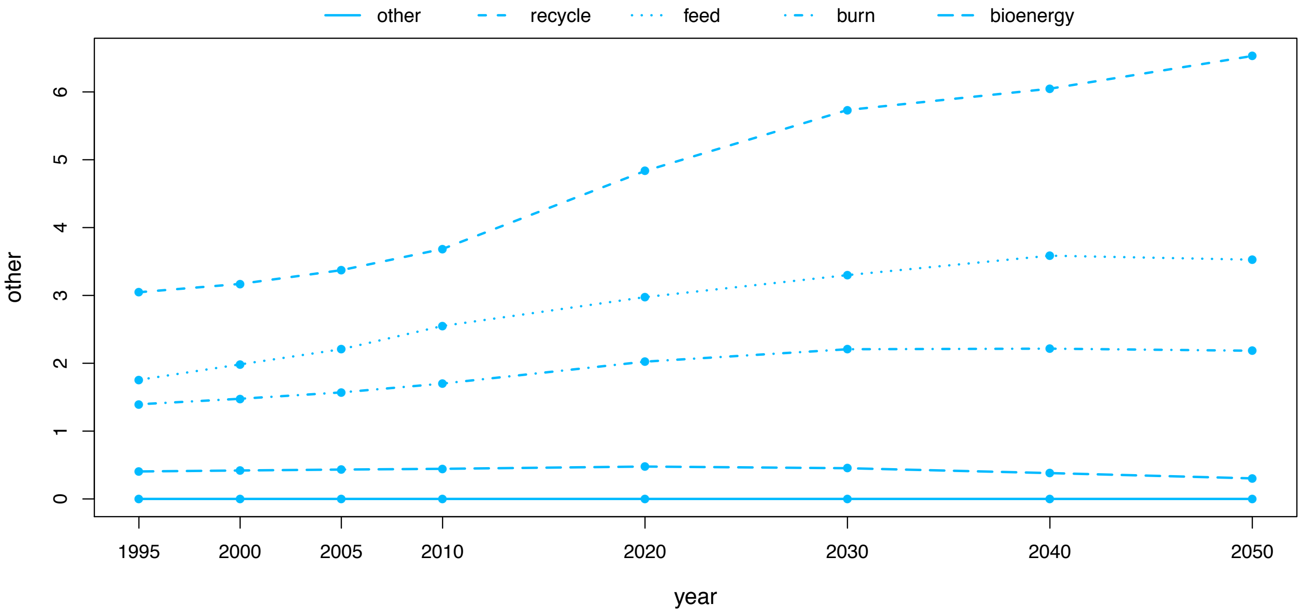

Figure 13: p_in_ag_res_use_glo

14 P in Convby Use Total (global)

14.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
GLO.1	2.59	2.81	3.01	3.19	3.55	3.88	4.16	4.38

Table 14: p_in_convby_use_glo_ges

14.2 Figures

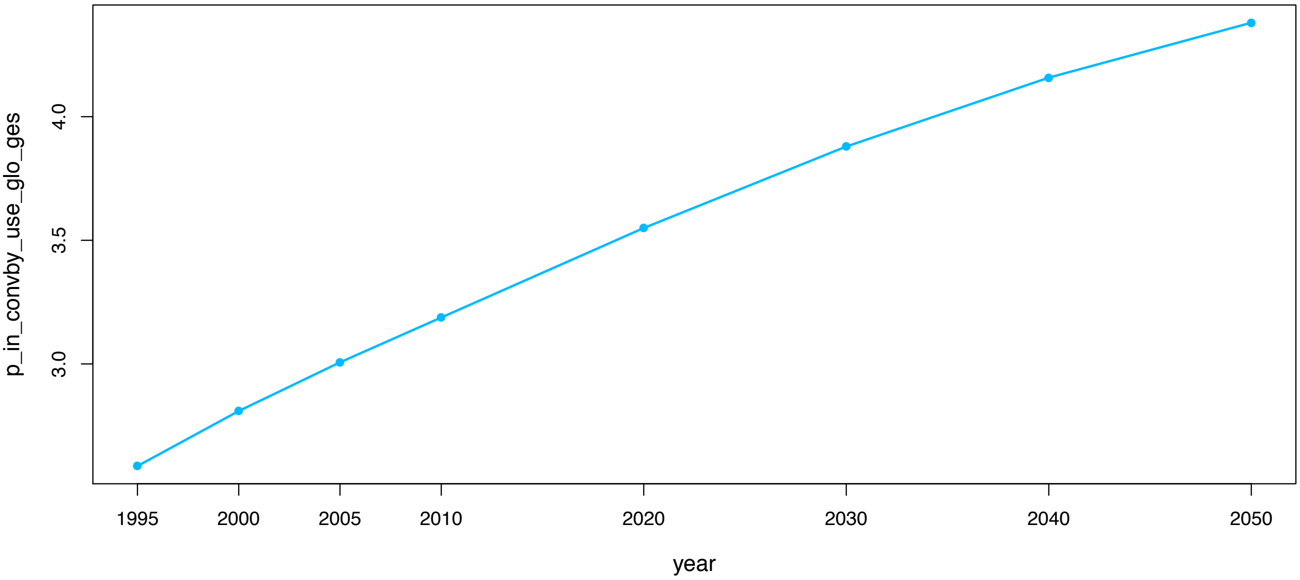

Figure 14: p_in_convby_use_glo_ges

15 P in Convby Use Total (regional)

15.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
AFR.1	0.08	0.10	0.11	0.13	0.13	0.15	0.20	0.16
CPA.2	0.50	0.53	0.56	0.60	0.64	0.68	0.71	0.73
EUR.3	0.56	0.57	0.57	0.57	0.55	0.54	0.46	0.45
FSU.4	0.11	0.11	0.13	0.13	0.14	0.15	0.16	0.17
LAM.5	0.27	0.32	0.37	0.40	0.51	0.60	0.71	0.79
MEA.6	0.09	0.11	0.12	0.14	0.17	0.20	0.24	0.27
NAM.7	0.35	0.39	0.41	0.43	0.43	0.42	0.40	0.37
PAO.8	0.09	0.10	0.09	0.10	0.11	0.12	0.13	0.14
PAS.9	0.20	0.22	0.24	0.26	0.31	0.35	0.38	0.41
SAS.10	0.32	0.36	0.40	0.43	0.55	0.66	0.78	0.89

Table 15: p_in_convby_use_reg_ges

15.2 Figures

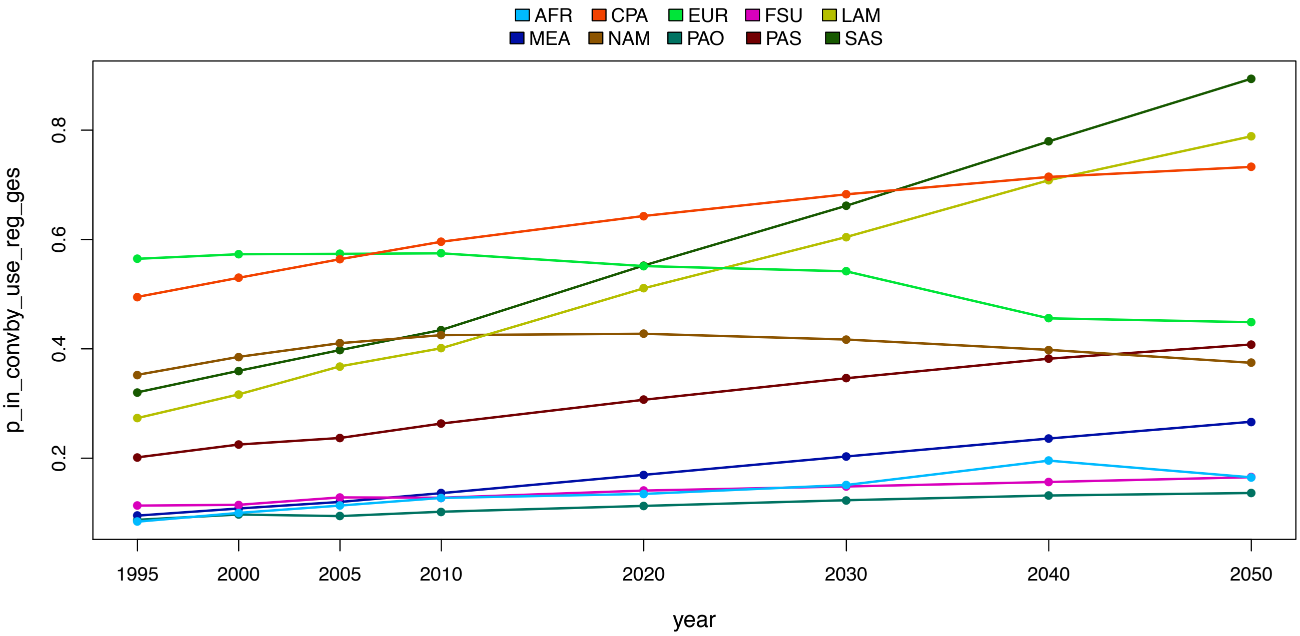

Figure 15: p_in_convby_use_reg_ges

16 P in Convby Use nach Verwendungen (global)

16.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
feed	2.07	2.29	2.49	2.67	3.03	3.36	3.64	3.86
waste	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
processing	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21
food	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19
other_util	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11

Table 16: p_in_convby_use_glo

16.2 Figures

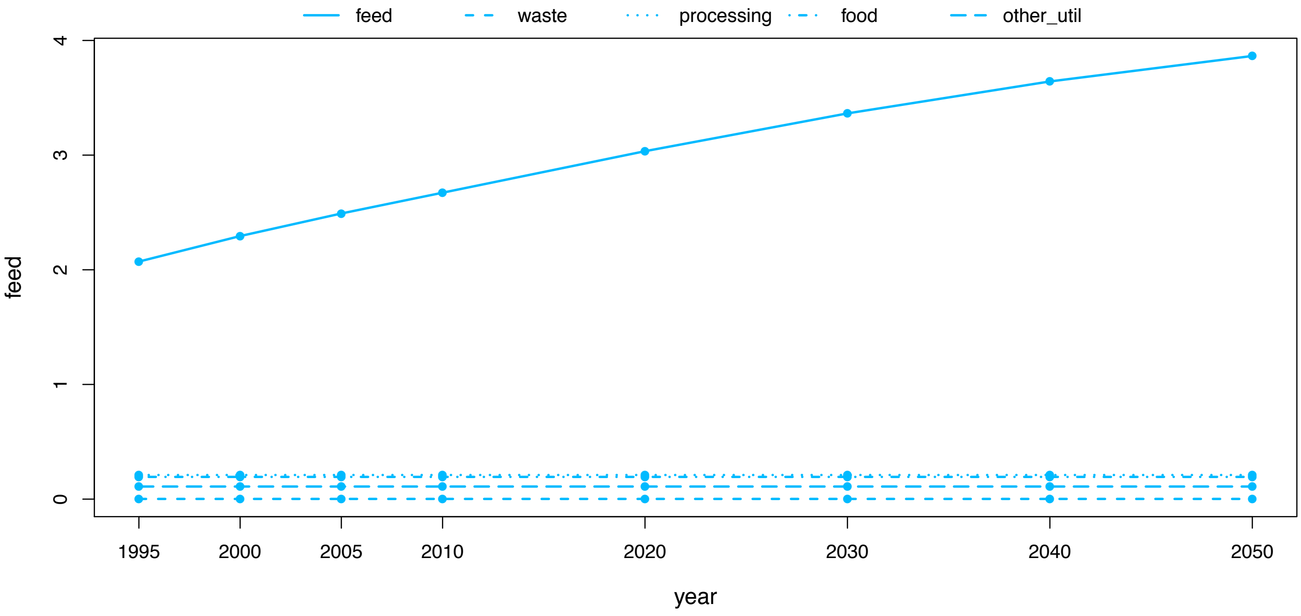

Figure 16: p_in_convby_use_glo

17 P in Convby Use Total (regional)

17.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
AFR.1	0.08	0.10	0.11	0.13	0.13	0.15	0.20	0.16
CPA.2	0.50	0.53	0.56	0.60	0.64	0.68	0.71	0.73
EUR.3	0.56	0.57	0.57	0.57	0.55	0.54	0.46	0.45
FSU.4	0.11	0.11	0.13	0.13	0.14	0.15	0.16	0.17
LAM.5	0.27	0.32	0.37	0.40	0.51	0.60	0.71	0.79
MEA.6	0.09	0.11	0.12	0.14	0.17	0.20	0.24	0.27
NAM.7	0.35	0.39	0.41	0.43	0.43	0.42	0.40	0.37
PAO.8	0.09	0.10	0.09	0.10	0.11	0.12	0.13	0.14
PAS.9	0.20	0.22	0.24	0.26	0.31	0.35	0.38	0.41
SAS.10	0.32	0.36	0.40	0.43	0.55	0.66	0.78	0.89

Table 17: p_in_convby_supply

17.2 Figures

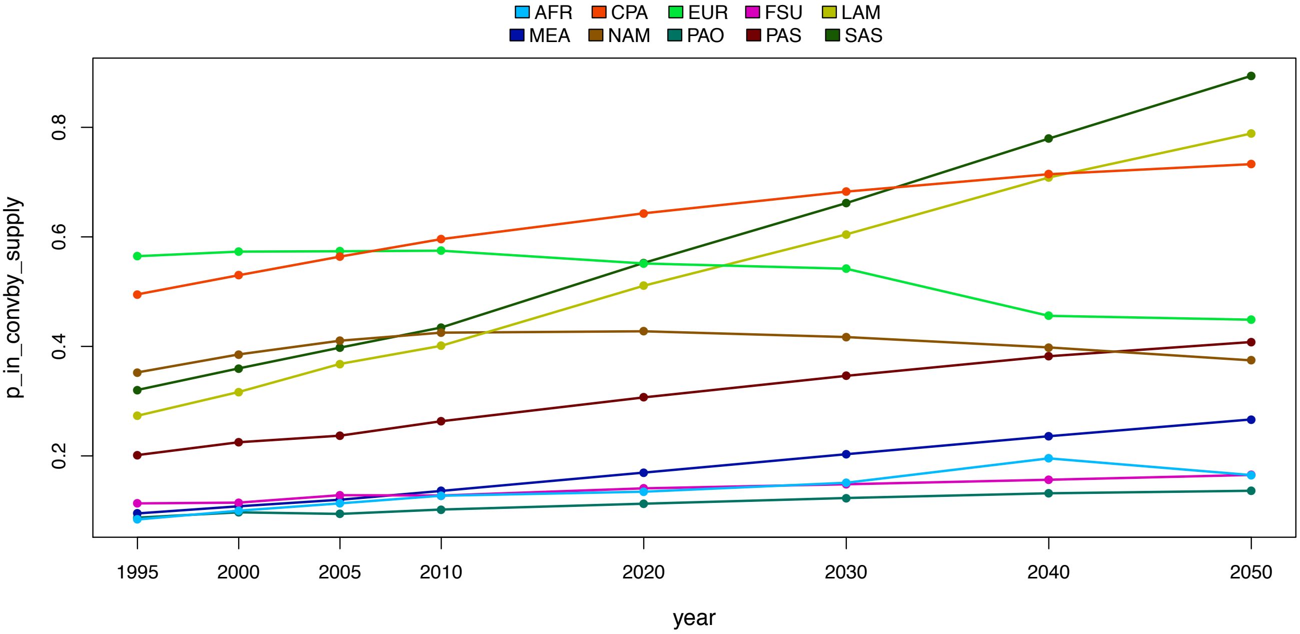

Figure 17: p_in_convby_supply

18 P in produzierten Convby_products (global)

18.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
GLO.1	2.59	2.81	3.01	3.19	3.55	3.88	4.16	4.38

Table 18: p_in_convby_prod_glo

18.2 Figures

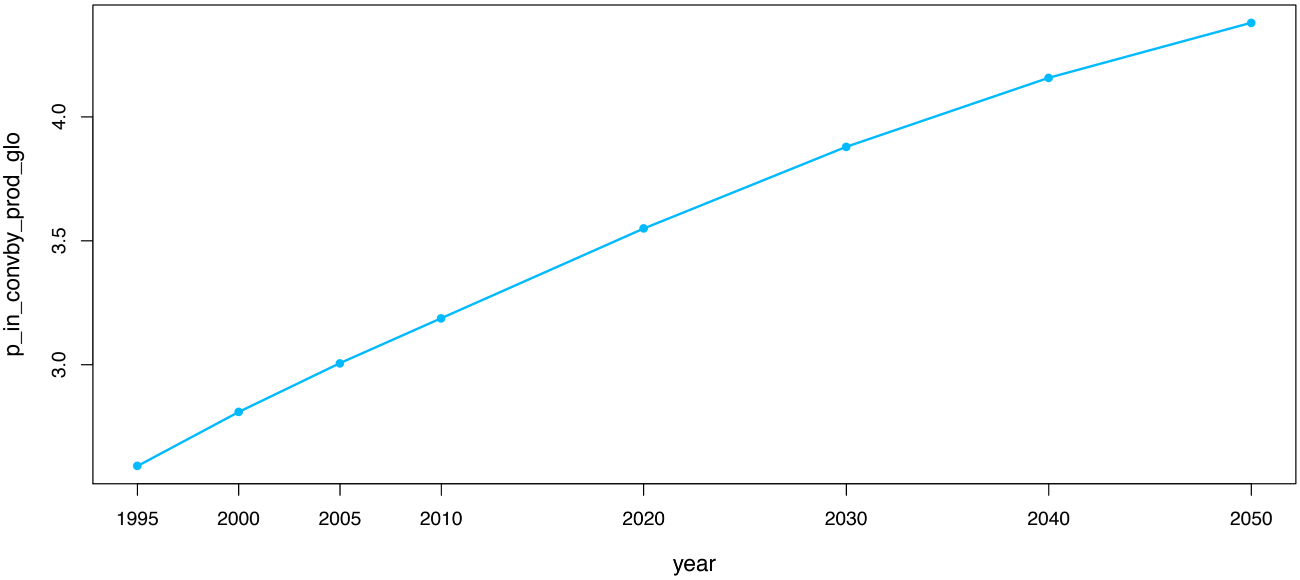

Figure 18: p_in_convby_prod_glo

19 P in produzierten Convby_products (regional)

19.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
AFR.1	0.09	0.10	0.12	0.14	0.18	0.23	0.28	0.32
CPA.2	0.49	0.51	0.54	0.56	0.57	0.58	0.57	0.56
EUR.3	0.36	0.38	0.40	0.41	0.44	0.47	0.49	0.51
FSU.4	0.11	0.11	0.12	0.12	0.13	0.13	0.13	0.13
LAM.5	0.43	0.47	0.52	0.55	0.62	0.67	0.72	0.75
MEA.6	0.07	0.08	0.09	0.10	0.12	0.14	0.15	0.16
NAM.7	0.40	0.45	0.47	0.50	0.57	0.63	0.69	0.74
PAO.8	0.08	0.08	0.08	0.08	0.09	0.09	0.10	0.10
PAS.9	0.18	0.20	0.22	0.24	0.27	0.29	0.31	0.32
SAS.10	0.37	0.41	0.44	0.48	0.57	0.65	0.72	0.78

Table 19: p_in_convby_prod_reg

19.2 Figures

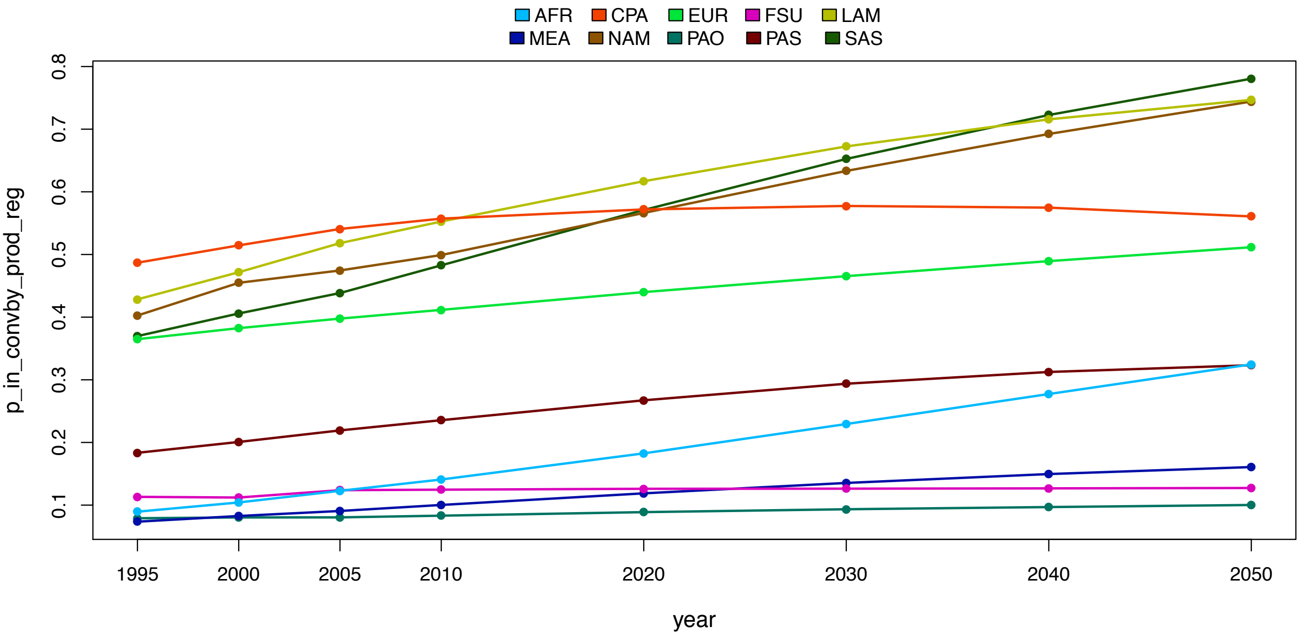

Figure 19: p_in_convby_prod_reg

20 P in vegetal products total (gobal)

20.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
GLO.1	6.27	6.79	7.30	7.76	8.69	9.56	10.33	10.97

Table 20: p_in_vegt_prod_glo_tot

20.2 Figures

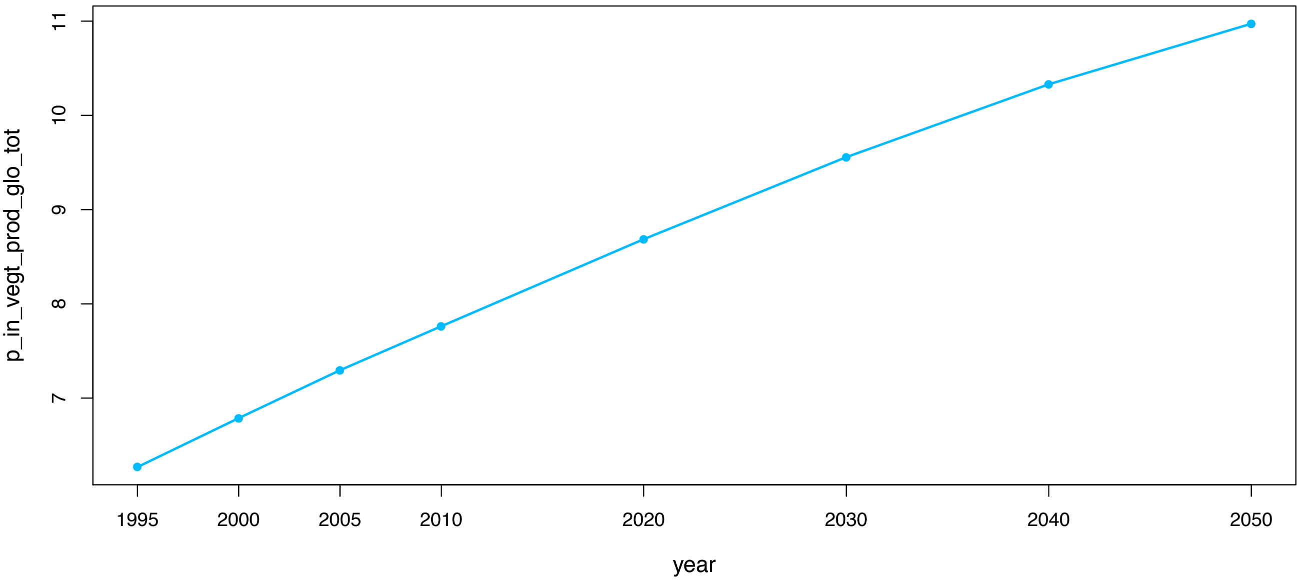

Figure 20: p_in_vegt_prod_glo_tot

21 P in vegetal products total (regional)

21.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
AFR.1	0.47	0.55	0.65	0.75	0.97	1.21	1.45	1.69
CPA.2	1.48	1.55	1.62	1.65	1.65	1.64	1.63	1.60
EUR.3	0.72	0.75	0.78	0.81	0.87	0.92	0.98	1.02
FSU.4	0.29	0.29	0.32	0.32	0.32	0.32	0.32	0.32
LAM.5	0.53	0.58	0.63	0.68	0.75	0.82	0.87	0.90
MEA.6	0.41	0.46	0.51	0.56	0.66	0.75	0.83	0.88
NAM.7	0.51	0.57	0.60	0.63	0.72	0.81	0.90	0.97
PAO.8	0.17	0.17	0.17	0.17	0.19	0.20	0.20	0.21
PAS.9	0.45	0.50	0.54	0.58	0.66	0.72	0.76	0.79
SAS.10	1.24	1.36	1.47	1.61	1.90	2.16	2.39	2.57

Table 21: p_in_vegt_prod_reg

21.2 Figures

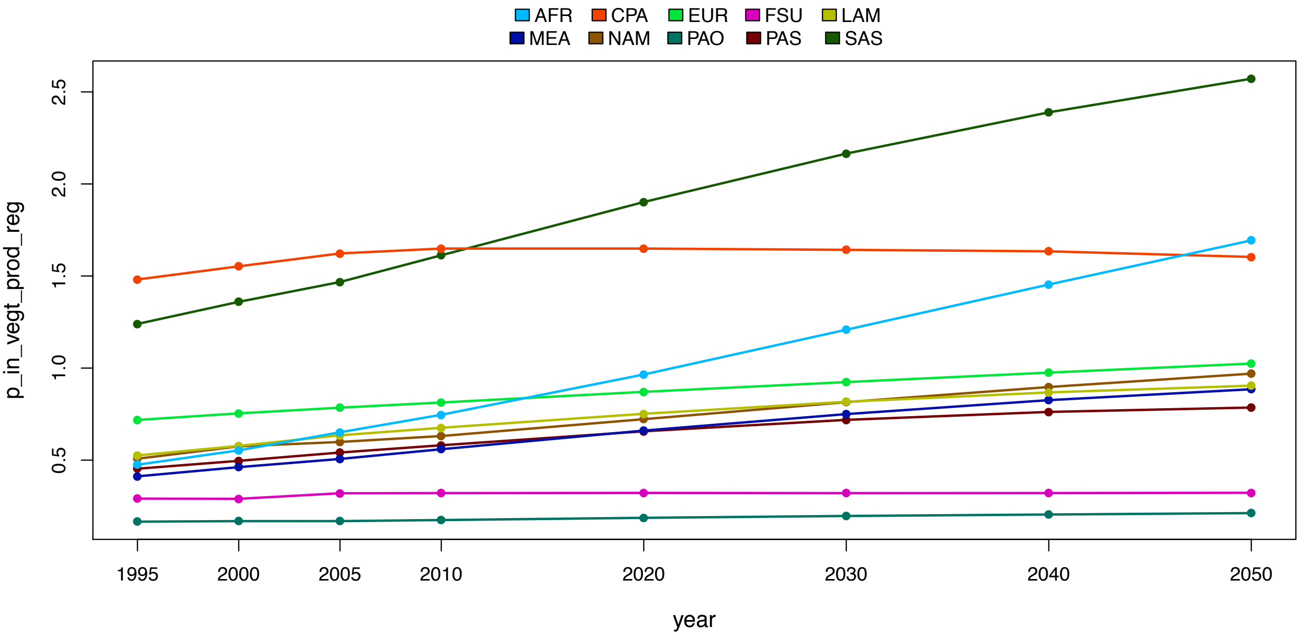

Figure 21: p_in_vegt_prod_reg

22 P in Livestock products total (gobal)

22.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
GLO.1	1.79	2.00	2.20	2.56	3.25	3.84	4.29	4.63

Table 22: p_in_livst_prod_glo_tot

22.2 Figures

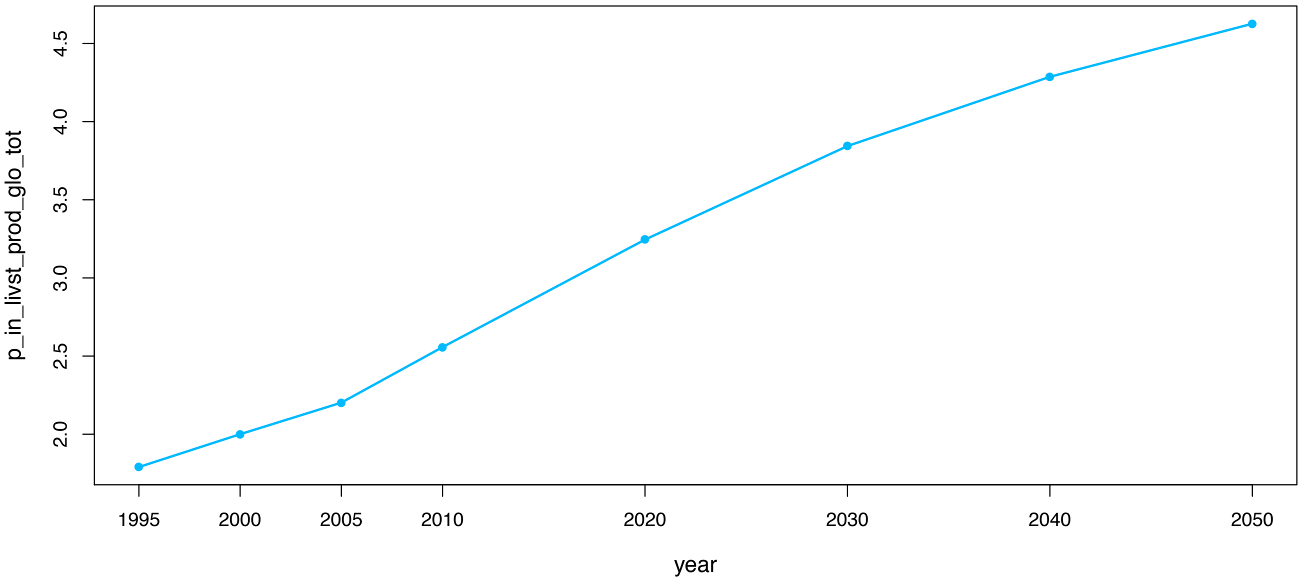

Figure 22: p_in_livst_prod_glo_tot

23 P in livestock products total (regional)

23.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
AFR.1	0.07	0.08	0.10	0.13	0.20	0.32	0.48	0.69
CPA.2	0.33	0.42	0.50	0.66	0.96	1.12	1.11	1.02
EUR.3	0.40	0.41	0.42	0.43	0.44	0.44	0.43	0.40
FSU.4	0.13	0.12	0.13	0.14	0.17	0.19	0.19	0.19
LAM.5	0.23	0.27	0.29	0.33	0.41	0.48	0.53	0.57
MEA.6	0.07	0.08	0.09	0.11	0.15	0.21	0.26	0.30
NAM.7	0.29	0.32	0.34	0.35	0.34	0.33	0.32	0.30
PAO.8	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.06
PAS.9	0.07	0.07	0.08	0.10	0.15	0.20	0.25	0.30
SAS.10	0.14	0.16	0.19	0.24	0.35	0.49	0.64	0.79

Table 23: p_in_livst_prod_reg

23.2 Figures

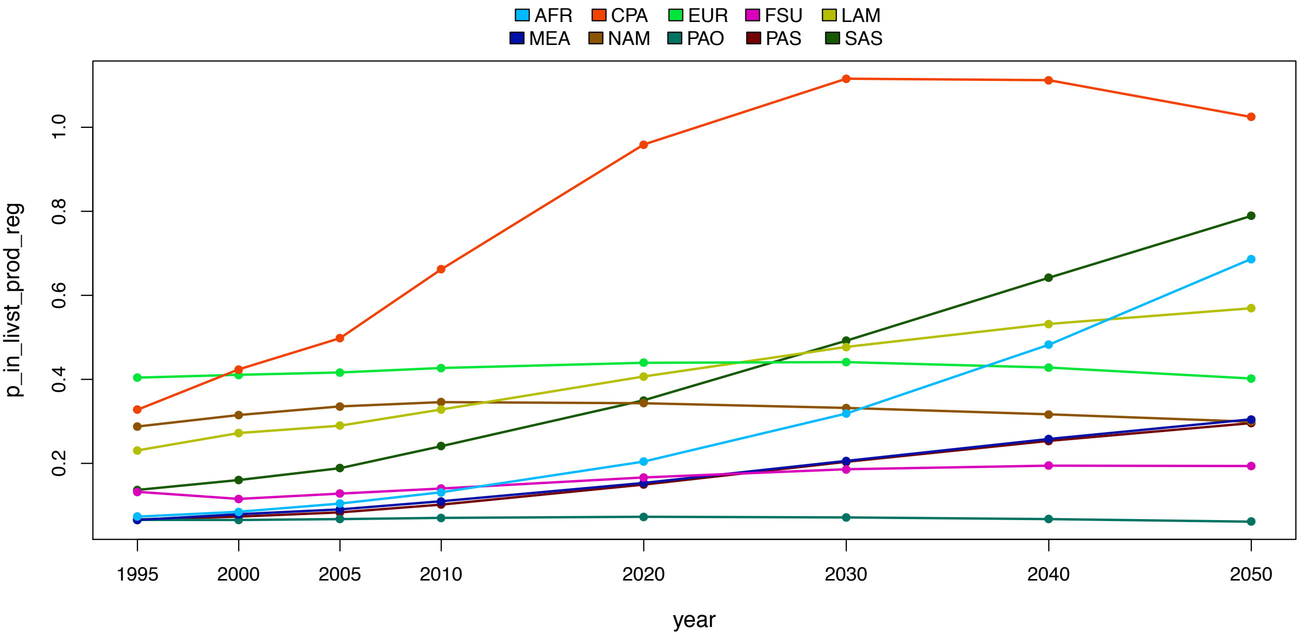

Figure 23: p_in_livst_prod_reg

24 P in Manure Total (global)

24.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
GLO.1	19.75	21.98	24.14	27.48	32.69	36.53	38.83	39.72

Table 24: p_in_manure_glo_tot

24.2 Figures

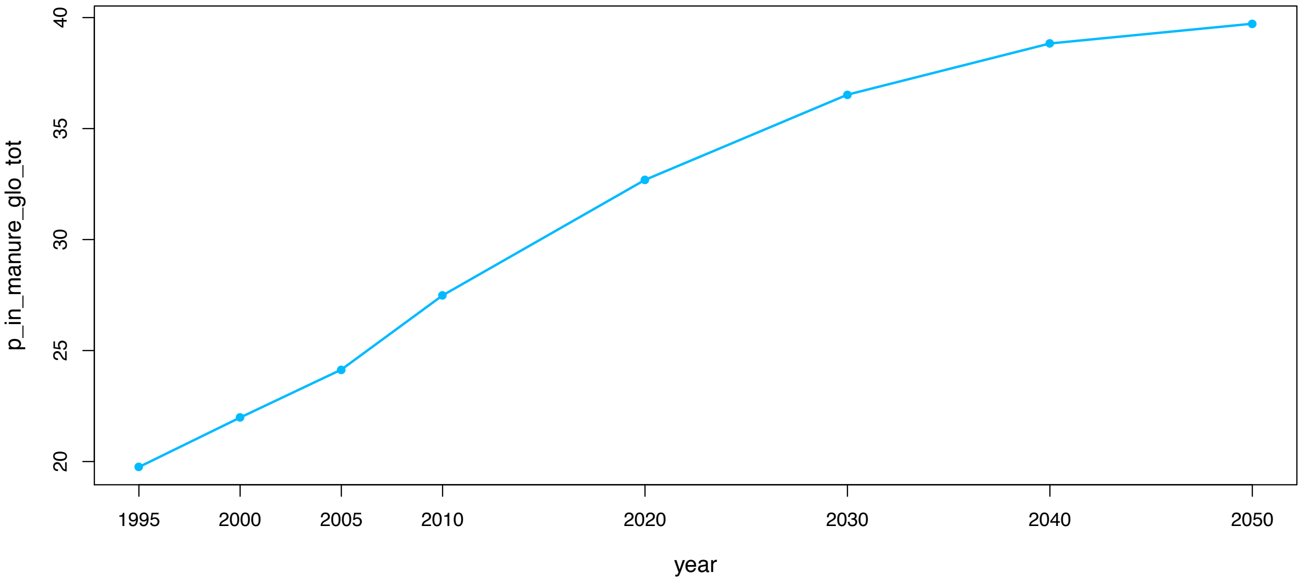

Figure 24: p_in_manure_glo_tot

25 P in Manure in different use (global)

25.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
grazing_pasture	10.45	11.58	12.59	14.17	16.86	18.90	19.85	20.19
grazing_cropland	0.41	0.44	0.47	0.49	0.46	0.42	0.36	0.27
fuel	2.14	2.54	2.92	3.52	3.82	3.54	3.04	2.46
confinement	6.76	7.42	8.16	9.30	11.55	13.67	15.58	16.79

Table 25: p_in_manure_glo

25.2 Figures

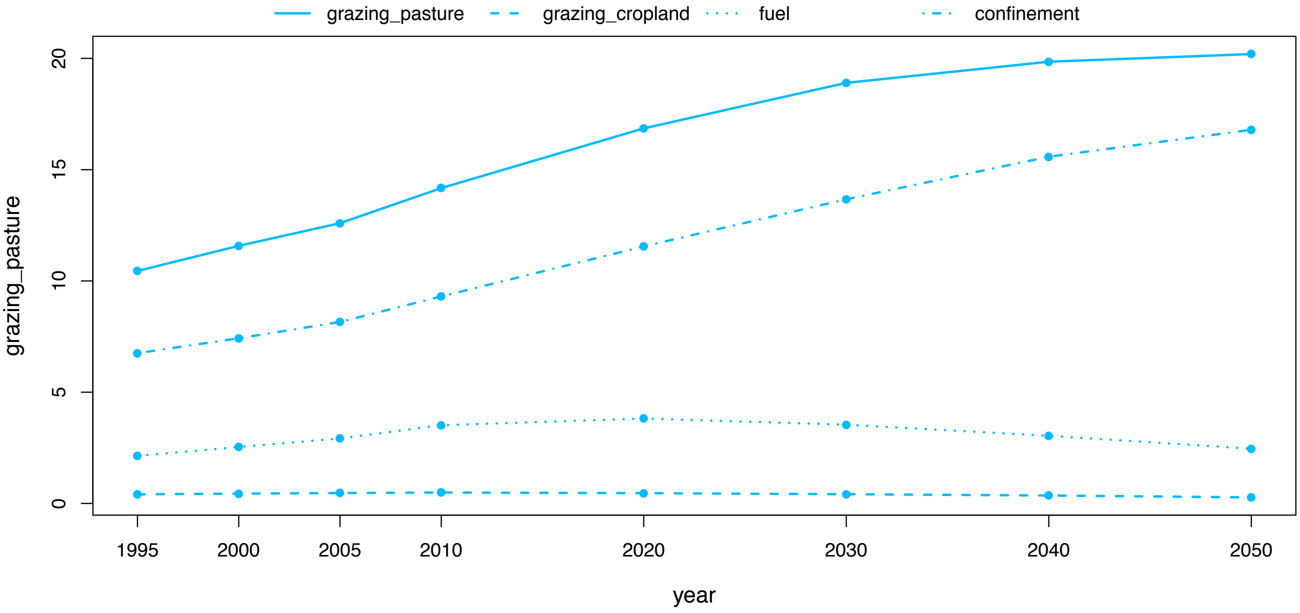

Figure 25: p_in_manure_glo

26 P in manure (regions)

26.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
AFR.1	2.16	2.39	2.74	3.07	3.84	4.85	5.94	6.78
CPA.2	1.82	2.29	2.65	3.34	4.44	4.81	4.93	5.10
EUR.3	2.33	2.35	2.37	2.39	2.39	2.35	2.22	2.06
FSU.4	1.35	1.18	1.27	1.30	1.37	1.39	1.37	1.21
LAM.5	4.26	4.75	4.91	5.22	5.94	6.93	7.65	7.63
MEA.6	0.56	0.65	0.71	0.84	0.98	1.16	1.30	1.39
NAM.7	1.83	1.96	2.04	2.02	1.91	1.79	1.61	1.41
PAO.8	0.87	0.87	0.88	0.89	0.89	0.88	0.83	0.78
PAS.9	0.49	0.52	0.56	0.61	0.78	0.97	1.00	1.07
SAS.10	4.10	5.03	6.01	7.81	10.13	11.39	11.98	12.29

Table 26: p_in_manure_reg

26.2 Figures

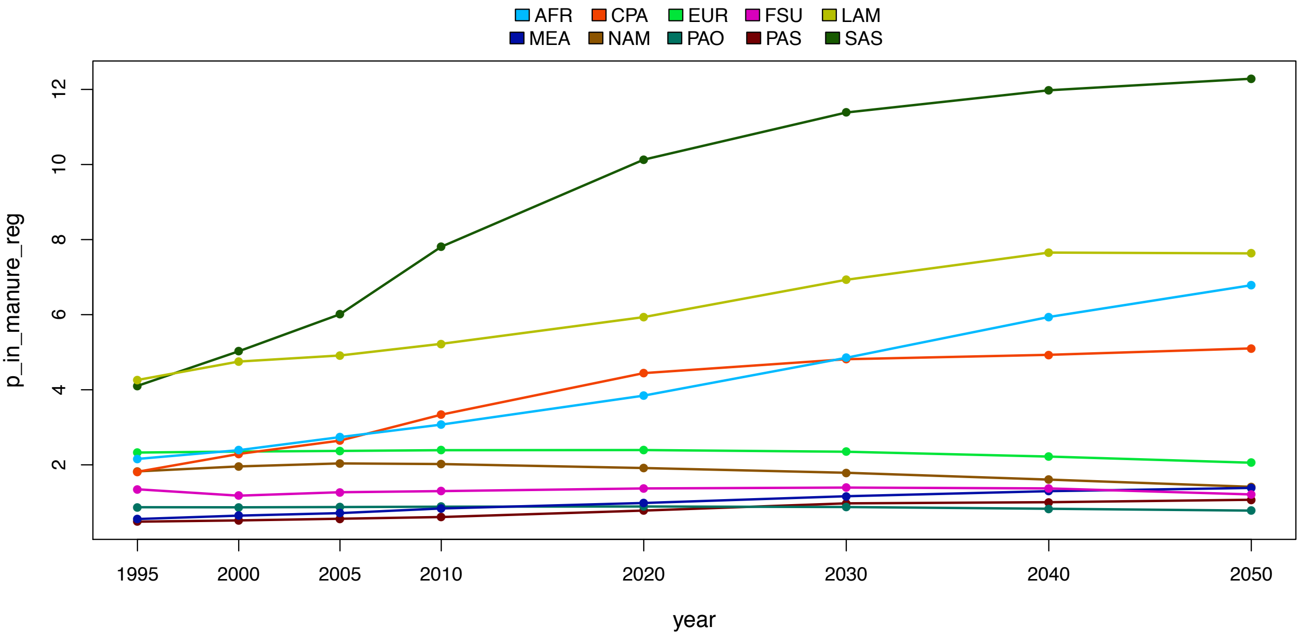

Figure 26: p_in_manure_reg

27 P in Schlachtkörpern total (global)

27.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
GLO.1	2.58	2.86	3.14	3.62	4.56	5.37	5.98	6.44

Table 27: p_in_sl_anim_glo_tot

27.2 Figures

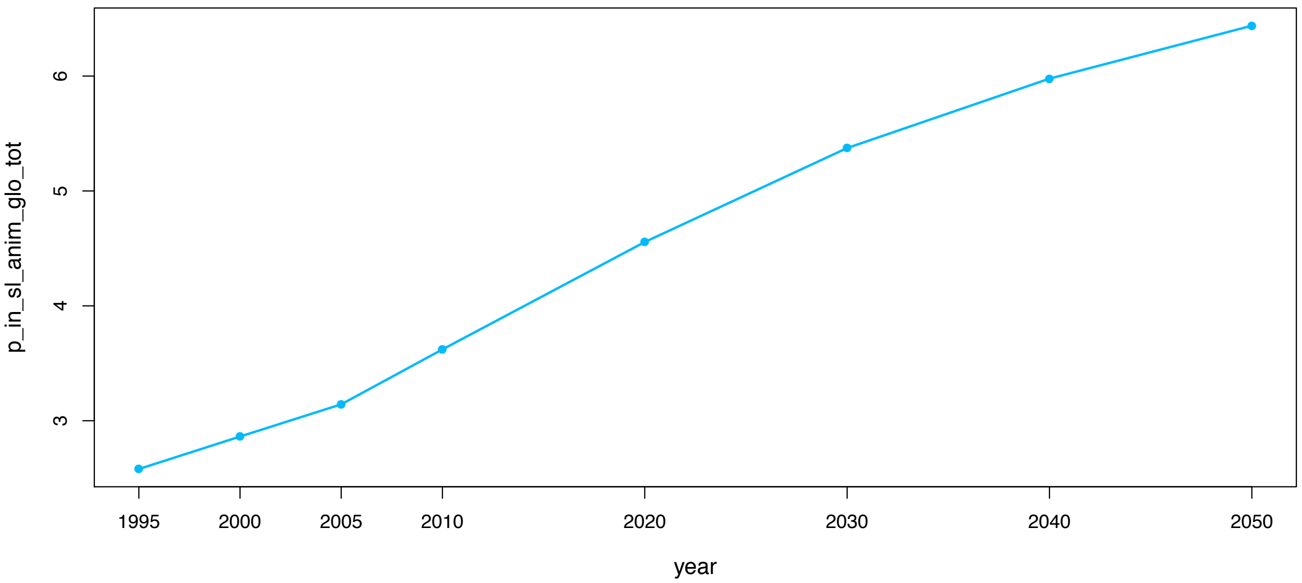

Figure 27: p_in_sl_anim_glo_tot

28 P in Schlachtkörpern nach Verwendung (global)

28.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
livst_rum	0.82	0.91	0.99	1.13	1.41	1.69	1.95	2.19
livst_pig	0.56	0.65	0.72	0.86	1.13	1.30	1.35	1.33
livst_chick	0.47	0.53	0.58	0.66	0.83	0.96	1.06	1.12
livst_egg	0.09	0.11	0.12	0.14	0.19	0.22	0.24	0.24
livst_milk	0.63	0.67	0.73	0.82	1.01	1.20	1.39	1.55

Table 28: p_in_sl_anim_glo

28.2 Figures

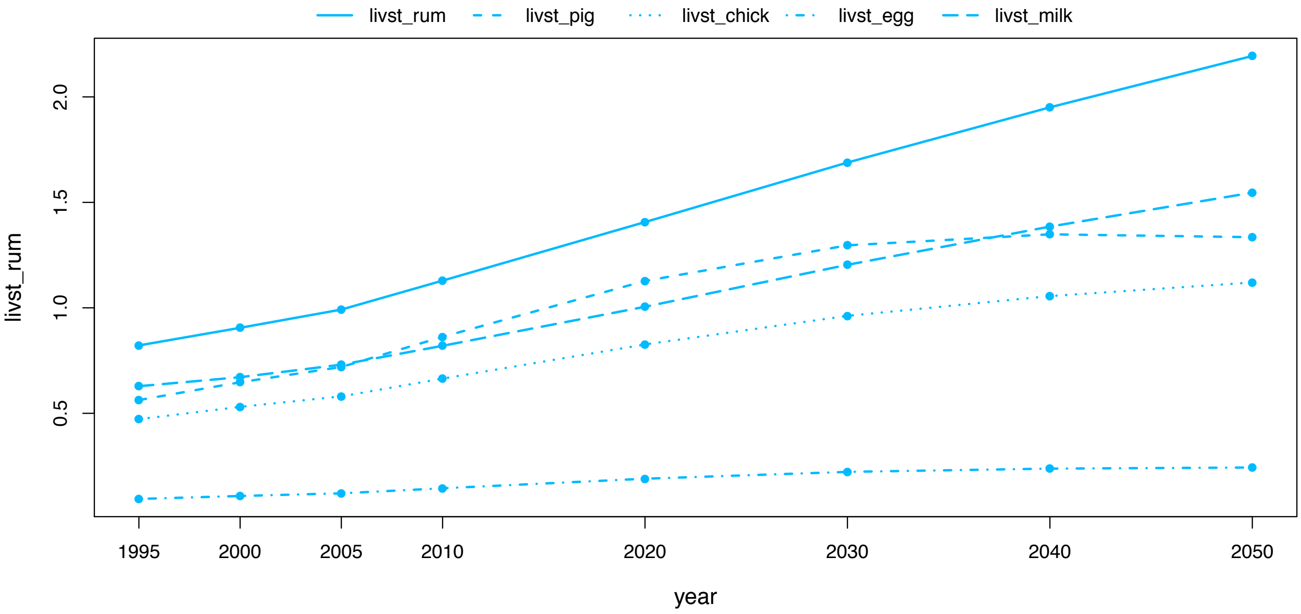

Figure 28: p_in_sl_anim_glo

29 P in Schlachtkörpern total (regional)

29.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
AFR.1	0.10	0.12	0.14	0.18	0.28	0.43	0.66	0.93
CPA.2	0.42	0.55	0.65	0.86	1.26	1.49	1.51	1.41
EUR.3	0.58	0.59	0.60	0.62	0.64	0.64	0.62	0.59
FSU.4	0.24	0.21	0.23	0.25	0.28	0.31	0.31	0.31
LAM.5	0.34	0.40	0.43	0.48	0.59	0.69	0.77	0.82
MEA.6	0.09	0.11	0.13	0.15	0.21	0.28	0.35	0.41
NAM.7	0.42	0.46	0.49	0.51	0.51	0.50	0.48	0.46
PAO.8	0.10	0.10	0.10	0.10	0.11	0.11	0.10	0.09
PAS.9	0.09	0.10	0.12	0.14	0.21	0.30	0.36	0.42
SAS.10	0.19	0.22	0.26	0.32	0.46	0.64	0.82	1.00

Table 29: p_in_sl_anim_reg_tot

29.2 Figures

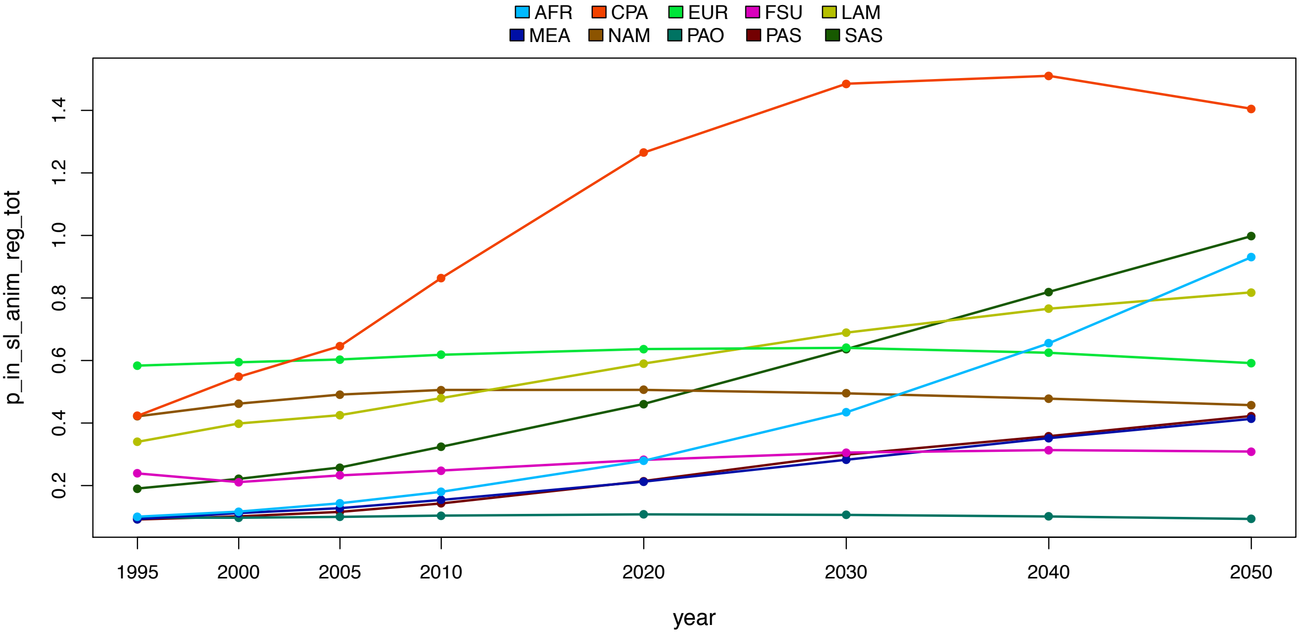

Figure 29: p_in_sl_anim_reg_tot

30 P Recycling on cropland (global)

30.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
GLO.1	5.85	6.46	7.05	7.88	9.34	10.56	11.54	11.94

Table 30: p_recycl_on_crpl_glo

30.2 Figures

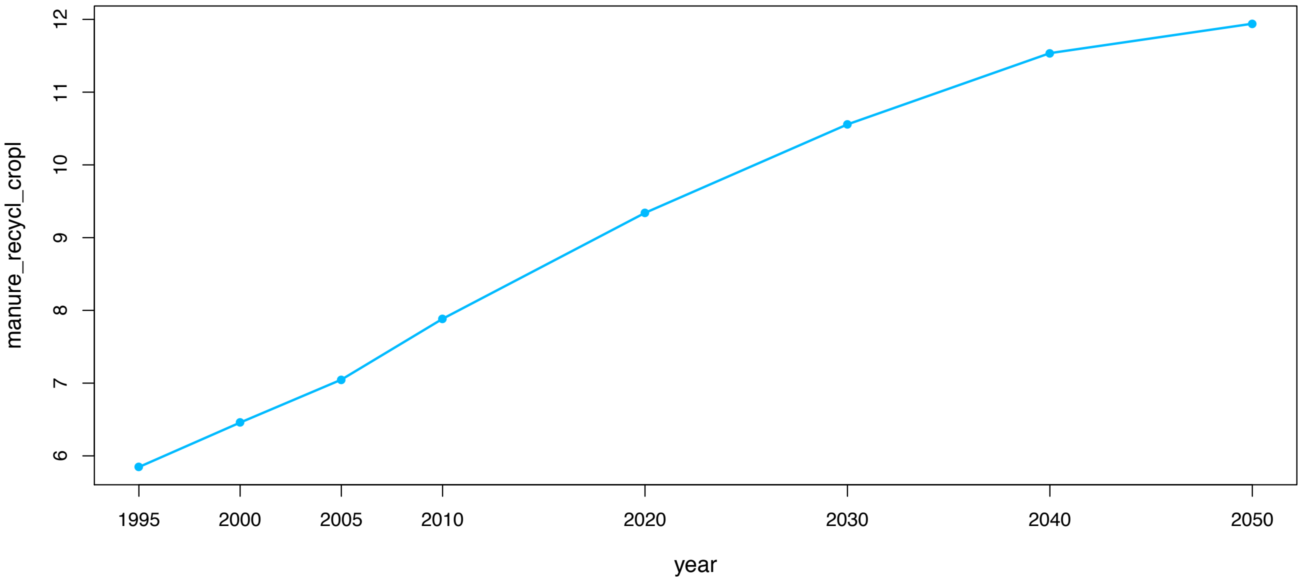

Figure 30: p_recycl_on_crpl_glo

31 P Recycling on croplands (regional)

31.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
AFR.1	0.28	0.33	0.39	0.44	0.61	0.85	1.16	1.45
CPA.2	0.79	1.02	1.21	1.56	2.17	2.43	2.63	2.70
EUR.3	0.85	0.86	0.86	0.87	0.86	0.83	0.78	0.71
FSU.4	0.63	0.55	0.59	0.60	0.63	0.63	0.59	0.52
LAM.5	0.72	0.85	0.94	1.10	1.37	1.78	2.17	2.15
MEA.6	0.24	0.28	0.31	0.38	0.44	0.52	0.58	0.63
NAM.7	1.06	1.13	1.17	1.13	1.03	0.91	0.80	0.70
PAO.8	0.26	0.26	0.26	0.27	0.28	0.28	0.27	0.26
PAS.9	0.20	0.22	0.23	0.25	0.34	0.44	0.45	0.50
SAS.10	0.81	0.94	1.08	1.27	1.62	1.89	2.11	2.32

Table 31: p_recycl_on_crpl_reg

31.2 Figures

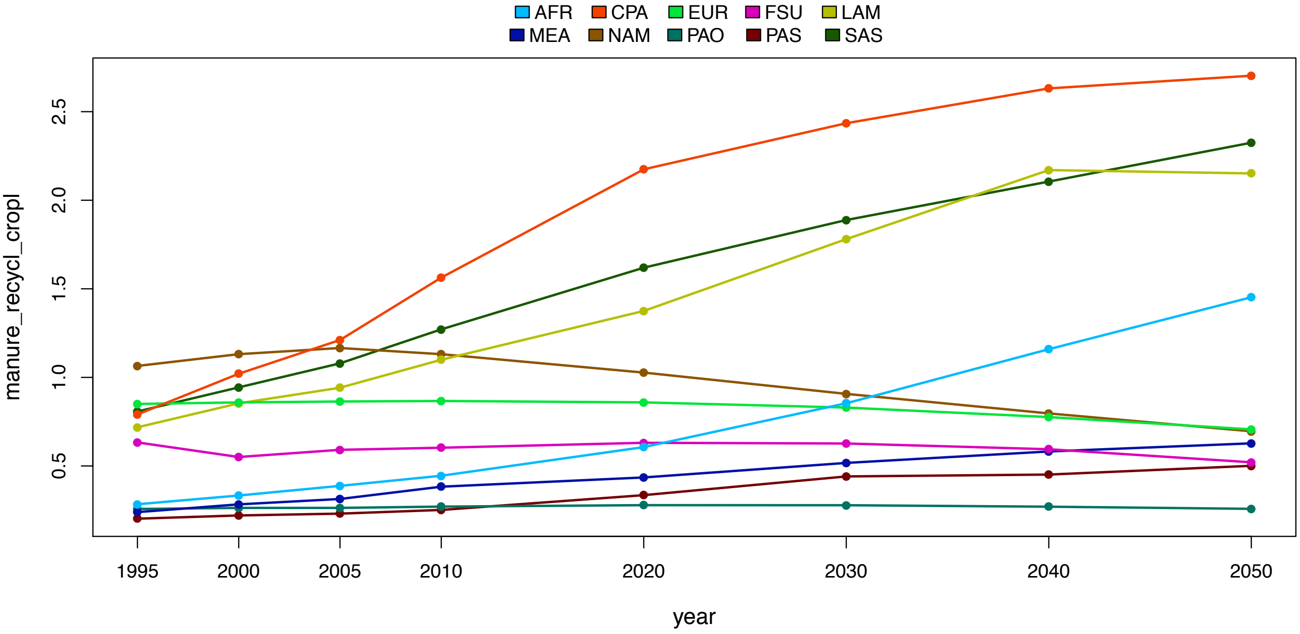

Figure 31: p_recycl_on_crpl_reg

32 P Recycling on Pasture (global)

32.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
GLO.1	0.60	0.70	0.81	1.05	1.63	2.32	3.05	3.71

Table 32: p_recycl_on_past_glo

32.2 Figures

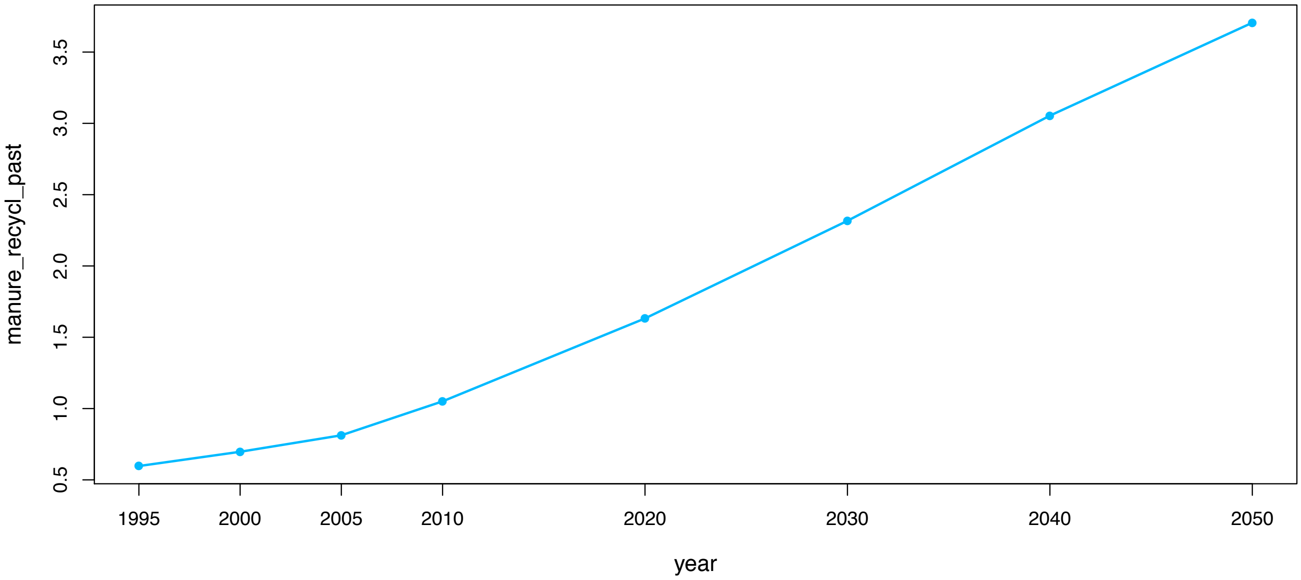

Figure 32: p_recycl_on_past_glo

33 P Recycling on Pasture (regional)

33.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
AFR.1	0.00	0.00	0.01	0.03	0.07	0.15	0.27	0.42
CPA.2	0.00	0.02	0.04	0.10	0.27	0.45	0.64	0.80
EUR.3	0.44	0.44	0.44	0.45	0.44	0.43	0.40	0.36
FSU.4	0.00	0.01	0.02	0.04	0.08	0.12	0.15	0.16
LAM.5	0.00	0.01	0.03	0.07	0.17	0.33	0.52	0.63
MEA.6	0.00	0.00	0.01	0.03	0.06	0.10	0.14	0.19
NAM.7	0.16	0.18	0.21	0.23	0.26	0.27	0.27	0.26
PAO.8	0.00	0.00	0.01	0.02	0.04	0.05	0.07	0.08
PAS.9	0.00	0.00	0.01	0.02	0.04	0.08	0.11	0.15
SAS.10	0.00	0.01	0.03	0.08	0.19	0.33	0.49	0.66

Table 33: p_recycl_on_past_reg

33.2 Figures

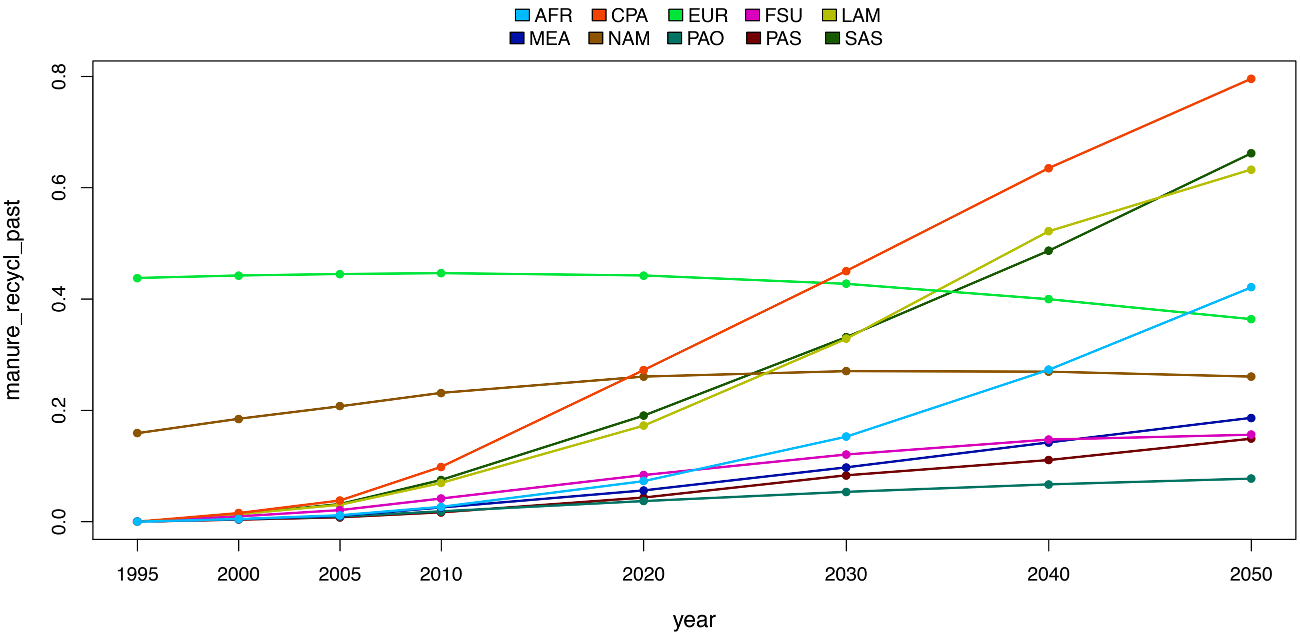

Figure 33: p_recycl_on_past_reg

34 AG_res Recycling (global)

34.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
GLO.1	4.44	4.65	4.94	5.39	6.86	7.94	8.26	8.71

Table 34: p_recycl_ag_res_glo

34.2 Figures

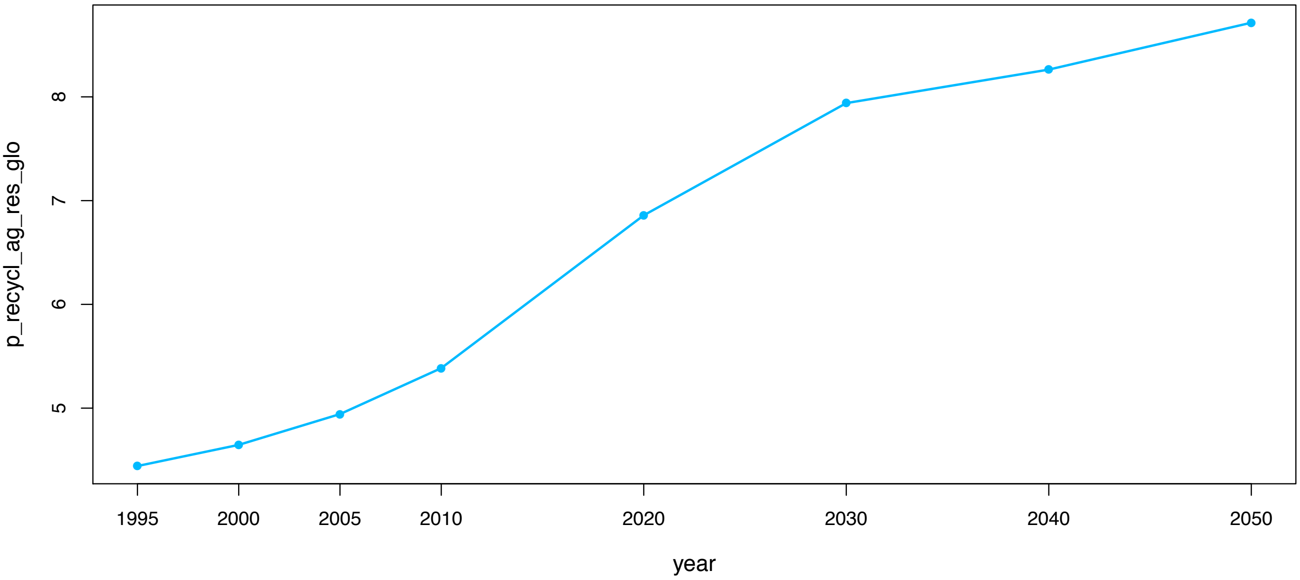

Figure 34: p_recycl_ag_res_glo

35 AG_res Recycling (regional)

35.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
AFR.1	0.24	0.28	0.36	0.51	0.85	1.18	1.34	1.63
CPA.2	0.50	0.50	0.53	0.57	0.76	1.11	1.63	1.85
EUR.3	0.81	0.84	0.87	0.91	0.92	0.92	0.90	0.91
FSU.4	0.44	0.42	0.45	0.46	0.49	0.48	0.48	0.49
LAM.5	0.50	0.56	0.61	0.72	1.45	1.73	1.35	1.16
MEA.6	0.11	0.11	0.12	0.14	0.18	0.21	0.24	0.25
NAM.7	1.00	1.09	1.15	1.23	1.29	1.34	1.35	1.38
PAO.8	0.17	0.17	0.17	0.18	0.19	0.20	0.20	0.21
PAS.9	0.30	0.31	0.33	0.34	0.37	0.40	0.40	0.41
SAS.10	0.37	0.36	0.34	0.32	0.36	0.37	0.38	0.41

Table 35: p_recycl_ag_res_reg

35.2 Figures

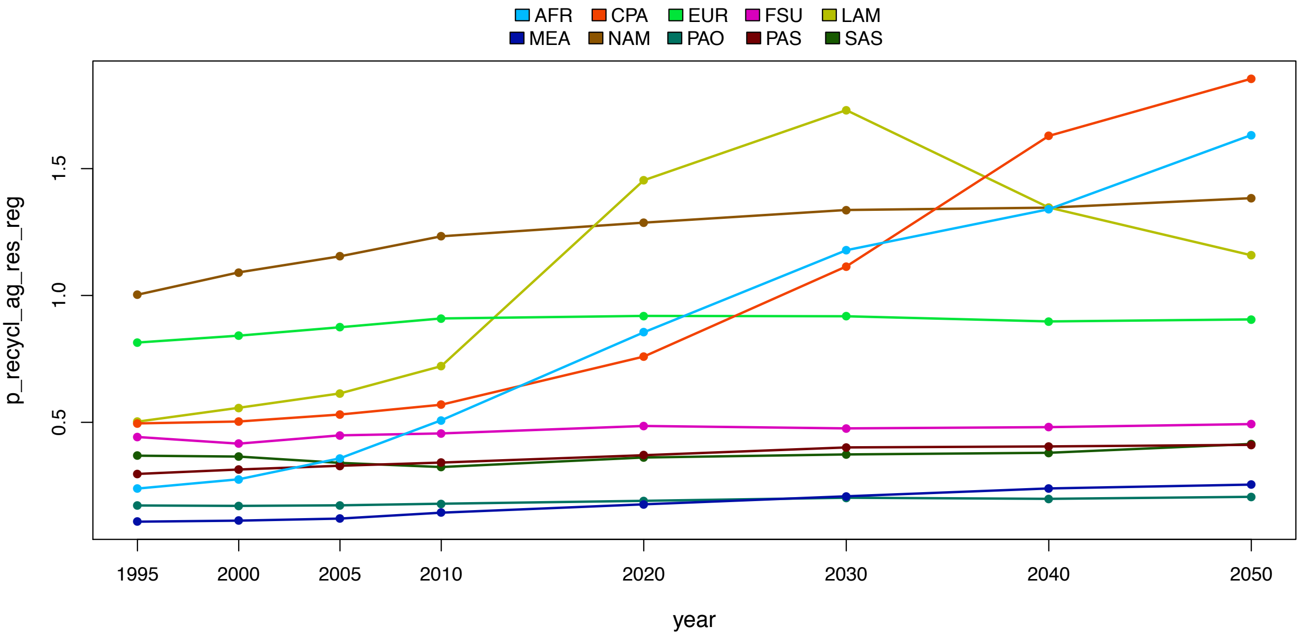

Figure 35: p_recycl_ag_res_reg

36 P in slaughter waste (Global)

36.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
GLO.1	0.50	0.56	0.61	0.71	0.89	1.05	1.18	1.27

Table 36: p_in_sl_waste_glo

36.2 Figures

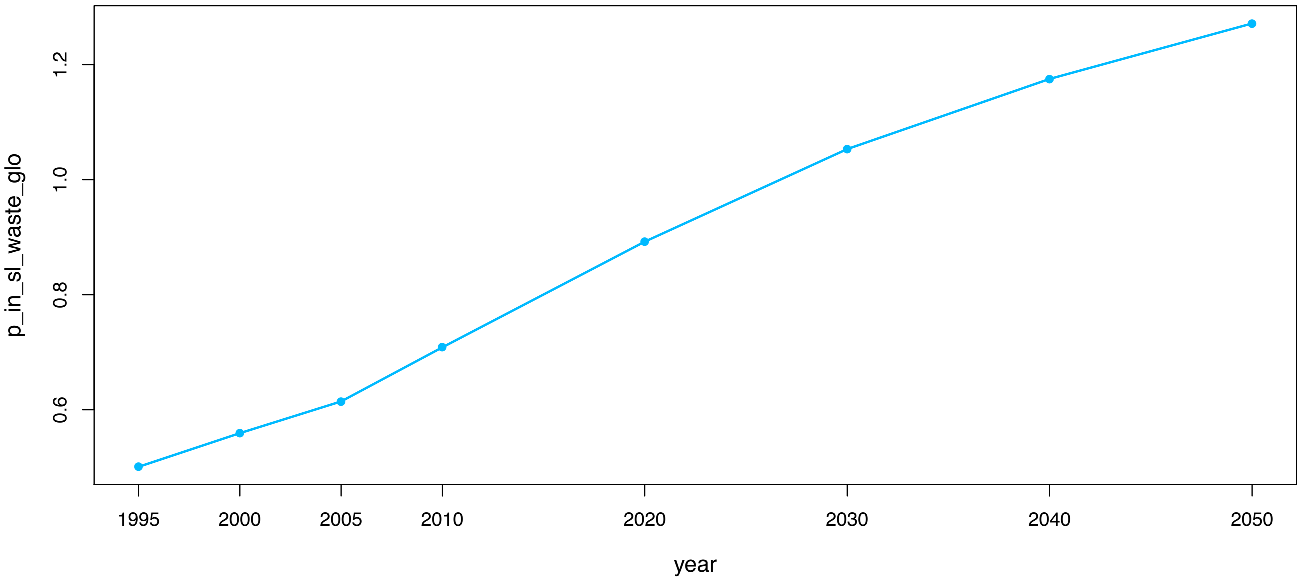

Figure 36: p_in_sl_waste_glo

37 P in Slaughter waste (regional)

37.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
AFR.1	0.02	0.03	0.03	0.04	0.07	0.10	0.15	0.22
CPA.2	0.08	0.11	0.13	0.17	0.25	0.29	0.29	0.27
EUR.3	0.10	0.10	0.10	0.10	0.11	0.11	0.10	0.10
FSU.4	0.04	0.03	0.04	0.04	0.05	0.05	0.06	0.06
LAM.5	0.08	0.09	0.10	0.11	0.14	0.16	0.18	0.19
MEA.6	0.02	0.02	0.03	0.03	0.05	0.06	0.08	0.09
NAM.7	0.09	0.10	0.11	0.11	0.11	0.11	0.10	0.10
PAO.8	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
PAS.9	0.02	0.02	0.02	0.03	0.04	0.06	0.07	0.08
SAS.10	0.03	0.03	0.04	0.05	0.07	0.09	0.12	0.15

Table 37: p_in_sl_waste_reg

37.2 Figures

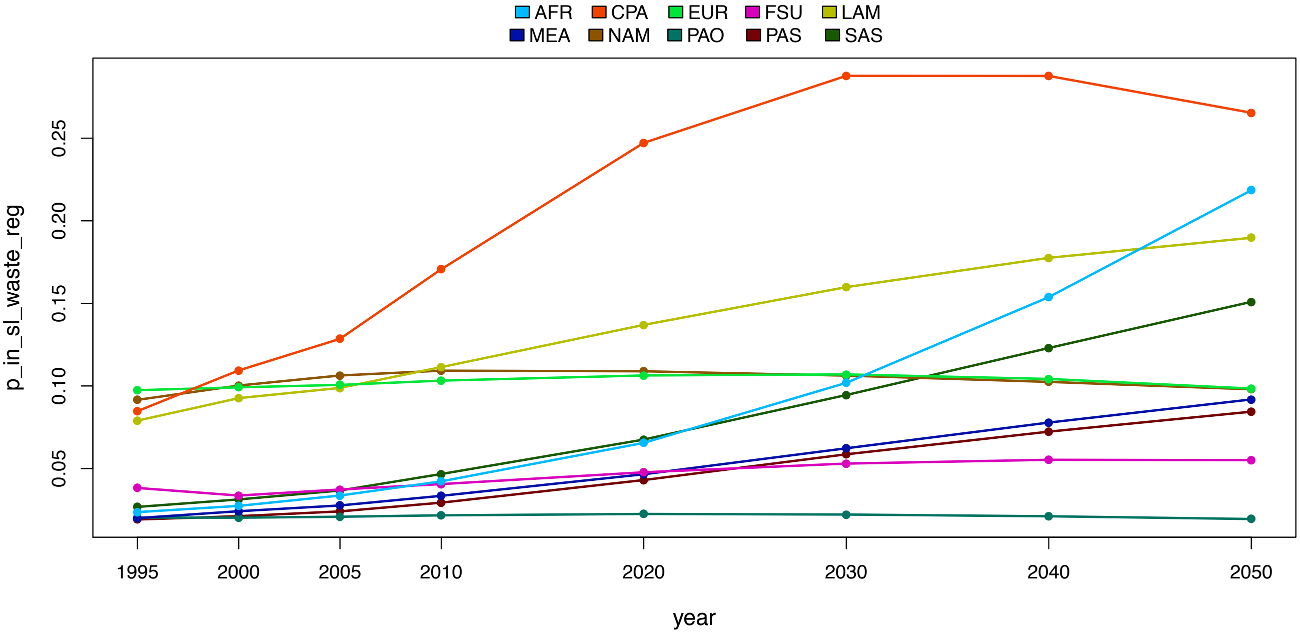

Figure 37: p_in_sl_waste_reg

38 P in plant products for fooduse (global)

38.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
GLO.1	3.68	3.98	4.29	4.57	5.14	5.68	6.17	6.59

Table 38: p_in_plant_prod_glo

38.2 Figures

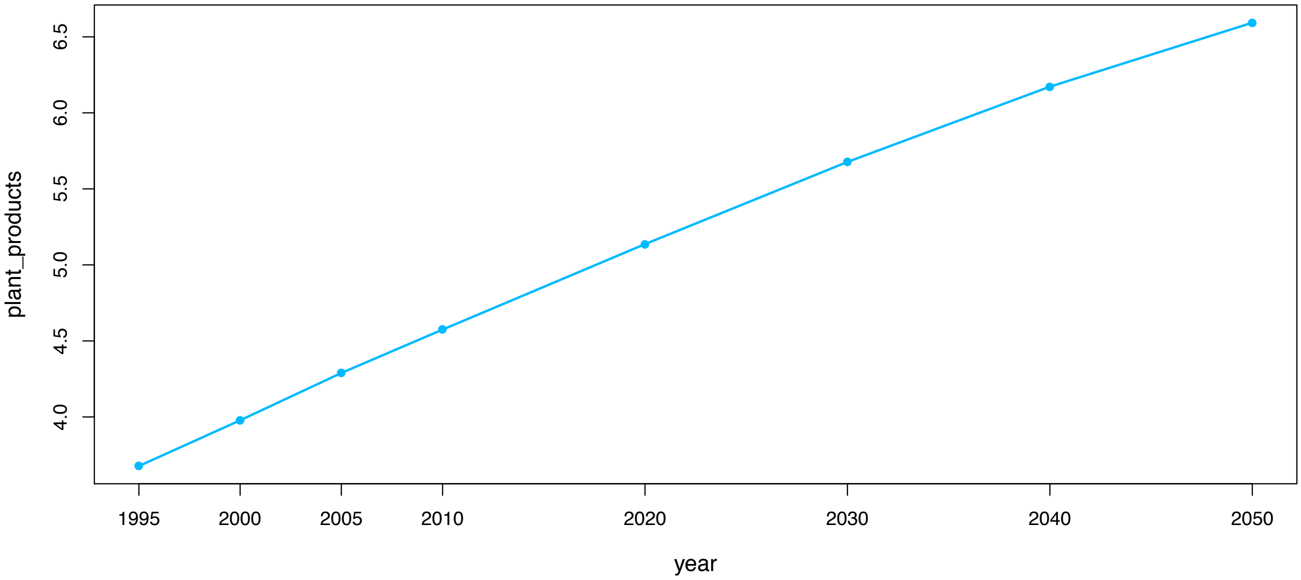

Figure 38: p_in_plant_prod_glo

39 P in plant products for fooduse (regional)

39.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
AFR.1	0.39	0.45	0.53	0.61	0.78	0.98	1.18	1.37
CPA.2	0.99	1.04	1.08	1.09	1.08	1.06	1.06	1.04
EUR.3	0.35	0.37	0.39	0.40	0.43	0.46	0.49	0.51
FSU.4	0.18	0.18	0.20	0.20	0.20	0.19	0.19	0.20
LAM.5	0.10	0.11	0.12	0.12	0.13	0.14	0.15	0.16
MEA.6	0.34	0.38	0.42	0.46	0.54	0.61	0.68	0.72
NAM.7	0.10	0.12	0.12	0.13	0.16	0.18	0.20	0.23
PAO.8	0.09	0.09	0.09	0.09	0.10	0.10	0.11	0.11
PAS.9	0.27	0.30	0.32	0.35	0.39	0.42	0.45	0.46
SAS.10	0.87	0.95	1.03	1.13	1.33	1.51	1.67	1.79

Table 39: p_in_plant_prod_reg

39.2 Figures

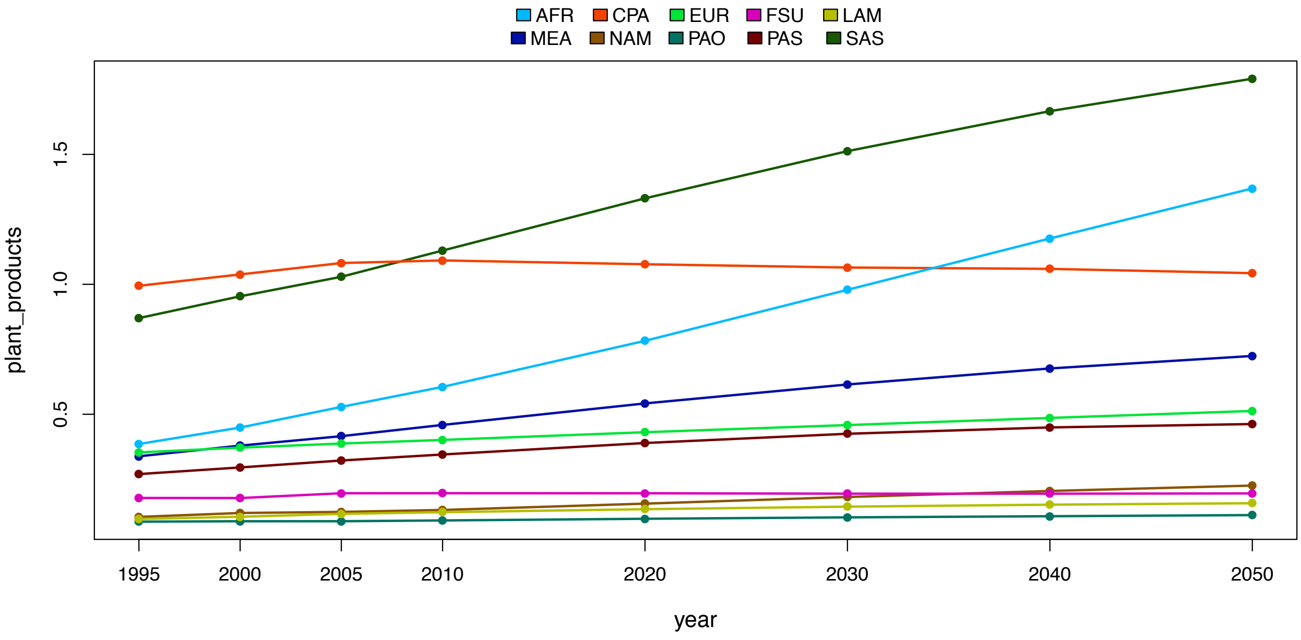

Figure 39: p_in_plant_prod_reg

40 P Pool

40.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
AFR.1	27.71	29.74	37.02	47.92	98.67	113.91	145.25	178.58
CPA.2	69.03	86.09	96.51	109.99	160.57	170.46	228.43	208.11
EUR.3	66.71	72.23	75.30	77.97	80.55	77.99	79.18	78.06
FSU.4	34.68	32.96	34.92	36.36	41.68	38.02	40.69	40.20
LAM.5	47.08	53.42	58.92	68.35	126.22	124.41	128.06	138.17
MEA.6	11.59	14.01	15.59	18.13	24.88	26.47	31.04	30.27
NAM.7	88.45	97.39	104.23	111.33	119.42	114.73	116.60	117.55
PAO.8	10.56	13.58	14.36	15.02	17.02	17.18	16.75	17.52
PAS.9	20.31	22.48	24.26	25.62	31.40	32.63	30.38	32.30
SAS.10	62.85	68.58	74.39	83.06	118.10	119.54	135.68	144.51

Table 40: p_pool

40.2 Figures

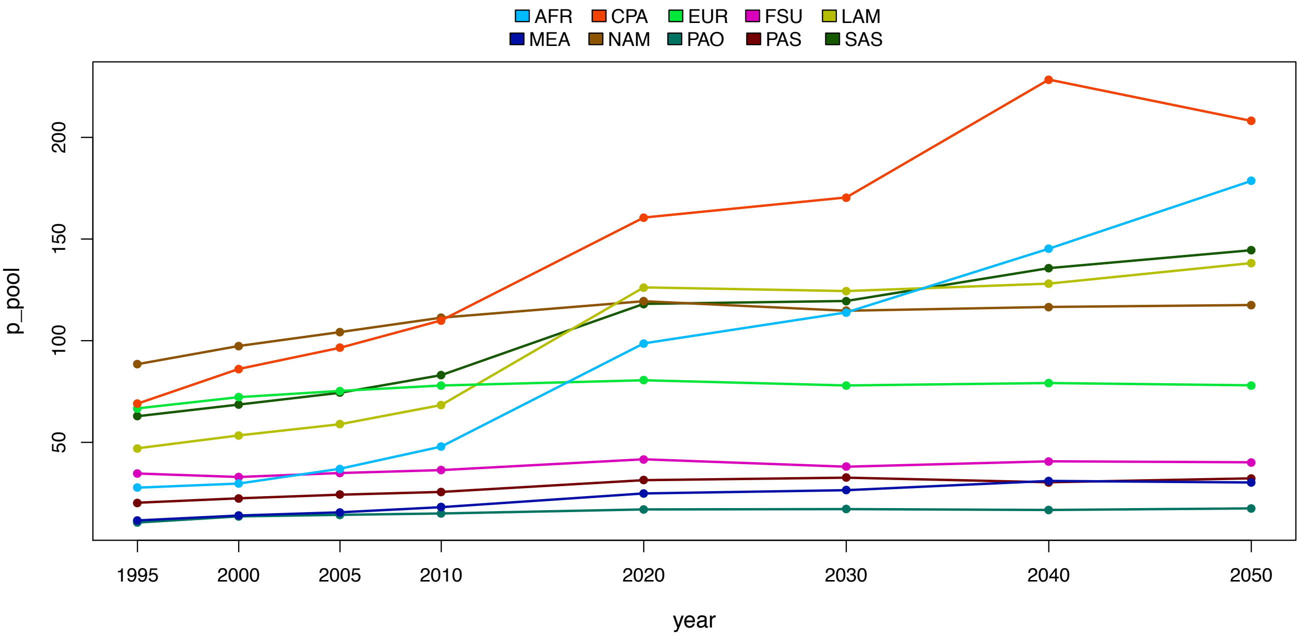

Figure 40: p_pool

40.3 tables

41 P Pool global

41.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
GLO.1	438.98	490.48	535.49	593.73	818.51	835.34	952.04	985.26

Table 41: p_pool_glo

41.2 Figures

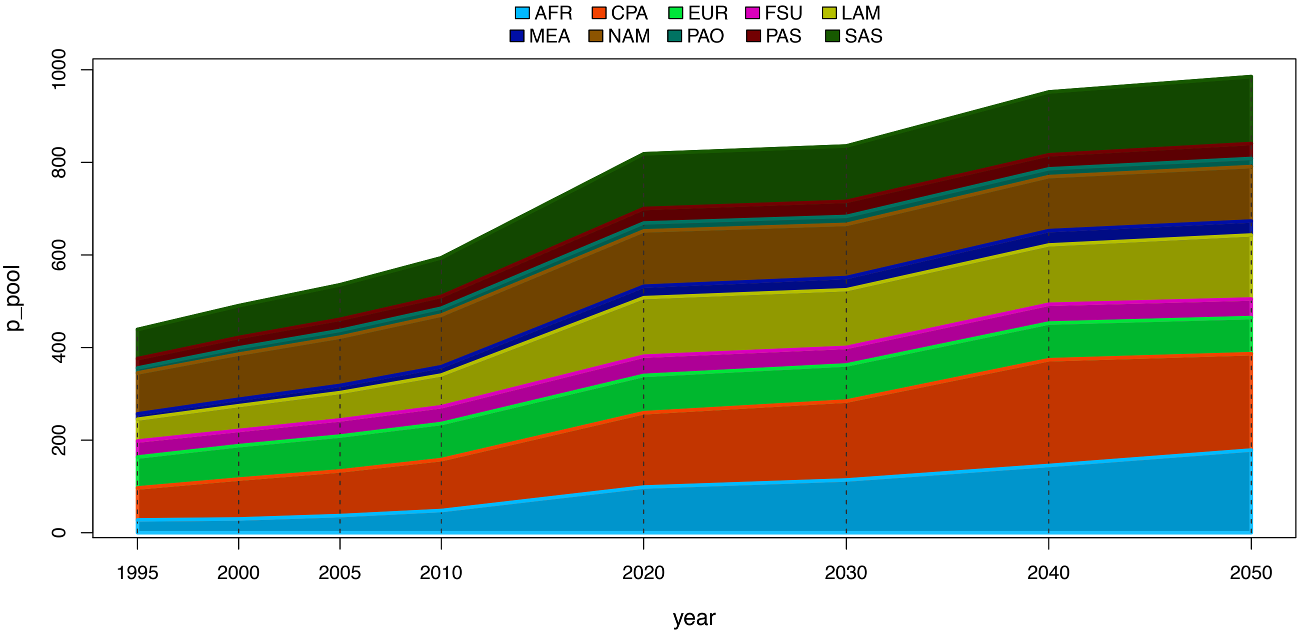

Figure 41: p_pool

41.3 tables

42 Out to P_pool (regional)

42.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
AFR.1	0.63	1.33	2.45	3.41	6.67	4.81	6.93	8.18
CPA.2	4.25	5.71	4.95	5.91	8.72	6.34	11.48	5.58
EUR.3	3.04	3.33	3.02	3.04	2.86	2.43	2.72	2.53
FSU.4	1.12	0.81	1.49	1.45	1.74	1.02	1.53	1.31
LAM.5	1.86	2.84	2.88	3.85	8.07	4.03	4.51	5.28
MEA.6	0.65	0.87	0.78	1.03	1.28	0.99	1.34	0.96
NAM.7	3.32	4.74	4.61	4.89	4.52	3.51	4.01	3.98
PAO.8	1.04	0.96	0.61	0.61	0.70	0.58	0.53	0.64
PAS.9	0.90	1.11	1.11	1.08	1.43	1.17	0.86	1.20
SAS.10	2.22	3.24	3.45	4.21	6.27	4.08	5.60	5.41

Table 42: out_2_p_pool

42.2 Figures

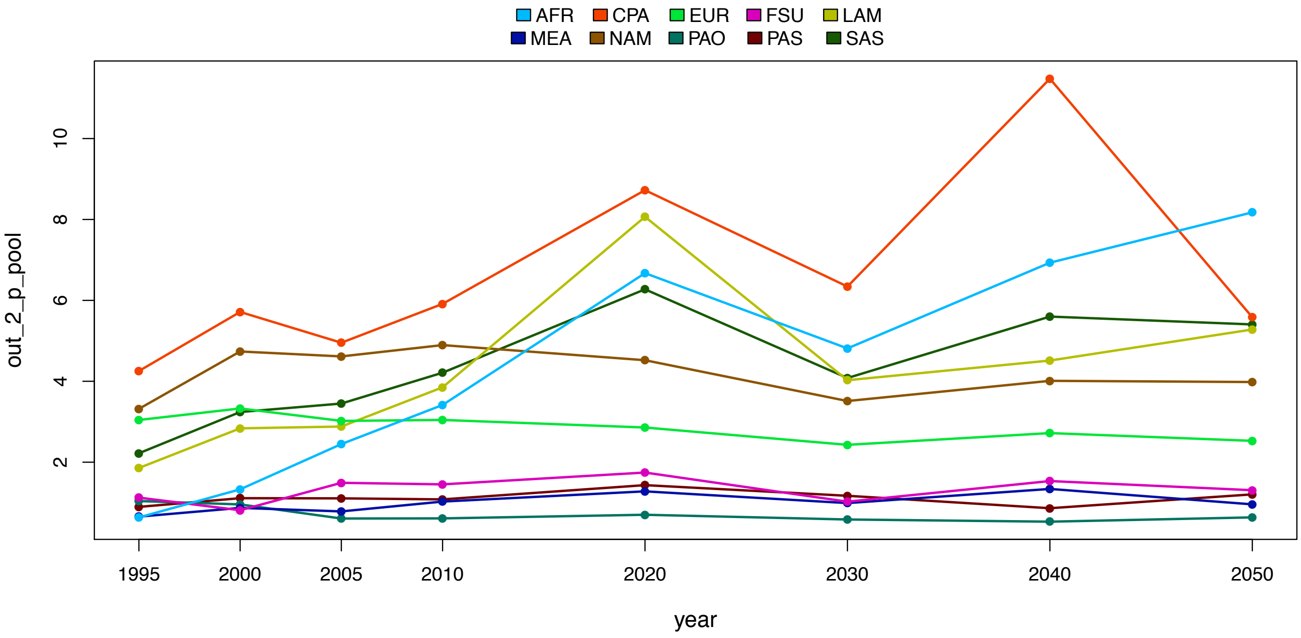

Figure 42: out_2_p_pool

43 Out to P_pool (global)

43.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
GLO.1	19.04	24.93	25.35	29.50	42.27	28.97	39.52	35.06

Table 43: out_2_p_pool_glo

43.2 Figures

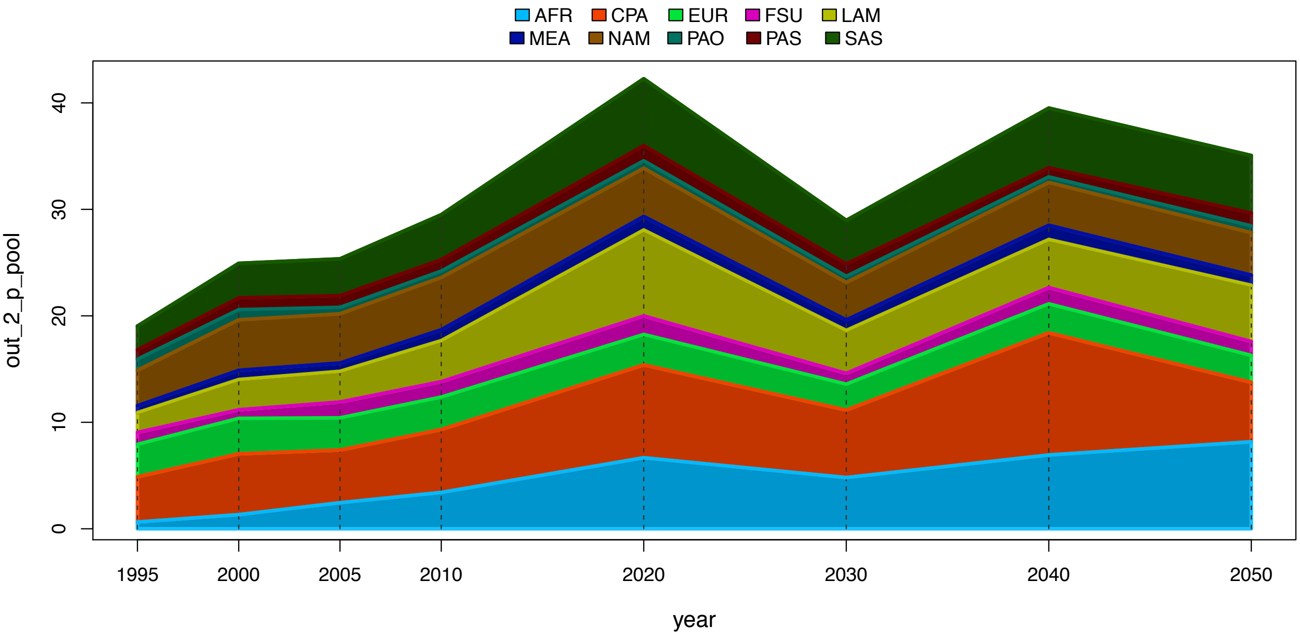

Figure 43: out_2_p_pool

44 n from P_pool (regional)

44.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
AFR.1	0.93	0.92	0.99	1.23	1.60	3.29	3.80	4.84
CPA.2	2.23	2.30	2.87	3.22	3.67	5.35	5.68	7.61
EUR.3	2.20	2.22	2.41	2.51	2.60	2.68	2.60	2.64
FSU.4	1.16	1.16	1.10	1.16	1.21	1.39	1.27	1.36
LAM.5	1.56	1.57	1.78	1.96	2.28	4.21	4.15	4.27
MEA.6	0.38	0.39	0.47	0.52	0.60	0.83	0.88	1.03
NAM.7	2.94	2.95	3.25	3.47	3.71	3.98	3.82	3.89
PAO.8	0.33	0.35	0.45	0.48	0.50	0.57	0.57	0.56
PAS.9	0.67	0.68	0.75	0.81	0.85	1.05	1.09	1.01
SAS.10	2.09	2.10	2.29	2.48	2.77	3.94	3.98	4.52

Table 44: in_from_p_pool

44.2 Figures

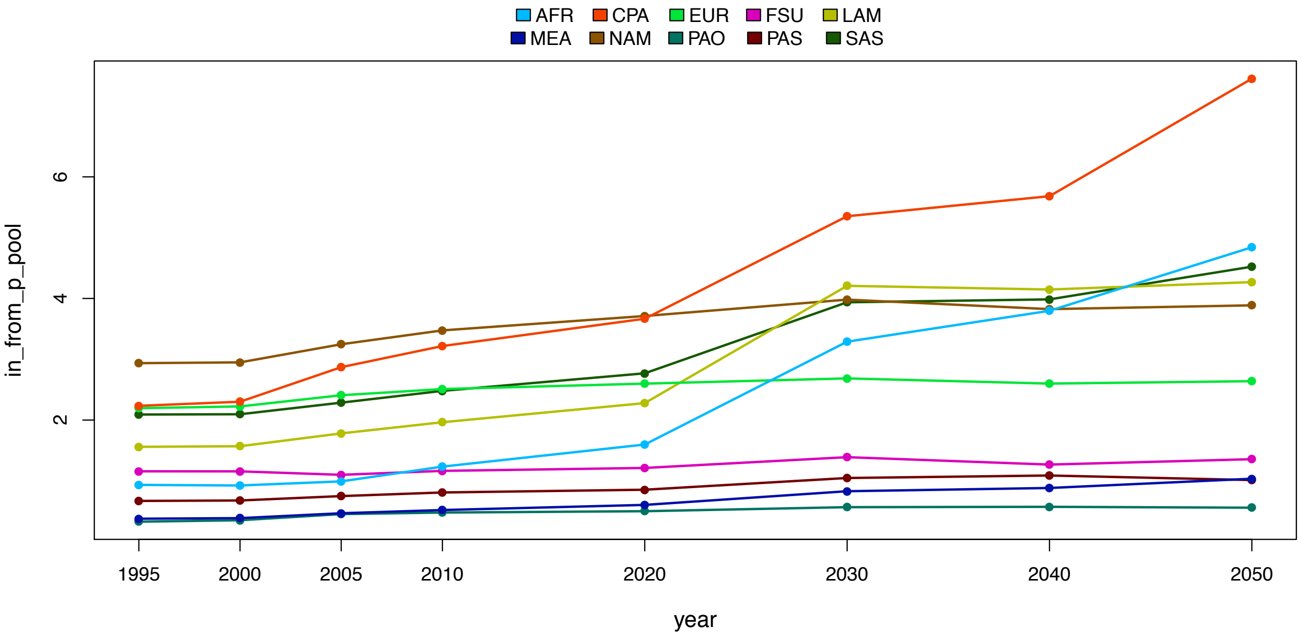

Figure 44: in_from_p_pool

45 n from P_pool (global)

45.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
GLO.1	14.48	14.63	16.35	17.85	19.79	27.28	27.84	31.73

Table 45: in_from_p_pool_glo

45.2 Figures

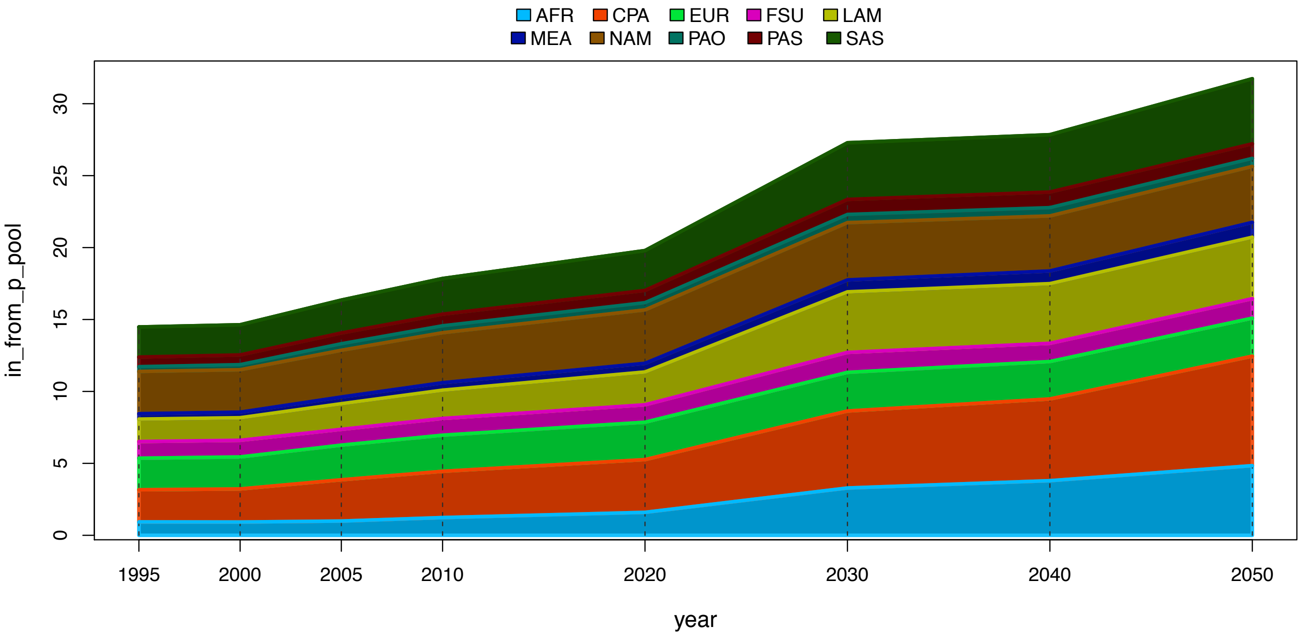

Figure 45: in_from_p_pool

46 Cropland Budgets

46.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
harvest	-13.05	-14.26	-15.60	-17.40	-20.72	-23.61	-26.36	-28.89
ag_residues	-6.60	-7.05	-7.58	-8.38	-10.31	-11.69	-12.23	-12.54
out_2_p_pool	-19.04	-24.93	-25.35	-29.50	-42.27	-28.97	-39.52	-35.06
in_from_p_pool	14.48	14.63	16.35	17.85	19.79	27.28	27.84	31.73
fix_fertilizer	13.51	20.06	19.70	23.60	36.64	17.71	29.59	23.17
manure	5.85	6.46	7.05	7.88	9.34	10.56	11.54	11.94
ag_residues_rec	4.44	4.65	4.94	5.39	6.86	7.94	8.26	8.71
seed	0.42	0.45	0.49	0.55	0.67	0.77	0.86	0.94
SUM	0.00	-0.00	0.00	0.00	-0.00	-0.00	0.00	-0.00

Table 46: Cropland Budget

46.2 Figures

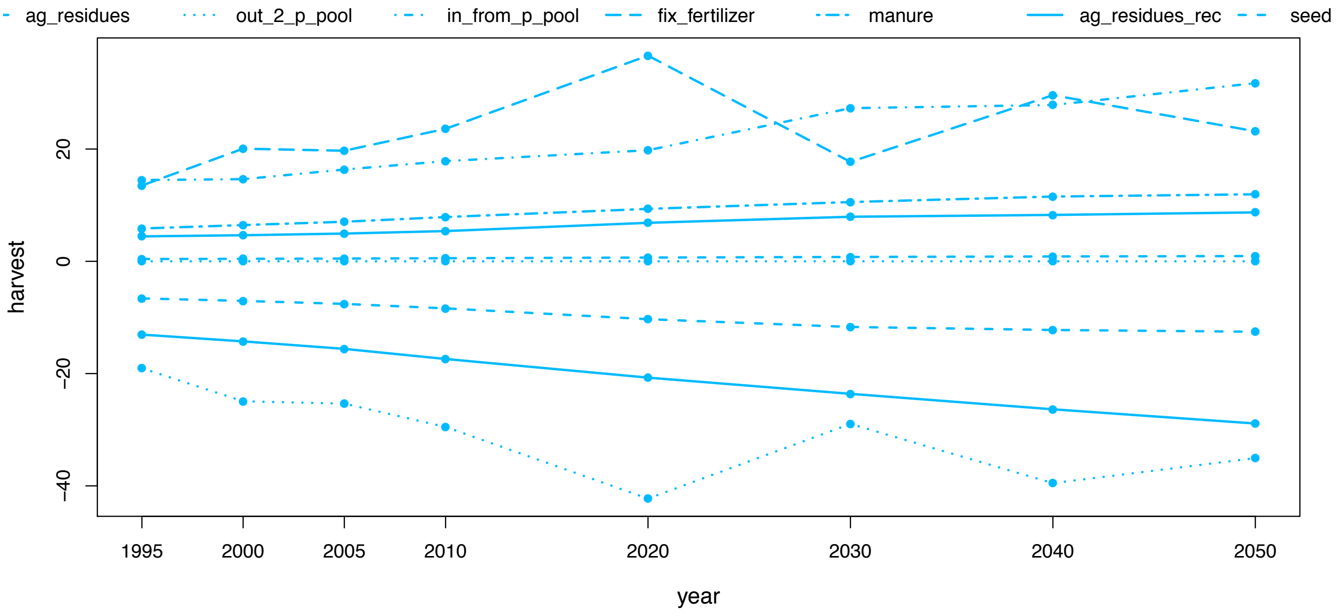

Figure 46: Cropland Budget

47 Cropland Dynamics

47.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
harvest	13.05	14.26	15.60	17.40	20.72	23.61	26.36	28.89
ag_residues	6.60	7.05	7.58	8.38	10.31	11.69	12.23	12.54
out_2_p_pool	19.04	24.93	25.35	29.50	42.27	28.97	39.52	35.06
in_from_p_pool	14.48	14.63	16.35	17.85	19.79	27.28	27.84	31.73
fix_fertilizer	13.51	20.06	19.70	23.60	36.64	17.71	29.59	23.17
manure	5.85	6.46	7.05	7.88	9.34	10.56	11.54	11.94

Table 47: Cropland Dynamics

47.2 Figures

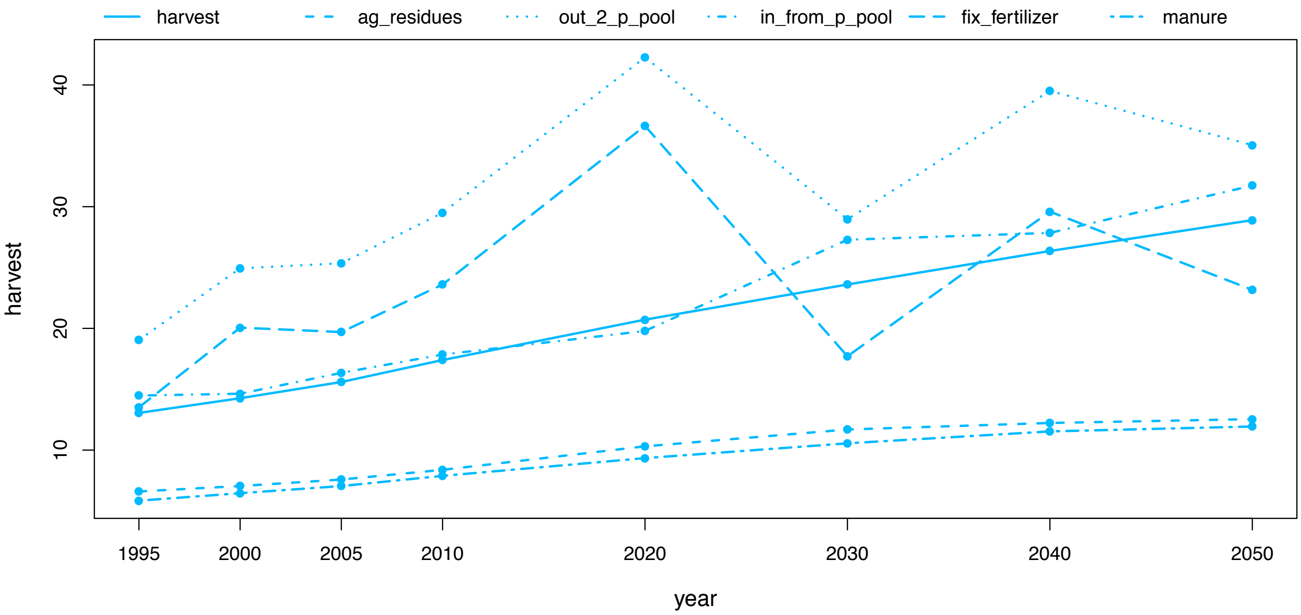

Figure 47: Cropland Dynamics

48 Losses AWMS (regional)

48.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
AFR.1	0.03	0.01	0.01	0.02	0.04	0.07	0.11	0.15
CPA.2	0.07	0.09	0.11	0.15	0.23	0.27	0.31	0.32
EUR.3	0.13	0.12	0.12	0.12	0.12	0.11	0.10	0.09
FSU.4	0.07	0.06	0.06	0.06	0.07	0.07	0.07	0.06
LAM.5	0.08	0.07	0.08	0.09	0.13	0.18	0.23	0.24
MEA.6	0.03	0.03	0.03	0.04	0.05	0.06	0.07	0.07
NAM.7	0.17	0.18	0.18	0.17	0.15	0.13	0.11	0.10
PAO.8	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
PAS.9	0.02	0.02	0.02	0.03	0.04	0.05	0.05	0.06
SAS.10	0.09	0.09	0.11	0.13	0.18	0.22	0.25	0.28

Table 48: loss_awms

48.2 Figures

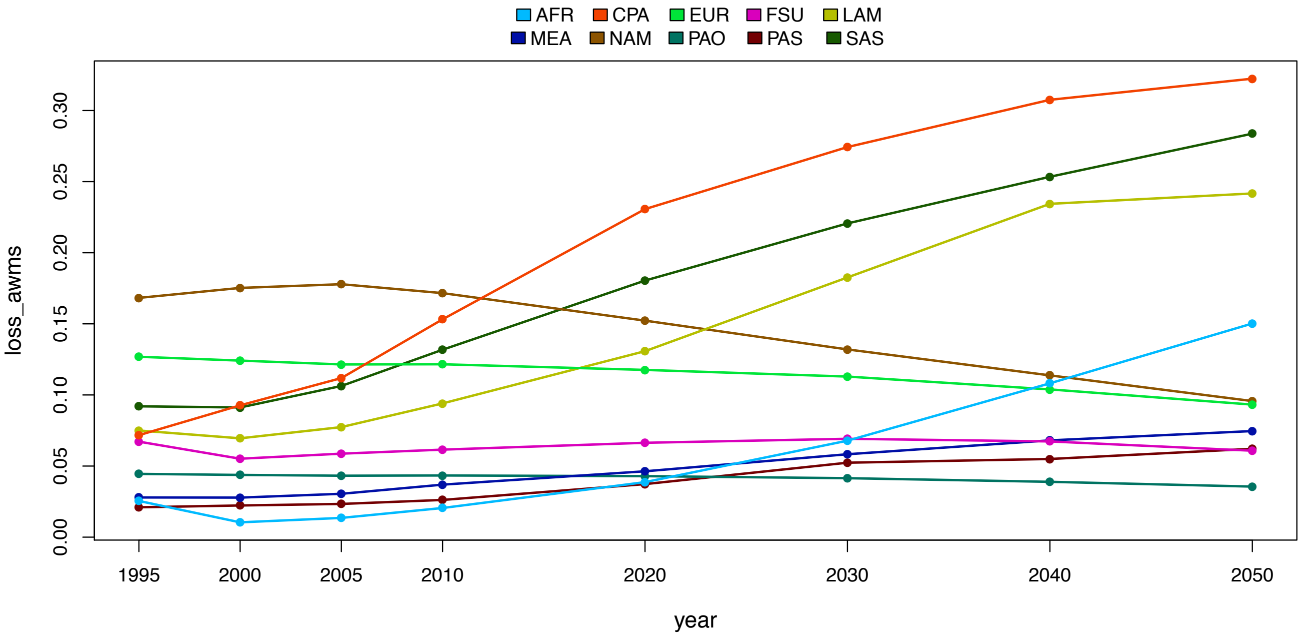

Figure 48: loss_awms

49 Losses material (regional)

49.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
AFR.1	0.10	0.12	0.14	0.16	0.21	0.26	0.32	0.39
CPA.2	0.36	0.39	0.42	0.45	0.50	0.53	0.53	0.51
EUR.3	0.23	0.24	0.25	0.26	0.27	0.28	0.29	0.30
FSU.4	0.11	0.11	0.12	0.12	0.13	0.13	0.13	0.13
LAM.5	0.16	0.18	0.19	0.21	0.24	0.26	0.28	0.30
MEA.6	0.10	0.11	0.12	0.13	0.16	0.19	0.21	0.23
NAM.7	0.21	0.24	0.25	0.26	0.29	0.32	0.34	0.36
PAO.8	0.04	0.04	0.04	0.05	0.05	0.05	0.05	0.05
PAS.9	0.10	0.11	0.12	0.13	0.15	0.16	0.18	0.19
SAS.10	0.22	0.24	0.27	0.30	0.36	0.42	0.47	0.52

Table 49: loss_mat

49.2 Figures

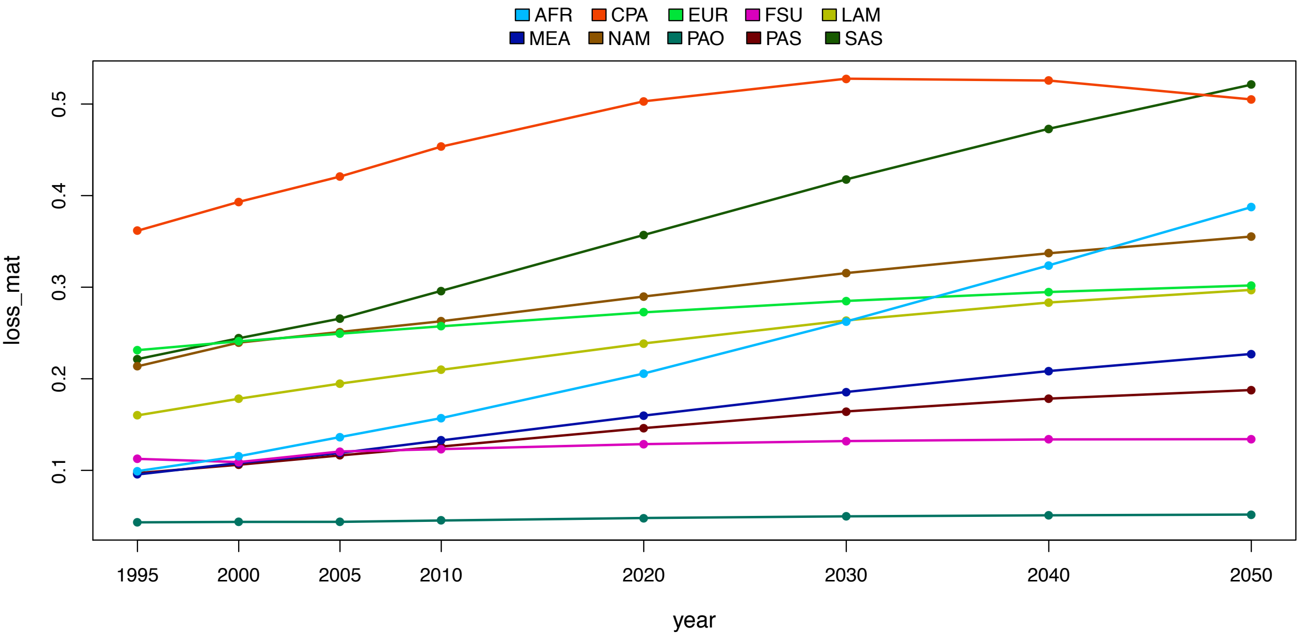

Figure 49: loss_mat

50 Losses bioenergy (regional)

50.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
AFR.1	0.05	0.05	0.06	0.07	0.09	0.09	0.09	0.12
CPA.2	0.10	0.11	0.13	0.13	0.12	0.11	0.11	0.10
EUR.3	0.00	0.04	0.08	0.13	0.09	0.00	0.00	0.00
FSU.4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LAM.5	0.10	0.11	0.12	0.14	0.26	0.29	0.30	0.67
MEA.6	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01
NAM.7	0.00	0.07	0.14	0.25	0.18	0.00	0.01	0.01
PAO.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PAS.9	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.02
SAS.10	0.11	0.11	0.11	0.11	0.11	0.09	0.08	0.06

Table 50: loss_bioen

50.2 Figures

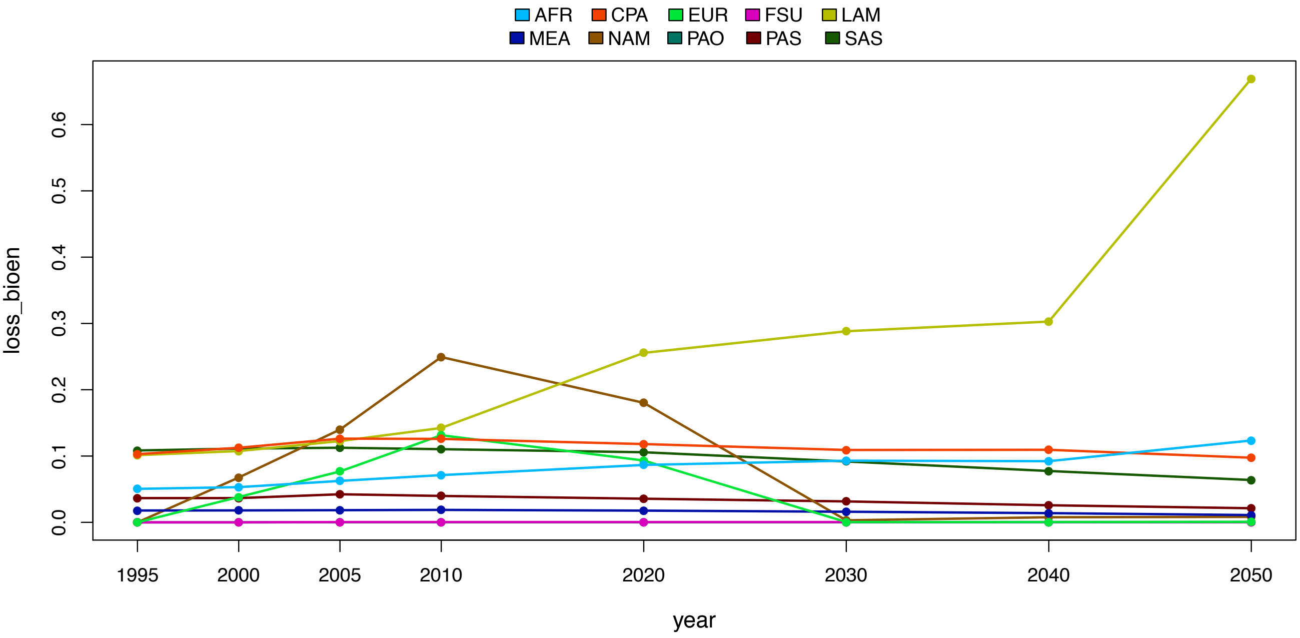

Figure 50: loss_bioen

51 Losses Slaughterwaste (regional)

51.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
AFR.1	0.02	0.03	0.03	0.04	0.07	0.10	0.15	0.22
CPA.2	0.08	0.11	0.13	0.17	0.25	0.29	0.29	0.27
EUR.3	0.10	0.10	0.10	0.10	0.11	0.11	0.10	0.10
FSU.4	0.04	0.03	0.04	0.04	0.05	0.05	0.06	0.06
LAM.5	0.08	0.09	0.10	0.11	0.14	0.16	0.18	0.19
MEA.6	0.02	0.02	0.03	0.03	0.05	0.06	0.08	0.09
NAM.7	0.09	0.10	0.11	0.11	0.11	0.11	0.10	0.10
PAO.8	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
PAS.9	0.02	0.02	0.02	0.03	0.04	0.06	0.07	0.08
SAS.10	0.03	0.03	0.04	0.05	0.07	0.09	0.12	0.15

Table 51: loss_slw

51.2 Figures

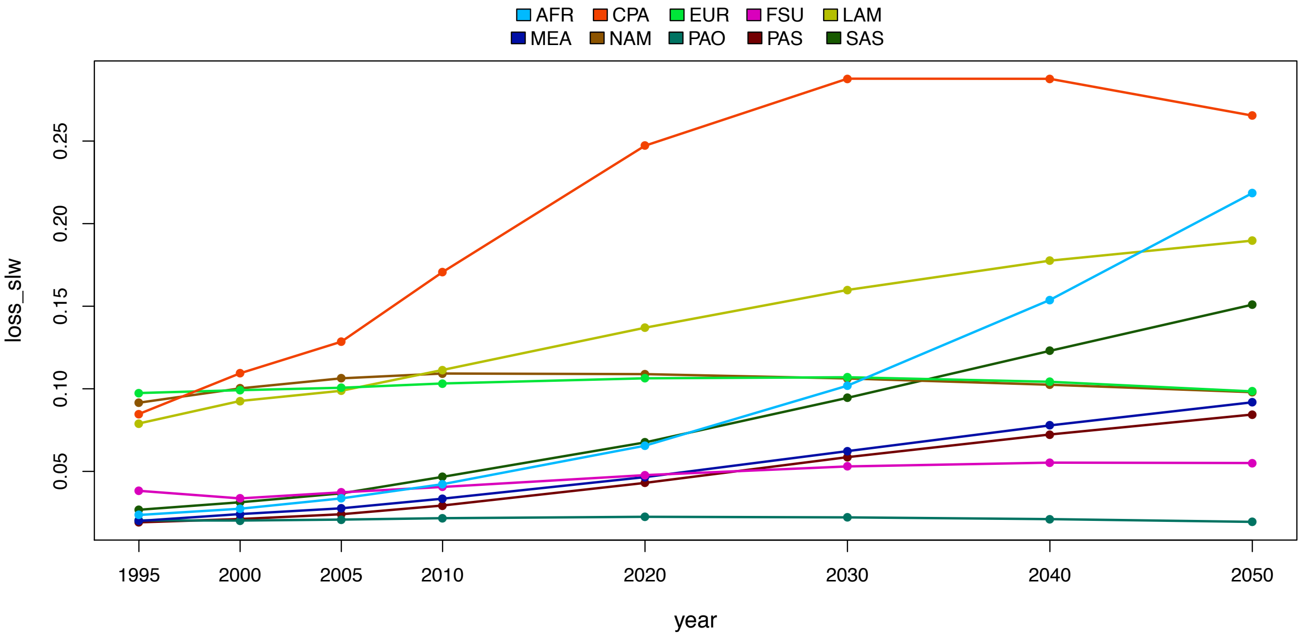

Figure 51: loss_slw

52 Losses Convby (regional)

52.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
AFR.1	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
CPA.2	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
EUR.3	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
FSU.4	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
LAM.5	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
MEA.6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NAM.7	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
PAO.8	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
PAS.9	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
SAS.10	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07

Table 52: loss_Convby

52.2 Figures

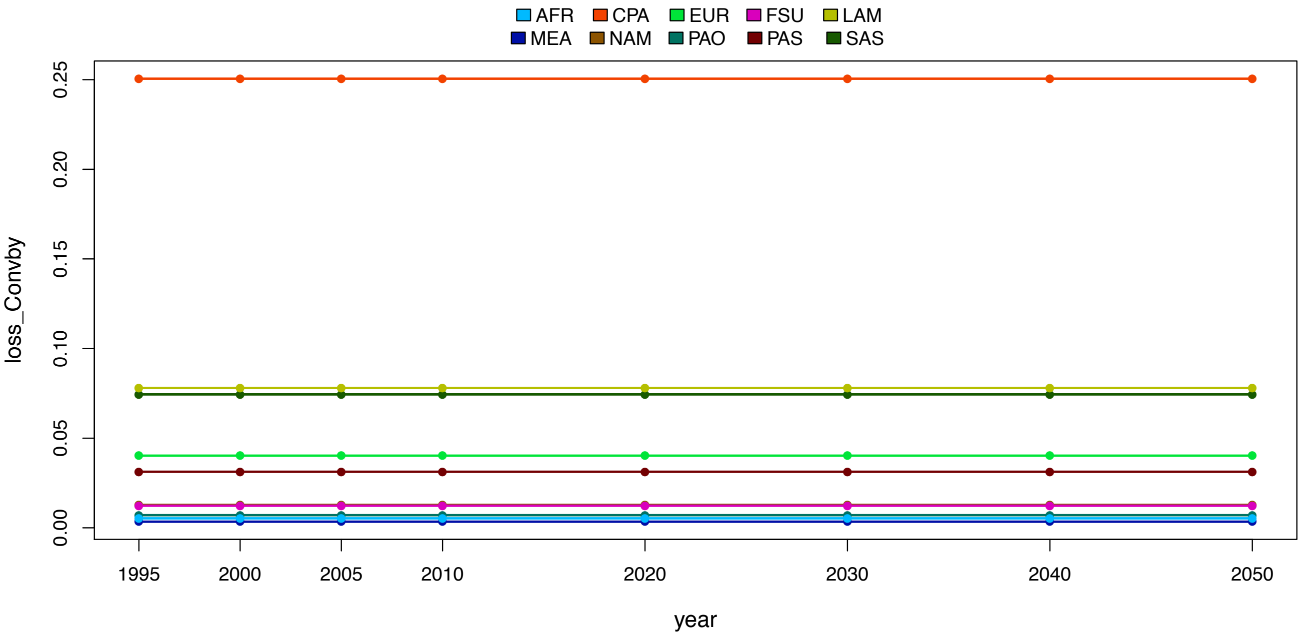

Figure 52: loss_Convby

53 Losses Total (regional)

53.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
losses_field	0.00	-0.00	0.00	0.00	-0.00	-0.00	0.00	-0.00
losses_awms	0.72	0.71	0.76	0.86	1.04	1.21	1.35	1.42
losses_slwaste	0.50	0.56	0.61	0.71	0.89	1.05	1.18	1.27
losses_resburn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
losses_resotherbioenergy	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
losses_bioenergy	0.42	0.54	0.70	0.89	0.89	0.63	0.63	1.00
losses_convby	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52
manure_recycl_past	0.60	0.70	0.81	1.05	1.63	2.32	3.05	3.71
losses_material	1.64	1.78	1.92	2.06	2.35	2.60	2.81	2.97

Table 53: Losses Gesamt

53.2 Figures

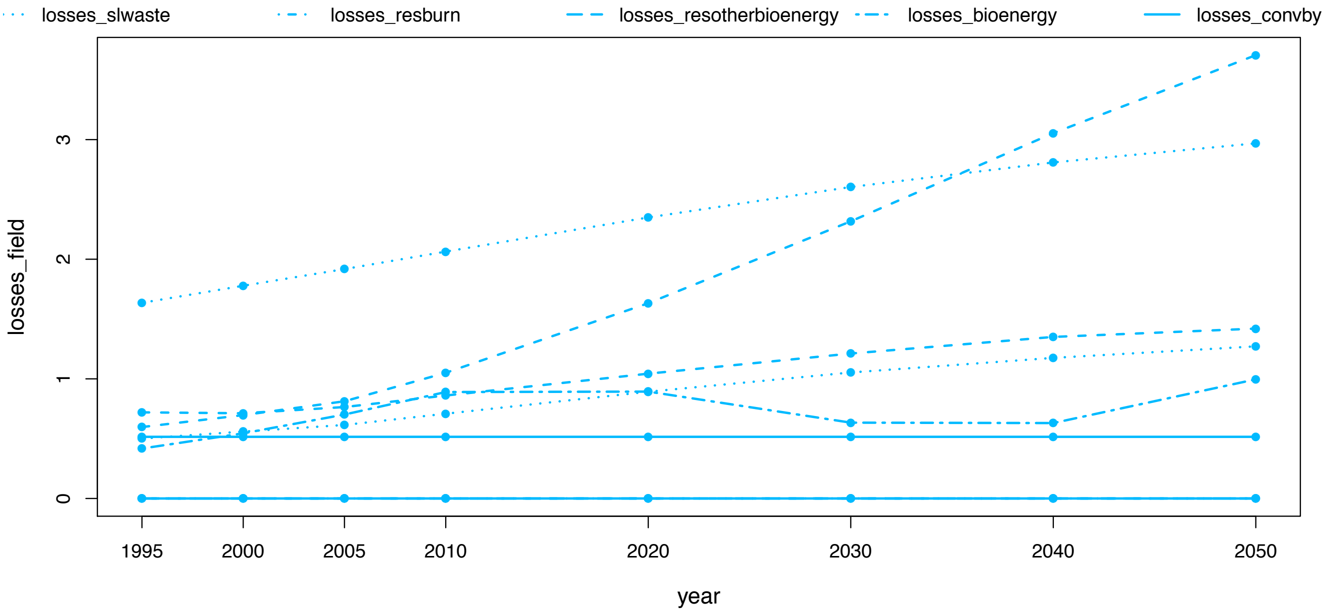

Figure 53: Losses Gesamt

54 Losses Total sum (global)

54.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
GLO.1	4.39	4.81	5.33	6.09	7.33	8.33	9.53	10.88

Table 54: Losses Gesamt Sum

54.2 Figures

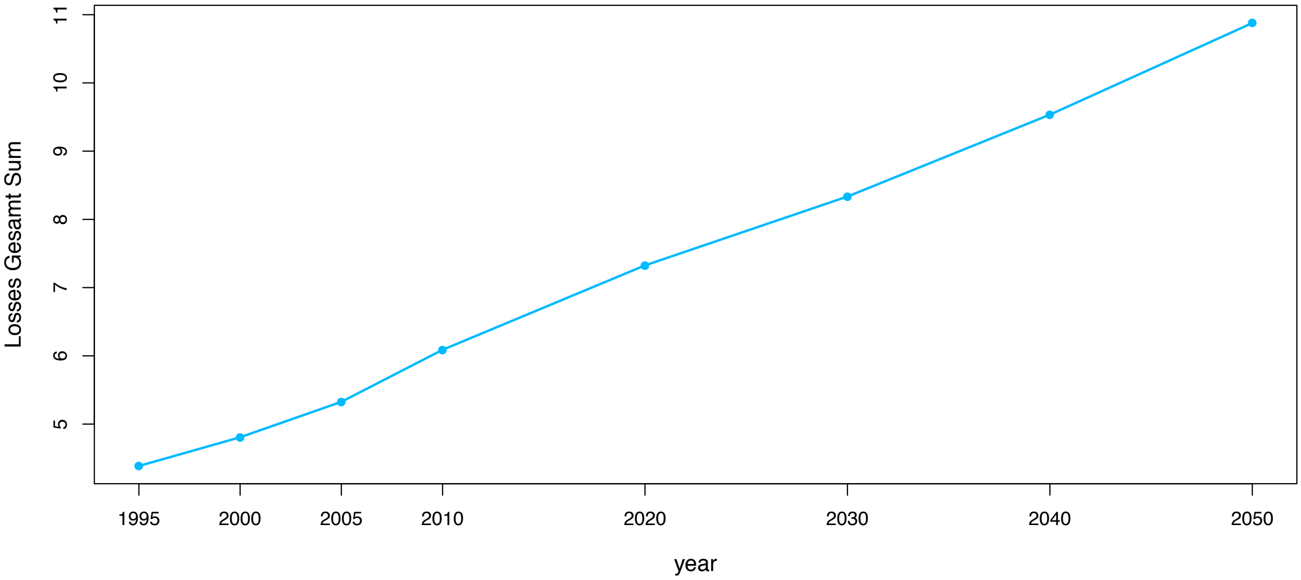

Figure 54: Losses Gesamt Sum

55 Animal Budgets

55.1 Tables

	y1995	y2000	y2005	y2010	y2020	y2030	y2040	y2050
concentrate	2.83	3.18	3.58	4.41	6.15	7.70	8.95	9.72
fodder	2.08	2.14	2.26	2.40	2.70	3.07	3.45	3.91
pasture	12.33	13.68	14.88	16.65	19.36	21.30	22.18	22.40
residues	1.76	1.98	2.21	2.55	2.98	3.30	3.59	3.53
convby	2.07	2.29	2.49	2.67	3.03	3.36	3.64	3.86
scavenging	1.27	1.56	1.87	2.43	3.02	3.17	3.00	2.74
losses_awms	-0.72	-0.71	-0.76	-0.86	-1.04	-1.21	-1.35	-1.42
manure_fuel	-2.14	-2.54	-2.92	-3.52	-3.82	-3.54	-3.04	-2.46
manure_grazing	-10.45	-11.58	-12.59	-14.17	-16.86	-18.90	-19.85	-20.19
manure_recycl_cropl	-5.85	-6.46	-7.05	-7.88	-9.34	-10.56	-11.54	-11.94
manure_recycl_past	-0.60	-0.70	-0.81	-1.05	-1.63	-2.32	-3.05	-3.71
slaughtered_animals	-2.58	-2.86	-3.14	-3.62	-4.56	-5.37	-5.98	-6.44

Table 55: Animal Budget

55.2 Figures

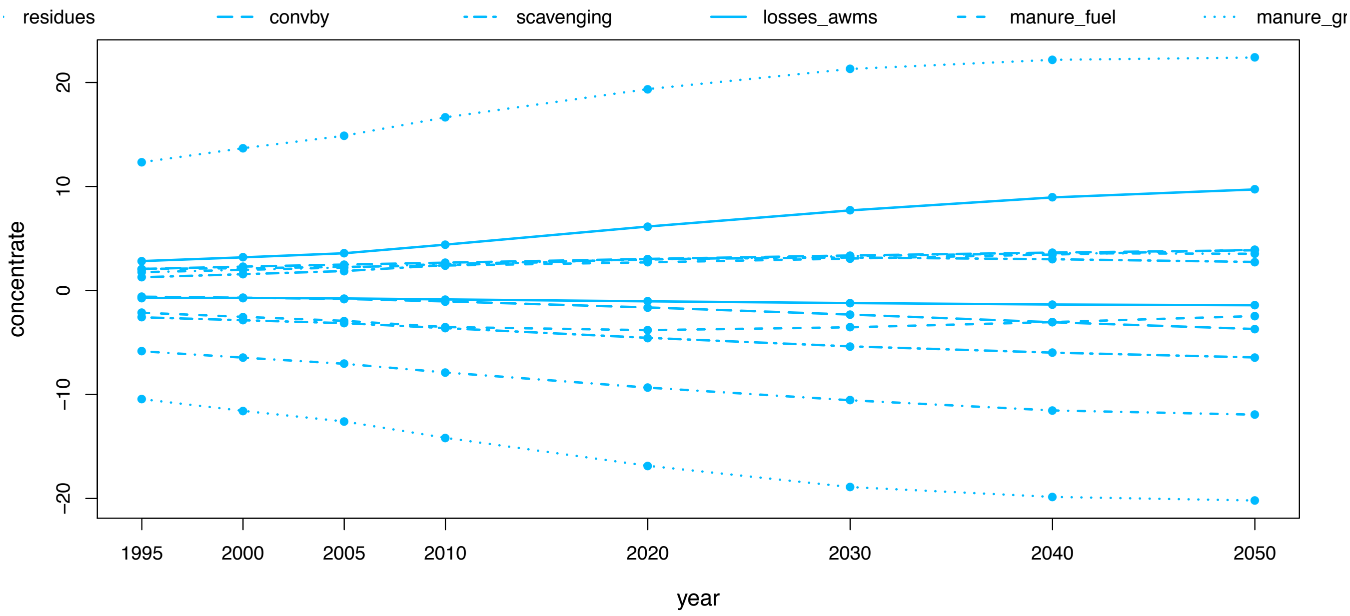

Figure 55: Animal Budget

Eidesstattliche Erklärung

Hiermit erkläre ich an Eides statt, die vorliegende Masterarbeit selbständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt zu haben.

Berlin, 28. Juni 2014