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Options for increasing nutrient use efficiency in Dutch dairy and arable farming towards 2030

An exploration of cost-effective measures at farm and regional levels

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rapporten

WOt

Wettelijke Onderzoekstaken Natuur & Milieu

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Options for increasing nutrient use efficiency in Dutch dairy and arable farming towards 2030

The 'WOt Reports' series presents the findings of research projects implemented for the Statutory Research Tasks Unit for Nature & the Environment by various centres of expertise.

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Abstract
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The study assessed nutrient use efficiency improvements and cost-effectiveness of measures at farm and regional levels in dairy and arable farming. The main improvements can be achieved in dairy farming, especially in the conversion of feed to useful products (meat and milk) through breeding efforts and feed improvements. In addition, phosphate use efficiency can be improved by banning mineral P fertiliser on P-saturated soils. End-of-pipe measures can increase efficiencies, though they are currently still relatively expensive; only by transforming agriculture to 'smart nature', like wetlands, can further gains be achieved. Taking nutrient use efficiency as a point of departure proves useful in clarifying and identifying the greatest challenges to Dutch agriculture. From a global perspective, only an increase in the efficiency of nitrogen and phosphate use can meet the increased demand for agricultural products while at the same time reducing losses to the environment.

Keywords: Nutrient management, nitrogen, phosphate, nutrient use efficiency

Referaat
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De mogelijkheden zijn onderzocht om de nutriëntengebruiksefficiëntie (N en P) te verhogen door de inzet van bedrijfs- en regionale maatregelen in de melkveehouderij en akkerbouw. Belangrijkste verbeteringen kunnen bereikt worden in de melkveehouderij, vooral in de conversie van voer naar nuttig product (vlees en melk) door fokkerijmaatregelen en voerverbetering. Daarnaast wordt de gebruiksefficiëntie van fosfaat vooral verhoogd door een verbod op P-kunstmest voor P-verzadigde gronden. *End of pipe* maatregelen kunnen verliezen van N en P verminderen maar zijn op dit moment nog tamelijk duur; alleen door het veranderen van landbouw in 'slimme natuur', zoals het creëren van wetlands in veengebieden, kan winst geboekt worden. Het gebruik van de indicator nutriëntengebruiksefficiëntie blijkt nuttig in het verduidelijken en onderscheiden van de belangrijkste milieu-uitdagingen in de Nederlandse landbouw. Bezien vanuit een globaal perspectief kan slechts een verhoging van de nutriëntengebruiksefficiëntie de verhoogde vraag naar landbouwproducten ondervangen, terwijl tegelijkertijd de verliezen naar het milieu verminderen.

Trefwoorden: Nutriëntenmanagement, stikstof, fosfaat, nutriëntengebruiksefficiëntie

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Executive summary

The study assessed nutrient use efficiency improvements and cost-effectiveness of measures at farm and regional levels in dairy and arable farming. The main improvements can be achieved in dairy farming, especially in the conversion of feed to useful products (meat and milk) through breeding efforts and feed improvements. In addition, phosphate use efficiency can be improved by banning mineral P fertiliser on P-saturated soils. End-of-pipe measures can decrease losses, though they are currently still relatively expensive; only by transforming agriculture to 'smart nature', like wetlands, can further gains be achieved. Taking nutrient use efficiency as a point of departure proves useful in clarifying and identifying the greatest challenges to Dutch agriculture. From a global perspective, only an increase in the efficiency of nitrogen and phosphate use can meet the increased demand for agricultural products while at the same time reducing loses to the environment.

Introduction

The great challenge to Dutch agriculture in the period leading up to 2030 is to maintain or increase productivity while at the same time decreasing nutrient inputs and thereby nutrient losses to the environment. In this respect, the adjustment of N and P supplies to crop and animal demand without excess or deficiency is the key to optimised trade-offs between yield, profit and environmental protection. In addition, the environmental measures that are being developed for the future should take into account the narrow profit margins that farmers have in the highly competitive agricultural markets. It is the cost-effectiveness of environmental measures that has a major impact on the adoption of new technologies by farmers.

In view of the above challenges, research was needed to assess how nutrient use efficiencies can be increased in Dutch agriculture in the period leading up to 2030. We have also evaluated the cost-effectiveness of the environmental measures, in order to assess the feasibility of their adoption by farmers.

What is lacking in current quantitative research efforts on nutrient management is a longer term perspective (2030) and management practices that can be implemented beyond experimental farm conditions. This study tried to look further and explore the options for increasing nutrient use efficiencies towards 2030. Data from experimental farms as well as theoretical (laboratory-based) insights were used to produce this outlook.

Nutrient use efficiency (NUE) is defined as:
NUE = tradable outputs / all inputs
= (exported crops + exported animals + exported milk, cheese & butter) / (imported animals + imported bedding + imported feed + mineral fertilisers + imported manure + deposition & biological fixation)

NUE improvements should come from increased outputs and/or decreased inputs. The greatest opportunities for doing this, however, lie in improving nutrient recycling *within* farms or within a region.

The present study deliberately used nutrient use efficiency as the indicator for environmental policy. This approach has many advantages, as well as some disadvantages, the most important of which are the following:

- NUE is an integrative indicator. NUE does not distinguish between the different losses and the different compartments the losses act on. NUE takes an integrated approach in which N losses to the atmosphere are as important as those to groundwater, etc.
- NUE can be a positive indicator for farm policy and farm management. Unlike the indicator of loss (input – output) and the rigid application standards, NUE can be used as a more positive indicator, as it focuses on increasing overall efficiency and makes use of 'end norms'.
- NUE takes a regional or even global approach. Overall, it focuses on increasing efficiency at any intensity level, optimising output for each input.

The major assumptions underlying this study are:

- This study investigated both nitrogen and phosphate use efficiencies.
- The environmental measures were divided into currently known measures and those foreseen for the future, the former allowing more scientific certainty and extensive research than the latter.
- The objects of investigation were the agricultural sectors of dairy and arable farming, i.e., the two sectors that environmental measures are aiming at. Pig farming was included as a black box.
- The 10% largest farms in 2006 were used as a model farm, in terms of size (ha) as well as inputs, outputs and farm economics.
- For the plant and soil effects, a distinction was made between various soil types: clay, sand and peat.
- Cost-effectiveness was calculated by internal costs only.
- Current application standards were used for N and P farm inputs.
- Farm level was taken as the point of departure for model analysis.

The model

The basis for our exploratory farm model is the Schröder *et al* (2003) whole farm flow model, which is depicted in Figure S1. Apart from import (IM) and export (EX), the 'buttons' which drive NUE are the conversion rates between the four compartments (soil, harvested crops, animal feed and manure). It is here that major improvements are being explored.

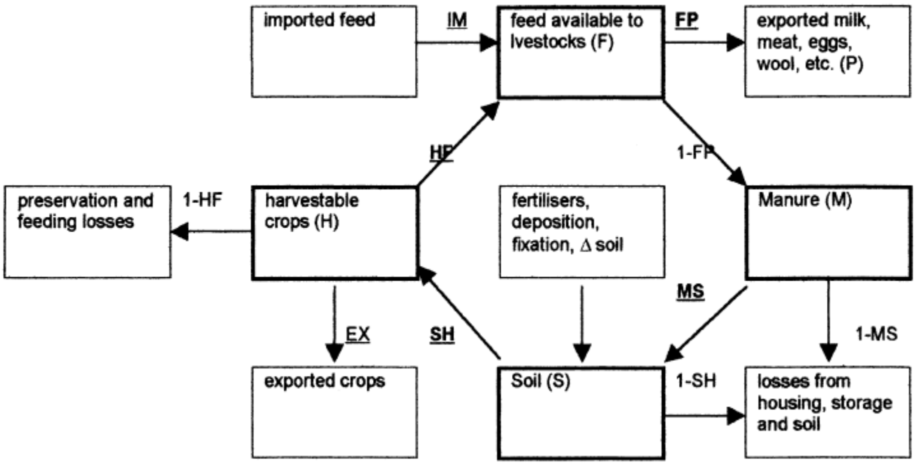


Figure S1: Flow diagram for a mixed farming system (Schröder et al, 2003), also representing an arable farm when the upper three boxes are ignored. The arrows indicate conversion factors.

The above model was coupled to an economic sub-model evaluating cost-effectiveness. Figure S2 visualises the overall model outline.

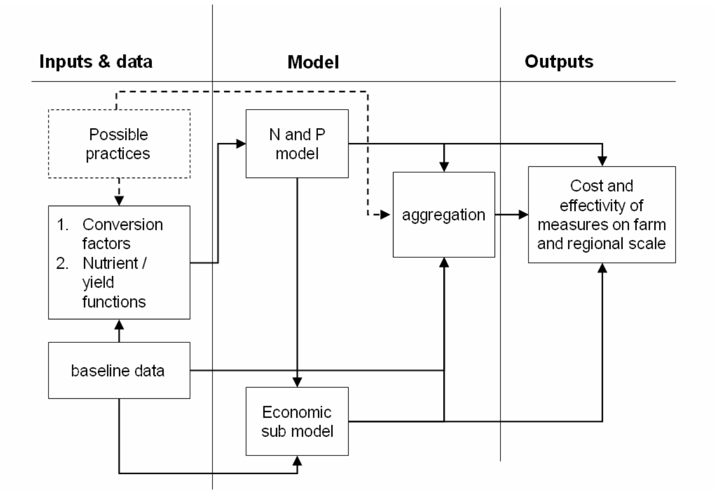


Figure S2: Flowchart of the framework for determining costs and benefits of N and P efficiencies; flows consist of data.

The model calculates the nutrient and capital flows using the available baseline information. A farm optimisation module was not included in the model described here, for a number of reasons: (i) after farm optimisation it is hard to compare the farm (because its structure changes); and (ii) we lacked resources to build a reliable optimisation model. The model assumes that the volume of production is constant, but the means needed for it (be it nutrients or capital) may be subject to change.

Measures

Table S1 gives an overview of possible measures on the regional nutrient use efficiencies.

Table S1: Overview of measures

Currently known	Foreseen for future
Catch crops	Phosphate mining
Herd management	Animal breeding for NUE
No tillage	Crop breeding for NUE
Time- and site-specific management	Nitrification inhibitors
Controlled release fertiliser	Bioreactor
Fodder quality	
Manure separation	
Manure processing	
Wetlands	
Riparian buffers	

The effects of some land use scenarios on the regional nutrient use efficiencies were also investigated. The land use scenarios are based on foreseen trends in Dutch agriculture, like an increase in dairy farming at the expense of arable farming. Other land use scenarios are: (i) more bio-fuel crops, (ii) habitat development on former agricultural land and (iii) large-scale water filtering areas.

Results

Results are given for the aggregate regional level for nitrogen and phosphorus use efficiencies (tables S2 and S3). The measures are ranked according to cost-effectiveness (€/ΔNUE%/ha).

For both N and P, measures that aim at the animal subsystem (conversion of feed to useful product) have the scores. Though animal breeding aimed at NUE improvement is still in its infancy, this measure offers great potential, while improved animal feed already showed good NUE results in the current research. Both measures need further attention for better implementation. As regards P use efficiency, a ban on mineral P fertiliser on P-saturated fields had particularly favourable effects on PUE.

Table S2: Ranking of all measures according to cost-effectiveness at regional level (€/ΔNUE%/ha)

	NUE change (ΔNUE%)	**N surplus change (Δkg/ha)**	**Cost (€/ha)**	**Cost-effectiveness (€/ΔNUE%/ha)**	**Cost-effectiveness (€/ kg N/ha)**
Improved feed	1%	-9	€ 84-	-91*	-10*
Animal breeding	5%	-42	€ 203-	-40*	-5*
No tillage (grassland)	1%	-10	€ 8-	-8*	-1*
Crop breeding	2%	-14	€ 80	52	6
Time- and site-specific management	0%	-3	€ 4	14	1
Bioreactors	0%	-4	€ 40	NA	11
Wetlands	0%	-22	€ 125	319	6
Catch crops	1%	-6	€ 24	34	4
Manure processing	4%	-76	€ 821	184	9
Riparian wet buffer	0%	-15	€ 547	NA	37
Riparian dry buffer	0%	-13	€ 528	NA	40
Nitrification inhibitors	0%	0	€ 17	461	48
P fertiliser prohibition	0%	0	€ 14-	NA	NA
P mining	-3%	29	€ 18	-6	-1

* Indicating a benefit (win-win)

Table S3: Ranking of all measures according to cost-effectiveness at regional level (€/ΔPUE%/ha)

	PUE change	**P_2O_5 surplus change (kg/ha)**	**Cost (€/ha)**	**Cost-effectiveness (€/PUE%/ha)**	**Cost-effectiveness (€/kg P_2O_5/ha)**
Animal breeding	5%	-8	€ 203-	-42*	-26*
Ban on mineral P	18%	-24	€ -14	-1*	-1*
No P on grass	5%	-8	€ 11	2	1
Wetlands	0%	-3	€ 125	355	46
Crop breeding	0%	1	€ 80	137	74
Improved feed	0%	0	€ 84	NA	NA
Riparian wet buffer	0%	-2	€ 547	NA	244
Riparian dry buffer	0%	-2	€ 528	NA	269
No tillage (grassland)	0%	0	€ 8-	NA	NA
Nitrification inhibitors	0%	0	€ 17	NA	NA
Bioreactors	0%	0	€ 40	NA	NA
Site-specific fertilisation	0%	1	€ 4	-10	-5
Catch crops	0%	1	€ 24	-48	-26
Manure processing	-10%	22	€ 782	-77	-35

* Indicating a benefit (win-win)

Implications and reflections

Dairy sector key to improving NUE

Overall, our findings show that the highest nutrient use efficiency gains can be achieved in the dairy sector. At the moment, this sector has a nitrogen use efficiency of 24%, while that in the arable sector is 51%. This is of great importance, especially because dairy farming occupies two-thirds of Dutch agricultural land. It is particularly in the conversion of animal feed to useful products that efficiencies are low, and increasing them can imply environmental and financial gains. The animal sectors convert large amounts of nitrogen in imported fodder into nitrogen in manure, which is currently inefficiently used. The most suitable way to improve this is by reducing the fodder required for producing milk and meat. Breeding efforts aimed at improving NUE in cattle, as well as fodder quality improvements, provide opportunities to increase NUE. The combined result of both measures can improve regional NUE and PUE (including arable farming) from 33% to 38% and from 51% to 56%, respectively. These measures imply that new technologies will become available in the course of the next twenty years and that breeding efforts will have to be directed towards more nutrient-efficient cattle. Policy makers can stimulate this development by reducing N and P application standards on grassland.

Banning mineral P on P-saturated soils: a promising tool to improve PUE

From the point of view of phosphate use efficiency (PhosphateUE), only a few measures showed promising results in our model study. We conclude that, of the currently available measures, P mining, improved feeding and animal breeding offer some potential. A ban on artificial P fertiliser in particular can have a great impact on overall PUE and should be considered by policy makers as a realistic measure to improve PUE.

Wetlands on peat decrease losses

The construction of wetlands, especially in peat soil areas, can also greatly decrease N and P *losses to the environment*, although it will not improve nutrient use efficiency because the nutrients stay within the system. Dairy farming is less profitable in peat areas than in other areas, and NUE is low. Consequently, it is cheaper to create wetlands in these areas. Within the context of the EU Water Framework Directive and nature management policy, smart, multifunctional nature (wetlands) offers opportunities for synergies.

Low-tech time and site-specific management has potential

In the plant sector, breeding efforts can also improve NUE, but efficiency gains are more difficult to achieve. Efforts focusing on time- and site-specific nutrient management are promising and should be stimulated. There is a need to make low-tech instruments available to farmers, allowing them to adjust nutrient supply more judiciously to nutrient demand.

Manure separation improves nitrogen use efficiency but challenges remain

Manure processing has been a popular instrument in current debates on sustainable agriculture. From an NUE (N) perspective, however, it is not the anaerobic digestion of manure but the subsequent separation and combustion of the solid fraction that looks promising. Both fractions (liquid and solid) reduce nitrogen emissions: the liquid fraction through its increased Nitrogen Fertiliser Value (NFV), which diminishes the need for artificial fertiliser and hence increases NUE, and the solid fraction because it can be combusted and leave the system as harmless N_2. The latter does not increase NUE but does decrease nitrogen pollution. It remains a challenge to turn the remaining P into a useful resource. At the moment, heavy metal concentrations (copper and zinc) in the combusted leftovers are too high, making the measure rather expensive.

Trend towards more dairy not necessarily bad for NUE
Autonomous trends in Dutch land use predict a shift from arable to dairy farming, a shift from agriculture to natural habitats, and a possible increase in the cultivation of biofuel crops. The shift from arable to dairy farming does not necessarily have to be negative, especially if dairy farming keeps on improving yields and if the overall efficiencies of NUE and PUE can remain equal or even increase, compared to current figures. Less promising are the nature management plans. If one third of current farmland is converted to natural habitats, NUE and PUE will decrease, at high costs (a loss-loss situation in terms of both nutrient use efficiency and cost-effectiveness). However, this scenario also offers opportunities for so-called smart nature: wildlife that converts nutrient losses to plant biomass (e.g. wetlands). The latter strategy will need a proper rethinking of the current bias towards oligotrophic habitat creation. The smart nature scenario requires a shift towards multifunctional, nutrient-rich nature. The Dutch public's preference for nutrient-rich forests shows a promising trend in this direction. The increased production of biofuels in crop rotations will have a negligible effect on nitrogen use efficiency and a small negative effect on phosphate use efficiency, since this requires less animal manure.

NUE approach useful
Taking nutrient use efficiency as a point of departure proves useful in clarifying and identifying the main challenges to Dutch agriculture. From a global perspective, only an increase in the efficiency of nitrogen and phosphate use can meet the increased demand for agricultural products while at the same time reducing losses to the environment. Consequently, further studies should try to build on our findings and also try to include efficiencies of imported products, as well as using other environmental indicators such as energy efficiency.

Samenvatting

In deze studie zijn de mogelijkheden onderzocht om de nutriëntengebruiksefficiëntie (N en P) te verhogen door de inzet van bedrijfs- en regionale maatregelen in de melkveehouderij en akkerbouw. Belangrijkste verbeteringen kunnen bereikt worden in de melkveehouderij, vooral in de conversie van voer naar nuttig product (vlees en melk) door fokkerijmaatregelen en voerverbetering. De gebruiksefficiëntie van fosfaat wordt daarnaast vooral verhoogd door een verbod op P-kunstmest voor P-verzadigde gronden. *End of pipe* maatregelen kunnen verliezen van N en P verminderen maar zijn op dit moment nog tamelijk duur; alleen door het veranderen van landbouw in 'slimme natuur', zoals het creëren van wetlands in veengebieden, kan winst geboekt worden. Het gebruik van de indicator nutriëntengebruiksefficiëntie blijkt nuttig in het verduidelijken en onderscheiden van de belangrijkste milieu-uitdagingen in de Nederlandse landbouw. Bezien vanuit een globaal perspectief kan slechts een verhoging van de nutriëntengebruiksefficiëntie (NUE) de verhoogde vraag naar landbouwproducten ondervangen, terwijl tegelijkertijd de verliezen naar het milieu verminderen.

Inleiding

Een belangrijke uitdaging voor de Nederlandse landbouw richting 2030 ligt er in om de productiviteit te handhaven of te verhogen en om tegelijkertijd het nutriëntengebruik te verminderen. Daarnaast zullen toekomstige milieumaatregelen de kleine marges in rekening moeten nemen die boeren ontvangen in zeer competitieve internationale markten. Het is de kosteneffectiviteit van milieumaatregelen die een grote invloed heeft op de adoptie van nieuwe technologieën door boeren.

De bovengenoemde uitdagingen maken het noodzakelijk dat onderzoek verricht wordt op hoe de nutriëntengebruiksefficiëntie in de Nederlandse landbouw verhoogd kan worden richting 2030. Aansluitend, evalueren wij de kosteneffectiviteit van de milieumaatregelen om de haalbaarheid van de maatregelen te bepalen.

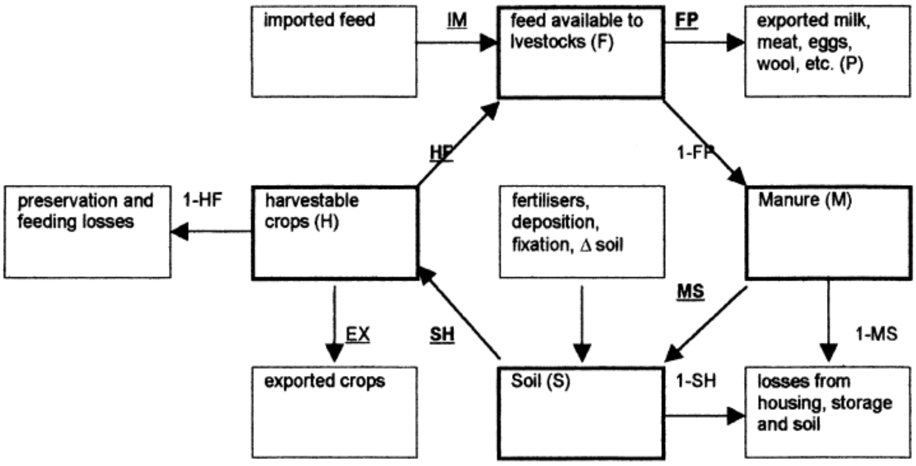
Nutriëntengebruiksefficiëntie (NUE) is gedefinieerd als:

NUE = nuttige output / alle inputs
= (geëxporteerde gewassen + geëxporteerde dieren + geëxporteerde melk, kaas & boter) / (geïmporteerde dieren + geïmporteerd stro + geïmporteerd voer + kunstmest + geïmporteerde dierlijke mest + depositie & biologische N fixatie)

Verbeteringen in NUE moeten komen van verhoogde nuttige outputs en/of verminderde inputs. De beste mogelijkheden om dit te bereiken liggen in verbeteringen in nutriënten recycling binnen de boerderij of binnen de regio.

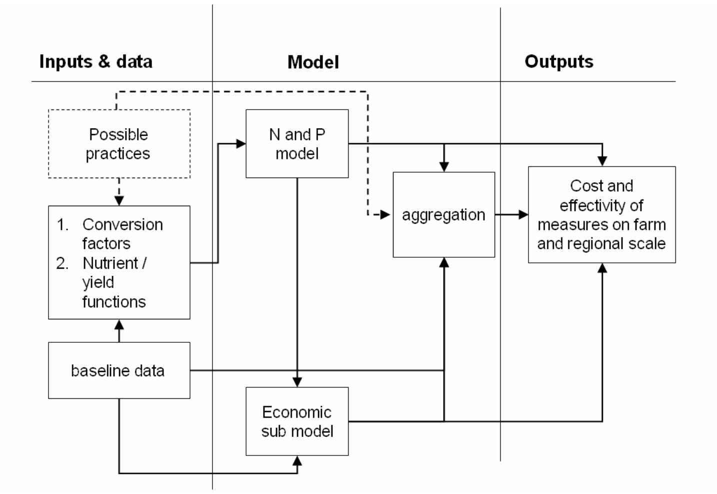
Het model

De basis voor ons verkennende bedrijfsmodel vormt het Schröder *et al* (2003) 'whole farm flow model'. Figuur S1 visualiseert dit model. De 'knoppen' die NUE aandrijven zijn, buiten import (IM) en export (EX), de conversie ratio tussen de vier compartimenten (bodem, geoogst gewas, voer en mest). Het is in deze conversiefactoren dat de grootste NUE verbeteringen mogelijk zijn.



Figuur S1: Stroomschema voor een gemengd system (Schröder et al, 2003). Beschrijft ook een akkerbouw bedrijf als de drie bovenste blokken niet meegenomen worden. De pijlen beschrijven de conversiefactoren.

Het bovenstaande model is gekoppeld aan een economisch submodel dat de kosteneffectiviteit evalueert. Figuur S2 visualiseert de totale modelomgeving.



Figuur S2: Stroomschema van het kader om de kosten en baten van N- en P-efficiënties te berekenen; stromen bestaan uit data.

Het model berekent de nutriënten- en kapitaalstromen door gebruik te maken van de aanwezige baseline informatie. Bedrijfsoptimalisatie is niet in het model betrokken om een aantal redenen:
i) na bedrijfsoptimalisatie is het moeilijk om het bedrijf te vergelijken (omdat de structuur is veranderd); en
ii) omdat ons de middelen ontbrak om een betrouwbaar optimalisatiemodel te bouwen. Het model neemt aan dat het productievolume constant is, maar dat de middelen noodzakelijk hiervoor (dan wel nutriënten dan wel kapitaal) kunnen verschillen.

Maatregelen

Tabel S1 geeft een overzicht van mogelijke maatregelen om de nutriëntengebruiksefficiëntie te verhogen.

Tabel S1: Overzicht van maatregelen

Huidig	**Toekomstig**
Vanggewassen	Fosfaat 'mining'
Jongvee management	Fokkerijmaatregelen
Geen grondbewerking	Plantenveredeling
Geleide bemesting	Nitrification inhibitors
Controlled release fertilizer	Bioreactor
Voerkwaliteit	
Mestscheiding	
Mestverwerking	
Wetlands	
Bufferstroken	

Daarnaast zijn een aantal effecten van landgebruikscenario's op de regionale nutriëntengebruiksefficiëntie (NUE) onderzocht. De landgebruikscenario's bouwen voort op de voorziene trends in de Nederlandse landbouw, zoals een grotere melkveehouderij ten koste van akkerbouw. Andere landgebruikscenario's zijn: i) meer verbouw van gewassen voor biobrandstof; ii) natuur in plaats van landbouw; en iii) grootschalige waterfilterings-gebieden.

Resultaten

Resultaten zijn gegeven voor het geaggregeerde regionale niveau voor stikstof en fosfaat gebruiksefficiënties (tabel S2: N en tabel S3: P). De maatregelen zijn geordend op basis van kosteneffectiviteit per NUE verandering (€/ΔNUE%/ha).

Tabel S2: Ranking van alle maatregelen op basis van kosteneffectiviteit per N-gebruiksefficiëntie verandering op regionaal niveau (€/ΔNUE%/ha)

	NUE verandering (ΔNUE%)	**N surplus verandering (Δkg N/ha)**	**Kosten (€/ha)**	**Kosten-effectiviteit (€/ΔNUE%/ha)**	**Kosten-effectiviteit (€/Δkg N/ha)**
Voerverbetering	1%	-9	€ 84-	-91*	-10*
Fokkerijverbetering	5%	-42	€ 203-	-40*	-5*
Geen grondbewerking	1%	-10	€ 8-	-8*	-1*
Plantenverdeling	2%	-14	€ 80	52	6
Geleide bemesting	0%	-3	€ 4	14	1
Bioreactor	0%	-4	€ 40	NA	11
Wetlands	0%	-22	€ 125	319	6
Vanggewassen	1%	-6	€ 24	34	4
Mestverwerking	4%	-76	€ 821	184	9
Natte bufferstrook	0%	-15	€ 547	NA	37
Droge bufferstrook	0%	-13	€ 528	NA	40
Nitrification inhibitors	0%	0	€ 17	461	48
P kunstmest verbod	0%	0	€ 14-	NA	NA
P mining	-3%	29	€ 18	-6	-1

* geeft dubbele winst aan (win-win: NUE-verhoging bij lagere kosten)

Zowel voor N als P, zijn het de maatregelen die zich richten op het dierlijke subsysteem (de conversie van voer naar nuttig product) die het best scoren. Hoewel fokkerijmaatregelen gericht op NUE nog pas in de kinderschoenen staan laat deze een grote potentie zien. Voerverbetering laat al goede resultaten zien in huidig onderzoek. Beide maatregelen verdienen meer aandacht in het onderzoek. Voor P-gebruiksefficiëntie (PUE) blijkt vooral een verbod op P-kunstmest op P-verzadigde bodems een groot effect te hebben. Ook op kosteneffectiviteit scoort deze maatregel goed.

Tabel S3: Ranking van alle maatregelen op basis van kosteneffectiviteit per P-gebruiksefficiëntie verandering op regionaal niveau (€/ΔPUE%/ha)

	PUE verandering (ΔPUE%)	**P_2O_5 surplus verandering (Δkg/ha)**	**Kosten (€/ha)**	**Kosten-effectiviteit (€/ΔPUE%/ha)**	**Kosten effectiviteit (€/Δkg P_2O_5/ha)**
Fokkerijverbetering	5%	-8	€ 203-	-42*	-26*
Ban on mineral P	18%	-24	€ -14	-1*	-1*
No P on grass	5%	-8	€ 11	2	1
Wetlands	0%	-3	€ 125	355	46
Plantenveredeling	0%	1	€ 80	137	74
Voerverbetering	0%	0	€ 84	NA	NA
Natte bufferstrook	0%	-2	€ 547	NA	244
Droge bufferstrook	0%	-2	€ 528	NA	269
Geen grondbewerking	0%	0	€ 8-	NA	NA
Nitrification inhibitors	0%	0	€ 17	NA	NA
Bioreactors	0%	0	€ 40	NA	NA
Geleide bemesting	0%	1	€ 4	-10	-5
Vanggewassen	0%	1	€ 24	-48	-26
Mestverwerking	-10%	22	€ 782	-77	-35

* geeft dubbele winst aan (win-win: PUE-verhoging bij lagere kosten)

Implicaties en reflecties

Melkveehouderij is sleutel tot NUE verbetering

Over het algemeen kan gesteld worden dat de hoogste NUE-verhogingen in de melkveehouderij bereikt kunnen worden. Op dit moment heeft de melkveehouderij een stikstofgebruiksefficiëntie van 24% tegenover 51% in de akkerbouw. Dit is van groot belang omdat de melkveehouderij tweederde van het Nederlandse grondgebied in beheer heeft. Vooral de efficiënties in de conversie van veevoer naar nuttig product zijn laag. Het verhogen hiervan kan grote milieu en economische winst betekenen. De meest logische weg om dit te verbeteren is door de benodigde hoeveelheid (N en P in) veevoer te verminderen om melk en vlees te produceren. Fokkerijmaatregelen die gericht zijn op het verhogen van NUE en het verbeteren van de voerkwaliteit leveren goede mogelijkheden om NUE te verhogen. Het gecombineerde resultaat van beide maatregelen kan zowel de N- als P-gebruiksefficiënties verhogen van respectievelijk 33% naar 38% en 51% naar 56% (op regionaal niveau inclusief akkerbouw). Deze maatregelen impliceren dat nieuwe technologieën beschikbaar komen in de loop van de komende 20 jaar en dat meer fokkerij middelen worden ingezet op NUE.

Verbod op P kunstmest op P verzadigde bodems

Bekeken vanuit P-gebruiksefficiëntie, laten slechts een klein aantal maatregelen goede resultaten zien. Wij concluderen dat van de onderzochte maatregelen P-mining, voerverbetering en fokkerijmaatregelen potentie hebben. Vooral een verbod op P-kunstmest op P-verzadigde bodems kan een grote invloed hebben op de totale PUE en zou door beleidsmakers overwogen moeten worden als een realistische maatregel om PUE te verhogen.

Wetlands op veen verminderen verliezen

Daarnaast kan de constructie van wetlands, vooral in veengebieden, een grote verlaging van N- en P-*verliezen* betekenen. Deze maatregel verhoogt echter niet de NUE omdat de nutriënten (in het plantenmateriaal) in het systeem blijven zitten. In de veengebieden is de melkveehouderij het minst winstgevend vergeleken met de andere gebieden. Bovendien is de NUE daar laag. Daarom is het goedkoper om wetlands in deze gebieden te creëren. Binnen de context van de Kaderrichtlijn Water en het natuurbeleid biedt slimme multifunctionele natuur mogelijkheden voor synergie.

Low-tech geleide bemesting biedt potentie

In het plant-compartiment van het onderzoek kan veredeling de NUE ook verbeteren, hoewel een stuk moeilijker dan in het dierlijke compartiment. Inspanningen gericht op geleide bemesting zijn veelbelovend. Er is een behoefte dat low-tech instrumenten beschikbaar komen voor boeren zodat de nutriëntengift beter aangepast wordt op de nutriëntenvraag van de plant.

Mestscheiding verbetert NUE maar uitdagingen blijven

Mestverwerking is een populair instrument in de huidige debatten over duurzame landbouw. Vanuit een perspectief van de stikstofgebruiksefficiëntie lijkt niet de vergisting van mest veelbelovend maar eerder de scheiding en verbranding van de vaste fractie. Beide fracties (vast en vloeibaar) kunnen de stikstof emissies verlagen: de vloeibare fractie door de verhoogde werkingscoëfficiënt, welke de behoefte aan kunstmest vermindert, en de vaste factie doordat deze verbrand kan worden en het systeem kan verlaten in de vorm van het onschadelijke N_2. Het laatste verhoogt NUE niet maar verlaagt wel de reactieve stikstof emissie. Uitdagingen zijn er nog in het nuttig inzetten van de overgebleven P uit de verbrande fractie. Op dit moment is het gehalte aan zware metalen in het residu nog te hoog om het product als nuttige P af te kunnen zetten, waardoor de maatregel duur uitvalt.

Trend richting meer melkveehouderij niet noodzakelijkerwijs slecht voor NUE

De autonome trends in het Nederlandse landgebruik voorspellen een shift van akkerbouw naar melkveehouderij, een shift van landbouw naar natuur, en een mogelijke verhoging van de verbouw van biobrandstofgewassen. De shift van akkerbouw naar melkveehouderij hoeft niet per definitie slecht te zijn voor de totale NUE. Vooral wanneer de melkveehouderij in staat is de ingezette verbeteringen in melkopbrengst en de totale gebruiksefficiënties vast te houden of te verbeteren. Minder goede vooruitzichten zijn er voor de natuurbeleidsplannen. Als een-derde van het huidige landbouwareaal geconverteerd wordt in natuur zullen NUE en PUE verlagen tegen hoge kosten (een loss-loss situatie in termen van zowel NUE als kosteneffectiviteit). Desalniettemin biedt dit scenario mogelijkheden voor zogenaamde ‘ slimme natuur’: natuur die tegelijkertijd stikstofverliezen om kan zetten in plantenmateriaal (bv. wetlands). Deze strategie vereist wel een zorgvuldige herbezinning op de huidige bias op oligotrofe natuur. In het ‘slimme natuur’ scenario is een shift nodig richting multifunctionele nutriëntenrijke natuur. De voorkeur van het gemiddelde Nederlandse huishouden voor nutriëntenrijke natuur laat wat dit betreft een veelbelovende trend zien. De verhoging van biobrandstofgewassen in gewasrotaties zal een verwaarloosbaar effect hebben op de stikstofgebruiksefficiëntie en een klein negatief effect op de fosfaatgebruiksefficiëntie omdat minder dierlijke mest toegepast kan worden.

NUE benadering is nuttig

Het nemen van NUE als startpunt van onderzoek blijkt nuttig om de belangrijkste uitdagingen in het nutriëntenmanagement van de Nederlandse landbouw te onderscheiden en te verduidelijken. Bezien vanuit een globaal perspectief kan slechts een verhoging van de nutriëntengebruiksefficiëntie de verhoogde vraag naar landbouwproducten ondervangen, terwijl tegelijkertijd de verliezen naar het milieu verminderen. Aansluitend zullen vervolgstudies moeten proberen om onze bevindingen te verdiepen en ook efficiënties van geïmporteerde producten van buiten het systeem en andere milieu indicatoren zoals energie efficiëntie op te nemen.

1 Introduction

1.1 Problem definition

Dutch agriculture is being confronted with a persistent nutrient surplus or “manure surplus”. The nutrient surplus is rooted in cheap artificial fertilizers and low fodder prices that came available after World War II. The rapid intensification of both arable and livestock farming, supported by EU subsidies, caused a large increase in nutrient surpluses. The nitrogen surplus is to a large extent lost to the environment, while the phosphorus surplus is piled up in agricultural soils and from there increasingly leaks to surface waters. The nutrient losses affect the quality of groundwater and surface water, the atmosphere and nature.

Since the 1980s policy has been put in place to reduce these losses. Though the policy measures have instigated a decline in nutrient application, some environmental quality standards are still exceeded. Towards 2030 less and less nitrogen and phosphate can be applied to agricultural fields. Both the stricter implementation of the Nitrates Directive and the introduction of the EU Water Framework Directive are responsible for tightening of nitrogen and phosphorus application limits.

The great challenge for Dutch agriculture towards 2030 is to maintain or increase productivity while at the same time to decrease nutrient inputs and thereby nutrient losses. In this respect the adjustment of N supply to crop demand without excess or deficiency is the key to optimize trade-offs between yield, profit, and environmental protection (Cassman *et al*, 2002). In addition, the future environmental measures that are being developed should take into account the small margins that farmers have in highly competitive agricultural markets. It is the cost-effectiveness of environmental measures that has a large influence on farmer adoption of new technologies. New agricultural concepts have been developed to combine agricultural productivity with economic profitability and environmental quality. Such concepts are described as “sustainable agriculture” (Bergström and Goulding, 2005) or “ecological intensification” (Cassman, 1999).

Considering the above mentioned challenges, research is needed on how nutrient use efficiencies can be increased in Dutch agriculture towards 2030. Subsequently, we evaluate the cost-effectiveness of the environmental measures in order to assess the feasibility for farmers’ adoption.

1.2 Relevance

A proper insight in the costs of (future) environmental measures is highly needed to be able to assess the feasibility of environmental quality goals and to give policy recommendations on future good agricultural practices. Our research shows possibilities for win-win and examines tradeoffs between ecology and economy. Furthermore, we will elaborate on the practical implications of the measures and on the applicability of the measures at farm level.

We argue that the nutrient use efficiency (NUE) is a useful indicator in the context of decreasing stocks of fossil fuels and phosphate rock reserves, and in the context of an increasing and more demanding world population that will need a higher productivity per hectare. These trends indicate that a more judicious use of fertilizers is required while at the same time productivity needs to be increased at minimal extra costs. Our research explores possibilities for these aims.

1.3 Current and past research

Various researchers in North-western Europe are or have been undertaking studies in the field of improving NUE in agriculture and the assessment of its cost-effectiveness. Firstly, in the Swedish catchment of Rönneå water and soil quality experts are investigating the most cost-effective scenarios to reduce N and P loading (Arheimer *et al*, 2005; Larsson *et al*, 2005). Their research is centered at catchment level and the evaluated measures are being implemented at this scale level.

Secondly, Wageningen based agricultural economists compare current management practices with best management practices (BMP) using so-called frontier functions (Reinhard *et al,* 1999; De Koeijer 2002). The best management practices comprise the vanguard farmers that have already implemented newest insights in nutrient management. The groups of Reinhard & De Koeijer conclude that current [at that time] practices are not as efficient as BMP.

Thirdly, there are a number of studies that evaluated nutrient use efficiency improvements in the Netherlands on experimental farms (e.g. Wolleswinkel, 1999; De Haan, 2001; Groot *et al*, 2003). The studies on dairy farming all take the Experimental dairy farm "De Marke" as the point of departure and all take into account the economic consequences of decreasing environmental losses. Groot *et al* (2003; 2006) simulated and evaluated nutrient recycling improvements for dairy farms (also in VEL/VANLA). Their research is important in providing adequate and extensive attention to the internal manure-soil-plant-animal-manure conversion rates of nitrogen and the possibilities for improvement. A comparison demonstrated that farming systems can be designed in such a way that improvement of internal nutrient cycling supports the same production with lower inputs and lower emissions.

What is lacking in all these studies is a longer term perspective (2030) and management practices that go beyond experimental farm conditions. Our research tries to look further and explores the options for increasing nutrient use efficiencies towards 2030. Both data from experimental farms as well as theoretical (laboratory) insights will be used to achieve this outlook.

1.4 Definitions and concepts

Nutrient use efficiency (NUE) is being proposed as the best indicator to integrate economical viability and ecological desirability. Increasing NUE while at the same time maintaining productivity can contribute to the aim of a sustainable agriculture or ecological intensification. In addition, improving NUE easily integrates the pluriform environmental effects of nutrient surpluses and losses: If the NUE increases, as compared to the previous situation, overall environmental effects per kg of produce decrease (no matter in which compartment; soil, water or air). However, the concept of NUE is not without controversies. As Schröder *et al* (2003) point out; the scale level at which research is undertaken determines to a large extent the efficiencies. For example, the efficiency increases by splitting a mixed farm into a livestock and arable farm. By increasing the overall outputs (to the other farm) overall efficiencies improve, while losses remain equal. In our research, we do not use these "type of tricks" but fix farm conditions to a specific size and production level and use a common framework for analysis.

There are many misconceptions on the exact definitions of NUE, which may lead to difficulties in comparing outcomes of similar research. The bottom-line pitfall in this debate is that NUE is calculated as the ratio between output and input. If one counts up the different internal farm flows as input and at the same time as outputs, different efficiencies will be the result while losses are equal. Schröder *et al* (2005) illustrate this for 4 EU countries. Thus, it is important to define NUE well.

Several definitions have been proposed to define NUE based on different research aims. Dobermann and Cassman (2004) provide a good overview of NUE of applied N-fertilizers. They distinguish the partial factor productivity (PFP), the agronomic efficiency (AE), the apparent recovery efficiency (RE) and the physiological uptake efficiency (PE). For here it must be emphasized that these indices are mainly used for crop response to fertilizer N. They are rarely used in systems where organic sources and biological N fixation are the major N inputs.

In our research, we take nutrient in- and outputs from and to the farm as the point of departure. Deducted from Dobermann & Cassman (2004) the total factor productivity or whole farm efficiency (WFE) (Schröder *et al*, 2005) seems most appropriate for our research. Contrary to Schröder *et al*, (2005) we do not include manure export in the marketable exports. Manure is nowadays still more waste than produce.

Nutrient surplus data is also provided. End of pipe measures do not contribute to any increase in tradable output, however they can decrease losses; hence, the effect of end-of-pipe solutions can better be evaluated in terms of losses. Therefore, we deducted the filtering capacity of filters, wetlands and other end of pipe structures from the N surplus in order to compare source from end of pipe measures.

Comparisons between WFE's can only be made between similar farm types or at a regional level (Schröder *et al*, 2003). For comparing the effectiveness of measures regional nutrient use efficiency can best be used. This can be done by considering the region as one productive unit and then calculate the whole nutrient use efficiency of this unit.

$$\begin{aligned}\text{NUE} &= \text{tradable outputs / all inputs} \qquad (1)\\ &= (\text{exported crops} + \text{exported animals} + \text{exported milk, cheese \& butter}) \,/\\ &\quad (\text{imported animals} + \text{imported bedding} + \text{imported feed} + \text{mineral fertilizers} +\\ &\quad \text{imported manure} + \text{deposition \& biological fixation})\end{aligned}$$

Equation 1: NUE adapted from whole farm efficiency (WFE)

NUE improvements should come from increased outputs and/or decreased inputs. The greatest possibilities for doing this, however, lie in the improvements of nutrient recycling *within* the farm or within the region although the latter may lead to higher logistic costs. Understand and influencing NUE processes needs a proper understanding of nutrient conversions (and losses) of the farm sub-systems (Fig. 1).

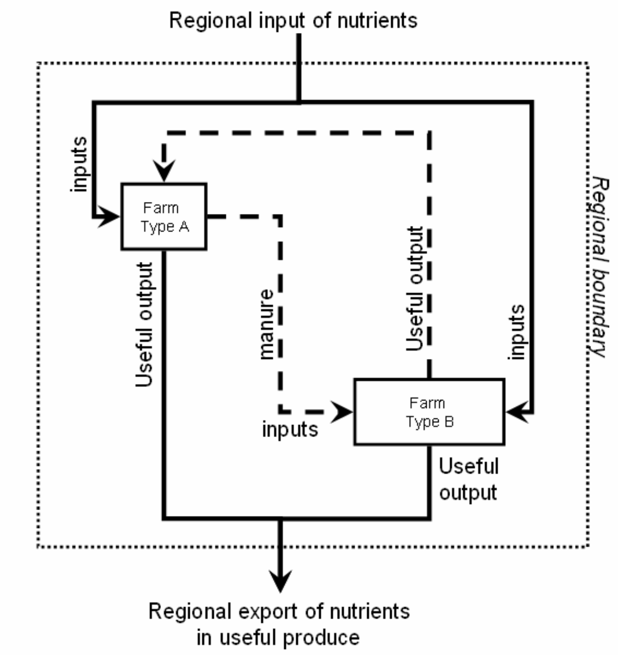


Figure 1: Overview of the flows that are used to calculate NUE. Regional inputs of nutrients include imported animals, imported bedding, imported feed, mineral fertilizers, imported manure, deposition & biological fixation. Exports consist of exported crops and exported animal products. The dashed arrows indicate inter-farm nutrient recycling processes.

In this research nutrient use efficiency is deliberately used as the indicator for environmental policy. This approach has many advantages and some disadvantages of which the following are the most important:

- NUE is an integrative indicator. NUE does not distinguish between the different losses and the different compartments the losses act on. NUE takes an integrated approach in which N losses to e.g. the atmosphere are as important as to e.g. groundwater.
- NUE can be a positive indicator for farm policy and farm managers. Unlike the indicator of loss (input – output) and the rigid application standards, NUE can be used as a more positive indicator as it focuses on increasing overall efficiency and makes use of 'end norms'.
- NUE has a regional or even global approach. Overall it focuses on increasing efficiency at any intensity level, optimizing output per input. Very intensive agriculture (with high inputs) can have high NUEs while at the same time cause serious local loss effects. At the regional or global scale level these high intensities may prove beneficial because at other places lower intensities are needed. Therefore, it can contribute to a diversified environmental policy in which extensive and intensive farms co-exist. On the other hand, for biodiversity policy (more used to generic threshold values and maximum loss norms) the NUE indicator might be less useful.

In the remainder of this report we will dig into the possibilities of improving NUE, while at the same time maximizing cost-effectiveness. In addition we will present our choices for nutrients, agricultural sectors, scale levels, soil types and the modeling approach.

2 Methodological considerations

This chapter outlines the assumptions that underlie the study. In brief we describe the methodological background, concerning: i) which nutrients are taken into account; ii) which measures are investigated; iii) in which agricultural sectors; and lastly iv) how we operationalize cost-effectiveness.

2.1 The nutrients

Nitrogen (N) and phosphorus (P) are the most important macronutrients in environmental regulations for groundwater- and surface water quality, and biodiversity. Till now most research on agronomic productivity has centered on N only. However, P will become increasingly important due to its more visible inclusion in the EU Water Framework Directive. Phosphorus is the nutrient with the highest and most persistent reserves in Dutch agricultural soils. As Schoumans *et al* (2002) estimate between 1950 and 2000 soils have on average been enriched by 8700 kg ha^{-1} of. P_2O_5, which is equivalent to 3800 kg ha^{-1} of P. As a consequence, about 1.2 million hectares are phosphate saturated (MNP, 2005). Therefore, phosphate will become, most probably, on a number of soil types, the most restricted nutrient in regulatory application standards in the upcoming decades.

For Dutch circumstances it is important to take into account both mineral and organic origins of N and P. Or as Schröder (2005) points out, it is undeniably easier to manage mineral fertilizers than manure. When proper attention is given to the composition of manure, and decisions on rates, timing and placement are made correspondingly, the N and P fertilizer value of manure can be enhanced. Consequently, it is also important to study the opportunities for improvement in organic N and P.

2.2 The measures

NUE improving measures can be categorized along different lines. We have chosen for two subdivisions that specify i) the stage of certainty the research is in, and ii) the type of measures.

The stage of current research on NUE improving measures varies widely. Some measures have been documented well: results have been cross-checked and measures have been applied to experimental fields and farms. On the other hand, there are measures that have only been tested in laboratory conditions or solely dwell on theoretical notions. We have made a distinction between these measures in: i) currently known, and ii) future foreseen. The certainty of the effects of the first group of measures is higher and sometimes the measures are already best management practices for vanguard farmers. The uncertainty of the results of the second group is higher and results moreover present an exploration of a wide range of promising pathways for agricultural development.

Secondly, we have distinguished the type of measures. This can be done in a number of ways, e.g. in: i) subsections of the farm (animal, plant, fodder, soil, manure); ii) management levels (best management, technological improvements, end of pipe, Oenema and Pietrzak, 2002); or iii) even more abstract, crop factors, environmental factors (e.g. radiation) and management factors (Balasubramanian *et al* 2004). In this research we have made a combination between i) and ii); we have separated between the dairy and arable farming and in addition have researched a number of end of pipe measures. Table 1 gives an overview of the measures.

Table 1: Overview of measures

Currently known	**Future foreseen**
Catch crops	Phosphate mining
Herd management	Animal breeding for NUE
No plowing for grassland renovation	Crop breeding for NUE
Time and site specific management	Nitrification inhibitors
Controlled release fertilizer	Bioreactor
Fodder quality	
Manure separation	
Manure processing	
Wetlands	
Riparian buffers	

Also, the effects of some land use scenarios on the regional nutrient use efficiencies have been investigated. The land use scenarios build on foreseen trends in Dutch agriculture, like an increase in dairy farming at the expense of arable farming. Other land use scenarios are: i) more bio-fuel crops; ii) nature for agriculture; and iii) large-scale water filtering areas.

Summarizing, four types of measures remain: i) dairy farm measures, ii) arable farm measures, iii) end of pipe measures, and iv) land use scenarios.

2.3 Agricultural sectors

For our research we take the dairy and arable sector as the main sectors of investigation. Together, dairy and arable farming are responsible for respectively 1.1 million and 0.6 million hectares of agricultural land. Out of a total of 1.9 million hectares used for agriculture, this means that these sectors occupy almost 90% of all agricultural land in the Netherlands (LEI-CBS, 2005). For studies towards 2030 it is important to take into account the viability of both sectors.

Current research concludes that especially the Dutch dairy sector, despite its high land and quota prices, has a promising (economic) future (Berkhout, 2002). Even with an anticipated decoupling of price support and income subsidies (in favour of the latter) Dutch dairy farming will prevail and might even expand. The effect of the abolishment of the milk quota for milk production in the Netherlands and EU is subject to debate. Lips and Rieder (2006) expect price declines and small production gains for the Netherlands (3%), Van Berkum & Helming (2006) included increased demands in developing countries and state that a 20–30 % growth till 2015 is more likely with favorable prospects for the years after 2015. Much however depends on other factors as manure policy and competitiveness of the arable farming sector (Berkhout, 2002; see also scenario in 4.8.1). Whilst dairy farming has a rather optimistic road ahead, the future for arable farming looks a bit grimmer. When decoupling of price support sets through, especially the profitability of starch potato and sugar beet will decrease. More specialized farms in seed and consumption potato and flower bulb growing have brighter prospects. Coping strategies that will develop due to declining (economic) margins involve: intensification, increased scale, extensification (see biofuel scenario) and extra-farming activities, like tourism (Smit, 2002).

Though intensive livestock farming does not have a direct influence on most of the agricultural land use, the indirect effects are enormous. The manure surplus it produces on a national scale has wide-spread implications on Dutch agriculture as a whole. We, therefore, have included intensive pig farming as black boxes that produce extra manure that needs to be applied, processed and/or exported from or in the region. However, we did consider measures to reduce nutrient emissions by calculating the environmental effects and costs of measures regarding the use and preparation of pig manure.

2.4 Farm specificaties

It is commonly accepted that farm management and farming production practices are no homogeneous and uniform activities on all farms. Farmers within a specific sector are different in their way of production and follow no uni-linear development patterns. Relations between scale and intensity, and farm (economic and ecologic) performance are not straightforward and different farming styles can be distinguished (Van der Ploeg, 1991). This also implies that farmers do not have the same nutrient management strategies which deal with reducing N and P losses. Therefore, farming styles diversity could be taken as the point of departure for farm research.

However, for our specific research we have decided not to do so. Though farming styles show successful results in the ex post description of consistent diversity in agricultural practices, it is more and more agreed upon that it is hazardous to apply the methodology to ex ante (future oriented) research and extension (Howden and Vanclay, 2000). The reification of farming styles by farmers themselves and a subsequent mythologisation or internalisation amongst farmers makes it hard to quantitatively justify the methodology for ex ante research. In addition, De Groot *et al* (2006) show that nutrient management development patterns change rapidly (within 5 years) amongst a rather homogeneous group of farmers (Table 2).

Table 2: Selected general characteristics of the modeled arable farms. Source: 1) Farm Accountancy Data Network for the year 2003 (LEI, 2006); 2) Simplified from LEI & CBS data (2006); 3) Regulatory maximum application (LNV 2006) 4) Nitrogen deposition from CBS (2006), 5) based on input data and uptake figures from Ten Berge (2006) and Aarts (2005) 6) Adapted form LEI (2006) using data from Aarts (2005), LNV (2006) & De Wolf & Van der Klooster (2006). Farm economic losses did occur in the years before and after 2003.

	Clay	**Sand**
Size(ha)[1]	152	152
Rotation[2]	Sugar beet/ ware potato / winter wheat / maize	
P_2O_5 (kg ha^{-1}) in[3]	90	80
PUE[5]	65%	71%
N (kg ha^{-1}) in [3,4]	239	236
NUE[5]	52%	51%
Benefit (k€)[6]	466	461
Cost (k€)[6]	383	382
Cost, including calculated labor and capital costs(k€)[1]	556	555
Farm economical result (k€)	-90	-93

For quantitative research, farm size (in hectares) and intensity (in production/hectare) are the most important variables. We have taken the current top 10% farms (in terms of area or Dutch cattle units) as the starting point for our analysis, assuming that these farms will be the common farms in 2030. Table 2, 3 and 4 provide an overview with the characteristics of our model farms. As can be observed we differentiated between soil types within the region (but not within farms) because soil type is very important for nutrient retention, uptake and leaching. A classic distinction is made between clay (40 % of area of region), sand (40%) and peat (20%). The distribution of the holding types in the region (dairy, arable, pig keeping) reflects the Dutch situation as best as possible (Alterra, 2006).

Table 3: Selected general characteristics of the modeled dairy farms. Source: 1) Farm Accountancy Data Network for the year 2003 (LEI, 2006); 2) Calculated for each soil type, using data from Aarts (2005), LNV (2006), Ten Berge (2006), LEI (2006) & CBS (2006); 3) Adapted from LEI (2006) by changing feed and fertilizer levels for distinct soil types based on Aarts (2005) and application standards (LNV 2006). Farm economic losses did occur in the years before and after 2003.

	Clay	**Peat**	**Sand**
Area (ha) (maize/grass/total)[1]	19/56/75	19/56/75	19/56/75
Dairy cows (#)/ total Dutch cattle units (#) / Quota (Mg)[1]	126/176/947	126/176/947	126/176/947
P_2O_3 (kg ha^{-1}) in[2]	90	90	92
Phosphate Use Efficiency (%)[2]	41	41	40
N (kg ha^{-1}) in [2]	337	357	344
Nitrogen Use Efficiency (%)[2]	25	24	24
Revenues (k€)[1]	401	401	401
Costs (k€)[3]	262	286	280
Total farm economic cost (k€)	467	492	485
Farm economic result (k€)	-66	-91	-84

Table 4: Selected general characteristics of the modeled fattening pig farms. Pig farms are considered as black boxes. No special measures are undertaken on these farms. Nutrient information from Timmerman & Smolders (2003 & 2004), economical data from LEI (2006).

Characteristics of model pig farms	
Pigs (average over the year)	918
Nutrient input N / P_2O_5 (Mg)	26 / 12
Nutrient in manure N / P_2O_5 (Mg)	13 / 7
NH_3 emission in Mg N	4
Nutrients in animals out N / P_2O_5 (Mg)	9 / 5
Annual profit (k€)	2

2.5 Cost-effectiveness

The adoption of NUE improving technologies by farmers is mainly driven by its cost-effectiveness (Cassman *et al*, 2002; Oenema and Pietrzak, 2002). Therefore, we propose cost-effectiveness analysis as the evaluation methodology for this research. Depending on the prevalent environmental policy three environmental cost accounting systems can be distinguished (adapted from Bulte, 1995): i) internal cost accounting; ii) internal and external cost accounting; and iii) internal cost accounting with additional information on the (qualitative) use of the measures that prevent external environmental costs.

In the above outline, external costs are accounted for as the environmental (and social) costs an enterprise produces. Examples are amongst others air and water pollution, noise, and health risks. To account for the external costs in agriculture is not common. Pretty *et al* (2000) are the first that undertook this “hazardous” exercise by assessing the total external cost of UK agriculture. They concluded that the environmental and health costs count up to 2343 million dollar which represents 89% of net farm income for 1996.

If we do not take into account the more philosophical and ethical debate on cost benefit analysis of the environment (e.g. Sunstein, 2005), the practical difficulties are numerous. This has partly to do with the relative difficulties of the issue (diverse and interacting effects and temporal difficulties in discounting) and secondly because of the historical sensitivity of the issue. Agriculture has for long been seen as a natural activity. Also Dobermann and Cassman (2004) criticize Pretty *et al*s study. They state that it is not clear that such estimates place an appropriate value on the large positive impact of N fertilizer on ensuring food security and adequate human nutrition and on the environmental benefits that accrue from avoiding expansion of agriculture into natural ecosystems and marginal areas that cannot sustain crop production. On the basis of the above mentioned difficulties we do not, for the moment, take into account the external costs of Dutch dairy and arable farming. Apart from the mentioned criticism, we think the idea of external costs links up badly with the concept of NUE, due to the fact that NUE is based on the *output to input ratio* and external costs are based on nutrient *losses*.

For the internal costs and benefits, we propose to look at each NUE improving environmental measure and assess its costs and benefits for labor, capital (machinery) and land. However the costs for research, technology development, testing and extension (though relevant) are not included. Cost and benefits can either be paid by governmental bodies or by farmers themselves. This study does not differentiate between these costs. Regional costs and benefits are determined by taking the sum of all farm costs and benefits. Extra regional costs or benefits are added to this grand total. Total costs of a given practice are determined by subtracting the costs by the benefits. So, negative costs imply that the measure is profitable. At the end of the research we then evaluate the cost for each percentage point of NUE improvement at farm and regional level as compared to the baseline situation.

2.6 Input-output relations

Input-output relations in agriculture, especially regarding nutrients, are subject to a long and ongoing dispute (De Wit 1992; Wadman & Noordwijk 1992; Zoebl 1996; Nijland & Schouls, 1997). In order to find a crop model that could be included in our model, we investigated four Dutch crop models which determine yield or nutrient uptake as a function of nutrient application (Ten Berge *et al*, 2000, Schröder *et al*, 2003; De Vries *et al*, 2003; Smit, 2006). Only one of these models (Quadmod of Ten Berge *et al*, 2000) was able to deal with current dry matter and nitrogen yields as on average achieved by the farmers described in the LEI database, the Dutch statistics agency (CBS, 2006) and the survey of Aarts *et al* (2005). Figure 2 describes the different model outcomes for sugar beet.

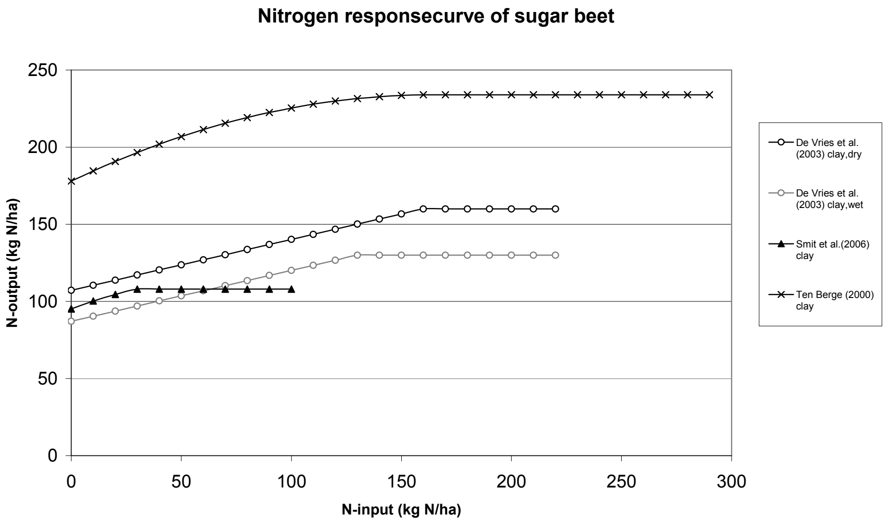


Figure 2: Overview graph of production functions of sugar beet (without leaves). The functions of de Vries et al (2003) are the same as for potatoes and winter wheat. Maximum allowed fertilization rate for beet is 220 kg/ha (clay) whereas the advice application is 150 kg/ ha

In the only model that is able to deal with current Dutch yields (Quadmod by Ten Berge *et al*, 2000) input levels at current yield levels are 50 to 90% lower than current Dutch practices according to Aarts *et al* (2005), LEI CBS (2005), ASG (2005). Therefore Quadmod can hardly be considered representative for current practices in the Dutch agricultural sector. Consequently, in this study regulatory application standards are considered as the reference application.

Although there will always be a difference in outcomes of crop production function and reality, due to risk perceptions and security reasons, we think a better fit is possible. As proper plant uptake curves are of utmost importance for farmers, scientists and policymakers, we recommend more research is conducted on gaining proper insights into the relationship between fertilizer advice and plant response to fertilization.

3 Model description

3.1 Farm model

We take the farm as the point of departure for our analysis, because the farm level is the level of aggregation at which the psycho-sociological, agro-economic and agro-ecological disciplines interact most profoundly (De Koeijer, 2002). As Ten Berge *et al* (2000) point out explorative modeling forms an effective approach to integrate knowledge on animals and crops, which in turn can outline the consequences of particular choices. Explorative modeling also seems the best method for our research. Prerequisite for such a modeling exercise is: the ability to link up farm and regional level; to have a clear understanding of farm specific activities; the applicability to both arable and dairy farming.

The basis for our exploratory farm model will be the Schröder *et al* (2003) whole farm flow model. Figure 3 portrays this model. Advantages of this model are its relative simplicity and the ease with which it can be upscaled to regional level. In addition, conversions can be easily performed between NUE and nutrient surpluses or losses. The 'buttons' which drive NUE are, apart from import (IM) and export (EX), the conversion rates between the four compartments (soil, harvested crops, animal feed and manure). It is here that major improvements are being explored. Baseline farm (economic and agronomic) data are available through other Wageningen research (like 'Koeien & Kansen', 'Telen met Toekomst', de Marke, etc).

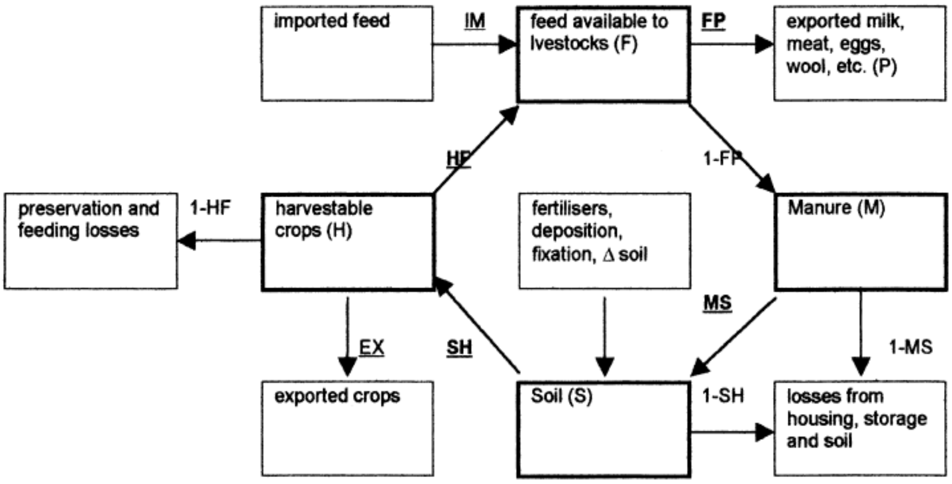


Figure 3: Flow diagram for a mixed farming system (Schröder et al, 2003) also representing an arable farm when the upper three boxes are neglected. The arrows indicate conversion factors. The values of the inner circle of arrows that we calculated for the use in our model are shown in Table 2.

3.2 Regional level

At regional level different NUE improving measures can be introduced that cannot be evaluated at farm level. Approached from the Oenema and Pietrzak (2002) scheme, it are especially steps 4 and 5 (system modification and end-of-pipe technology) that are more easily implemented at regional level than at farm level. In this way upscaled farm strategies can be (cost-benefit) compared to regional strategies. E.g. strategies that better apply to regional level instead of farm level: expansion of natural areas, removal of duckweed, water filtering.

The area of the region is divided over 40%-40%-20% clay, sand and peat areas. The area is representative for the entire Netherlands (Alterra, 2006) with farm sizes that are indicative for the 2030 period. To get the proportions right the model consists of 425 dairy farms (150 on clay and sand and 125 on peat), 100 arable farms (50 on sand 50 on clay) and 100 intensive pig farms. This adds up to a total of 47032 ha.

3.3 Model overview

The design of our model is the result of a literature study and extensive discussions with leading nutrient modelling scientist from Belgium, Netherlands, Denmark, Sweden & Norway (Berentsen 1995; Vatn *et al*, 1997; Van Huylenbroeck *et al*, 2000; De Haan, 2001; Arheimer *et al*, 2005; Brady 2003; Belcher *et al*. 2004; Buysse *et al*, 2005; Berntsen *et al* 2005; Ekman, 2005; Lacrois 2005; Gibbons *et al*, 2005; Brown *et al*, 2005)

The aim of this study, however, was not the building of a model but the evaluation of future nutrient management measures. Regrettably, there were no suitable models available for direct use in this study. Existing models were either not accessible for use by third parties, poorly documented or not general enough. Because the amount of time for this study is relatively short, we decided not to build a highly sophisticated model including user interfaces, input files etc. Instead, we used a number of excel sheets that minimally but transparently describe the main capital and nutrient flows within farms and within an agricultural region. Some extra functionality was added by a group of visual basic for applications (VBA) macros that calculate nutrient uptake, nutrient application and/or yield using a number of existing soil-plant models and by a macro that produces a sensitivity analysis. Figure 4 gives a schematic outline of the approach of this study.

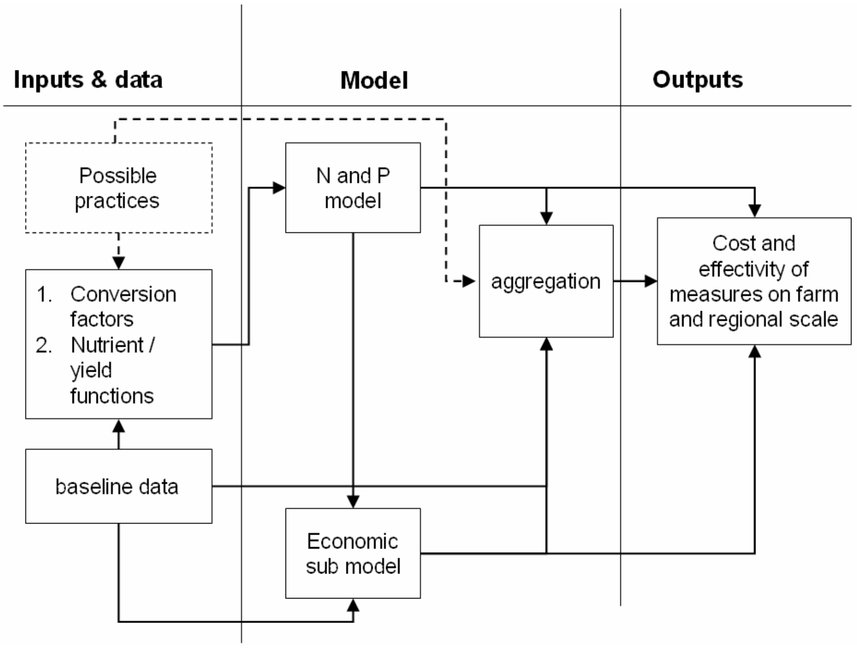


Figure 4: Flowchart of the framework for determining costs and benefits of N and P efficiencies, flows consist of data.

3.3.1 Inputs

The left side of the framework as shown in Figure 4 consists of the inputs. Two input types can be distinguished, a list of future nutrient management measures and their potential effects (dashed box) baseline data on Dutch agriculture. Together these inputs form the major parameters of the model. The future management practices are not included in the model but their effects can be included in the model by altering some parameters. Measures can act on a regional and non-regional scale.

The baseline information forms the core of the excel model and consists of:

- Production data, which was derived from Timmerman *et al*, 2003; Timmerman *et al*, 2004 and LEI (2006) for pig farms; Aarts *et al* (2005), LEI (2006), ASG (2005) provided production data for dairy farms, while datasets from Ten Berge *et al* (2000), De Wolf & Van der Klooster (2006), LEI (2006) were used for the arable production data.
- A selection of crop production models (Schröder *et al*, 1993; Ten Berge, 2000; Smit *et al*, 2006; De Vries *et al*, 2003), advice fertiliser applications (Commissie Bemesting Grasland en Voedergewassen, 2002; Van Dijk *et al*, 2003; fertilizer and manure regulations for the year 2007 LNV, 2006). As a standard application rate we used the fertilizer and manure regulations for the year 2007 because crop production models were not satisfactory.
- Manure use efficiencies (Van Dijk, 2004; Schröder 2005; Schröder *et al*, 2005), manure loss fractions during application and storage (De Vries *et al*, 2003) and manure deposition distribution (LEI, 2006).
- Basic farm characteristics (Aarts *et al*, 2005; LEI, 2006; De Wolf & Van der Klooster, 2006; ASG 2005) including the economic situation of the model farms which is the reference for any suggested change. The economic situation of the model farms is derived from LEI (2006). LEI, however, does not differentiate per soil type, therefore the feed (in case of dairy) and fertiliser input data and their respective costs were changed to differentiate the costs structure of the model farms (using data from Ten Berge (2000), Aarts (2005), ASG (2005), and De Wolf & Van der Klooster (2006)).
- Geographical information of the model region (Alterra, 2006; CBS/LEI, 2006), including number of farms, soil type distribution etc. Other important regional parameters are the amount of fodder produced in the region and the amount of regionally produced manure that is used within region.

The baseline data were used to calculate the coefficients and functions that describe the nutrient flows (Figure 3; Table5). In the excel model the baseline data is stored in the basedata sheets (Figure 5) and in the functions sheets. The coefficients and functions that describe the nutrient flows are provided in the calibration, functions sheet. There is some overlap and cross linking between the sheets.

*Table 5: Calculated conversion factors between the components in dairy and arable ** Excluding losses in manure storage*

Farm types	**Dairy**						**Arable**			
Soil types	Clay		Peat		Sand		Clay		Sand	
Conversion factors	N	P	N	P	N	P	N	P	N	P
Fodder to meat & milk	0.22	0.25	0.22	0.25	0.22	0.25				
Soil to plant (grass / average)	0.64	0.48	0.55	0.41	0.55	0.43	0.77	0.73	0.58	0.65
Crop to fodder / product	0.82	0.85	0.82	0.85	0.82	0.85	1	1	1	1
Manure to Soil (grass)	0.75	1	0.75	1	0.75	1	0.9**		0.9	

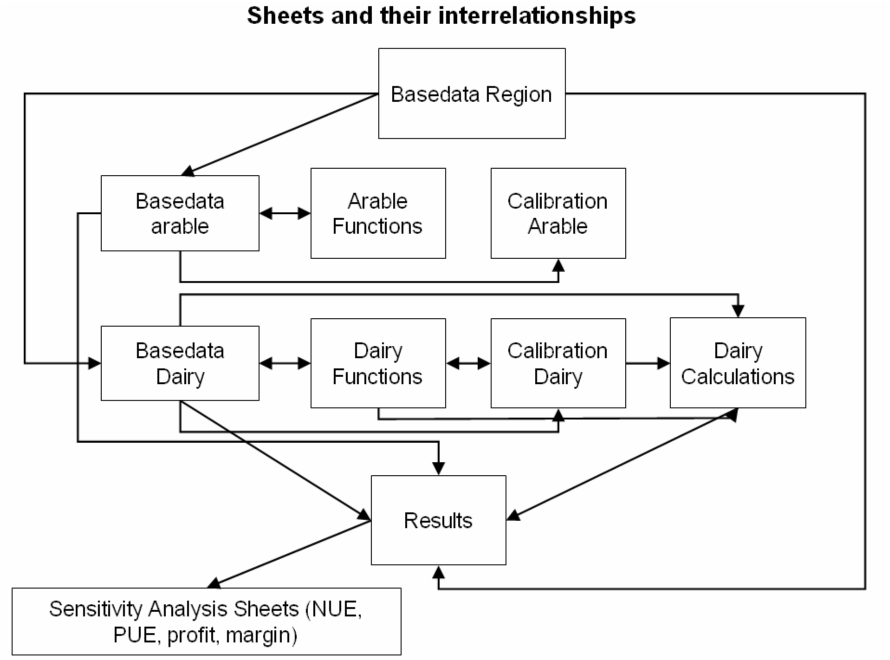


Figure 5: Overview of sheets in the model. The calculation, at farm level, is done in the arable database sheet, and the dairy calculation sheet. Crop production functions can be calculated using the arable or dairy functions sheets. In these sheets some VBA macros add some optional functionality. The aggregation of farms to a region and the inclusion of the effect of regional measures is done in the results sheet. Finally the sensitivity of the parameters can be determined using the sensitivity analysis sheet and a VBA macro.

3.3.2 The model

The model (Figure 5) calculates the nutrient and capital flows using the available baseline information. The model and an extensive model description is freely available from the authors.

Numerous existing farm models use optimization techniques for cost-effectiveness analysis of certain farm practices. This means that after adding a certain practice to the model farm, the model farm is re-optimized again. Optimization often implies radical shifts in the farm structure. A farm optimization module was not included in the model described here because of a number of reasons: i) after farm optimization it is hard to compare the farm (because its structure changes); and ii) because we lacked resources for building a reliable optimization model. Therefore efforts were focused on the content and modeling limited to relatively simple Excel calculations.

To keep things workable, we developed the model from a strong ceteris paribus principle. This model assumes that the volume of production is constant, but the means needed for it (be it nutrients or capital) may be subject to change. For each measure, we determined the factors that would be changed by this measure, then these factors were changed according to the best available insights and the effects were calculated without changing the volume of production.

However, as a result of a measure the cost, benefits and the amount of inputs used and manure exported (among others) may change on farm and regional level. Costs include the implementation costs of a measure combined with the losses in benefits. Implementation costs can consist of: i) equipment and housing; and ii) hired labor. Reduction in benefits may not always occur, as we look for measures that can decrease inputs as well. Cost effects caused by the changes of prices because of the introduction of a measure are assumed to be zero.

In the aggregation module, the results from processes that take place at farm level are combined with processes and measures that take place at regional scale. It is not just the sum of costs, inputs and outputs of individual farms because regional effects are added as well. Regional costs include costs for purifying drinking water, while regional nutrient outputs can consist of water cleaning by for example wetlands. We assume that there are no micro-macro price effects of the implemented measures.

$$regionalCosts = \sum_i farmCosts_i + regionalSpecificCosts$$

$$NUEofRegion = \frac{\sum_i farmNutrientOutput_i - nonFarmOutputs}{\sum_i farmNutrientInput_i + nonFarmInputs}$$

Equation 2: Calculation of regional costs and regional Nutrient Use Efficiency

3.3.3 Outputs

The outputs are a list of tested measures, their effect on NUE, on farm level and regional scale, and the costs of the measure at both levels.

3.4 Sensitivity analysis

Sensitivity analysis is a means to evaluate a model, demonstrating the nature and magnitude of the change in output value per unit change in input value. A simple method, a 'one-by-one' approach was adopted, varying all input variables individually (i) from their starting (default) values to +100% of their initial value. The +100% range is in many cases unrealistically large, but it gives an indication of the outputs sensitivity to parameters whose distribution and range are unknown, allows the relative influence of input parameters to be assessed and provides a good basis for scenario testing.

The results of the sensitivity analysis are provided in Table 6. Changing the size of the sectors especially influences profit. Farm profit however is highly volatile. In the arable sector the prices of potato and beet are most important for profit. This illustrates that the liberalization of the sugar market will have a great impact on arable farms. In the model there is no coupling between prices of arable produce and fodder prices for dairy. The price of fertilizer is little influential in the formation of the profit of arable farms. An increase in fertilizer value lowers P use efficiency because it will lead to a lower use of manure in the model which causes greater P exports from the region. In the dairy sector the price of feed is of far great importance for profit than the price of fertilizer. The conversion from N and P in fodder to N and P in animal produce is also highly influential.

Table 6: Sensitivity of the model output variables to a 100 % change in the key parameters (one-by-one analysis). The sensitivity is provided as % change in regional N and P use efficiency as % change in profit.

Variable	**Change in Nitrogen use efficiency (%)**	**Change in phosphate use efficiency (%)**	**Change in profit (%)**
Regional			
# dairy farms clay	-3.9%	-1.9%	-21.9%
# dairy farms peat	-4.4%	-1.5%	-26.0%
# dairy farms sand	-4.3%	-2.2%	-28.9%
# arable farms clay	6.4%	6.1%	-11.6%
# arable farms sand	6.9%	6.5%	-12.2%
# pig farms	1.3%	-5.2%	0.5%
N deposition	-8.0%	0.0%	0.0%
Fraction of harvested beet mineral that is recovered in beet pulp fodder	-1.9%	-1.3%	0.0%
Fraction regional fodder that is used inside region	-9.2%	-6.8%	0.0%
Manure use fraction in arable farming	0.9%	12.3%	2.4%
Arable			
Price beet	-	-	23.6%
Price potato	-	-	38.8%
Price wheat	-	-	8.3%
Price maize	-	-	16.0%
Price N fertilizer	-	-	-4.0%
Price P fertilizer	-	-	-4.0%
P_2O_5 content beet	-	9.5%	0.0%
P_2O_5 content potato	-	8.4%	0.0%
P_2O_5 content wheat	-	8.4%	0.0%
P_2O_5 content maize	-	18.3%	0.0%
N fertilizer value manure	-	-5.5%	-0.4%
Price feed	-	-	-79.2%
Price N fertilizer	-	-	-10.1%
Price P fertilizer	-	-	-0.5%
Fodder to meat and milk conversion	17.6%	-9.2%	21.9%
Crop to fodder efficiency of cut grass (N)	11.3%	-6.2%	12.2%
Crop to fodder efficiency of grazed grass(N)	3.2%	-1.1%	3.8%
Crop to fodder efficiency of maize (N)	2.1%	-1.7%	2.4%
Manure loss (shed & storage) total (N)	-2.1%	-	-
% of manure deposited in meadow (N)	-0.8%	-0.2%	-0.2%
N fertilizer value shed manure	11.3%	-	-1.4%
N fertilizer value manure droppings	2.2%	0.0%	0.0%

4 Measures

This chapter outlines, in brief, the NUE improving measures. The measures presented were selected after intensive literature study and portray the state of the art, most promising measures that are able to increase N and P use efficiencies. The measures are cut into two categories, as described in chapter 2: currently known and future foreseen measures. More extensive measure descriptions can be found in a forthcoming WOt-publication. Here we only summarize the functioning of the measure and its results on nutrient use efficiency and cost effectiveness. More elaborated and quantified results are presented in chapter 5: results and discussion.

4.1 Currently known measures: Arable farming

4.1.1 Catch crops

In temperate conditions the soil is often left with no plant cover during the winter period. The autumn and winter periods are also the parts of the year where highest percolation of water through the soil occurs, due to low evaporation and high autumn and winter precipitation. Hence, plant nutrients available in the soil can be leached downwards with percolating water and eventually be lost from the root zone. This decreases the availability of nutrients in the succeeding growing season, decreasing overall NUE of the system.

During the autumn and spring period, after the harvest or before the start of the main crop, temperature and light conditions allow some plant growth, though not enough to produce commercial crops. Many attempts have been made to use this period to grow plants, which prevents nutrient leaching and can improve overall soil quality. Such crops are often termed catch crops, cover crops or green manures. Here we use the term catch crops. A catch crop has become obligatory from 2006 onwards on sand and loess soils after maize, following Dutch manure policy. In arable farming N reducing catch crop possibilities are not yet codified. In arable land we have studied the use of winter rye, oil radish and fodder rape after potato, spring wheat, sugar beet and oats.

To reach the best goals at farm level, the farmer has several management tools to optimize the nitrogen beneficial effect of the catch crop: (i) The placement of the catch crops within the crop rotation; (ii) the choice of time and method of catch crop establishment; (iii) The choice of catch crop incorporation time; (iv) the choice of catch crop species (Thorup-Kristensen *et al*, 2003). The catch crops were especially successful after potato, spring wheat and oats, and when ploughed under two to three months before the growing season of the succeeding crop. A catch crop after sugar beet hardly showed any positive effects.

The mineralization of the catch crop is dependent on soil temperature and soil moisture. Taking into account several studies in the Netherlands on sandy soils we conclude that catch crops could cater for an on average additional 20 kg N/ha for the succeeding crop (converted to a nitrogen fertilizer value (NFV) of 100%) in three of the four crops of the rotation, namely after potato, oats and spring wheat (Van Dam, 2006; Vos & Van der Putten, 2000). This indicates that due to catch crops for arable farming on average 15 kg fertilizer N ha^{-1} less is needed.

Including catch crops in three of the four rotation crops involves additional tractor plowing and seeds. This adds up to an average of €53 per hectare costs while benefits are on average restricted to €16 less nitrogen fertilizer. Therefore, it is concluded that catch crops can improve nitrogen use efficiency on arable farm level with 4% (to 55%). For phosphate use efficiency the measure has a negligible effect. On arable farm level, the measure costs 15 € / NitrogenUE% improvement or 3 € / kg N surplus reduction.

4.1.2 Time and site specific management

Judiciously fine-tuning fertilizer application to crop demand can be achieved by time and site specific management. Within the Netherlands the project of 'Geleide Bemesting' (a PPO project; Radersma *et al*, 2004) has been particularly active, working on methods of precision agriculture (PA) in the arable sector.

One of the measures is the 'bladsteeltjes' (stem-leaf) measure, which assesses the N-content in the stem-leaf in the laboratory and links fertilizer demand to this figure. The stem-leaf method assesses the N content in the stem of the leaves. This N content is compared to the desired N content in the leaf. This then forms an indicator for the amount of N needed in the soil for plant uptake. The leaves are sent to the laboratory for analysis.

The main process involved in site and time specific management is the fine-tuning of nutrient demand and supply of the plant. This can be done in several ways. For this moment the above described leaf-stem method looks most promising. In the recently published 'Best fertilization practices for the arable sector' (De Haan & Dekker, 2005) it is considered a promising measure that is already in use by a group of vanguard farmers.

It has been concluded that this measure as well as the measure of 'gewasvensters' (crop windows) shows potential. Radersma *et al* (2004) conclude that by means of these measures nutrient input can be reduced by 48 kg N /ha for ware potatoes at a cost of 72 €/ha. Because the measure has only been researched for potatoes, the effect of the measure is limited to 1/4th of the arable sector, and as a result only on less than 10% of the region as a whole. The result is a decrease of 14 kg N in inputs for the arable sector at 1 €/kg N reduction per hectare. On a regional level this results in 14 €/NitrogenUE% improvement per hectare.

4.1.3 Controlled release fertilizer

Controlled release fertilizers (CRFs) are seen as a technological innovation for improved nutrient use efficiency. By fine-tuning nutrient supply to plant demand NUE can be increased. CRFs do this through their semi-permeable or polymer coatings which delay the solubility of nutrients. Currently, 0.15% of worldwide fertilizer consumption consists of these types of fertilizers.

Literature shows that the main difficulty with CRFs at the moment is that 10-20% of the fertilizer comes available after harvest (Shoji *et al* 2001). This timing problem has not yet been overcome with newer CRFs (Pack *et al*, 2006). More positive side effects are that both leaching and N_2O volatilization are decreased in CRF experiments. However, these figures can be misleading because the 10-20% that comes available after harvest (in leaching and volatilization) is never accounted for in current studies.

For now we conclude that CRFs in 2030 will be 2.5 to 3 times as expensive as regular fertilizers (Trenkel, 1997). As for the NUE benefits it seems that current CRFs do not perform better than current practices. Only in one case of onions the results were very positive, though this study contradicted an earlier study's findings. Practices of site and time specific applications ('precision agriculture') seem more promising for the moment.

4.2 Currently known measures: Dairy farming

4.2.1 Manure processing

Within the context of mineral surpluses in agriculture, manure-processing techniques have two goals. The first is to increase the acceptability for organic manure through increasing homogeneity and the relative nitrogen fertilizer value (NFV) of manure. Here, the purpose is to find a better purpose within agriculture. The second goal can be to process manure in such a way that it gets a market value outside of agriculture.

The first goal relates to the NFV of the applied manure. The relative fertilizer value, or fertilizer equivalent, is the ratio between N recovery of manure (NR_{man}) and that of mineral fertilizer (NR_{fer}): NRman/NRfer (Schröder, 2005). If a processing technique results in a higher NFV fewer nutrients are necessary from other sources like fertilizers. This would increase the acceptability for organic manure in the arable sector.

There are many different manure processing techniques. In this report seven techniques were studied. These are: anaerobic (co-)digestion, mechanical separation, membrane filters, nitrification/ denitrification, composting, drying and combustion. From the described techniques, only mechanical separation into a liquid and solid fraction improves the overall NFV and thereby has the potential to increase NitrogenUE. Though, the NFV of the solid fraction decreases in the process, which is due to the fact that the N that remains is mostly bound in organic forms that are less easily available for plant growth or comes available during winter.

In the Netherlands the legal fertilizer value of the liquid fraction of manure is 0.8, while the NFV of slurry is 0.6 (LNV, 2007). However it is not clear whether the NFV of the liquid fraction is really higher than that of slurry. Both Schröder *et al* (2007) and Sorensen & Thomson (2005) did not find significant differences in NFV between slurry and the liquid fraction. Schröder *et al* (2007) found that both are around 0.8 when applied to grass. Therefore the effect of a more widespread use of the liquid fraction is more likely to be caused by the legal differences between the two manure types than the real differences.

(Co-)digestion and drying do not change the NFV but do increase costs, while all other techniques reduce the NFV significantly and thereby decrease NUE if the digestate is not exported from the region. The costs of the different manure processing techniques on regional level vary between 9 and 20 € kg^{-1} N ha^{-1}, transportation costs included. The measures are calculated separately for N and P, indicating that, if efficiency improvements are sought on both nutrients, costs per kg N and P can be halved.

Much research is going on in the field of manure processing techniques. Especially anaerobic digestion and combustion are popular, since both can provide energy. For the purpose of this research, the most promising technique appears to be separation at farm level. The combination of applying the liquid fraction (with the higher NFV) on the field, while on the other hand combusting the solid fraction. The thick fraction can also be used for the production of methane (e.g. Moller *et al*, 2007).

This results in an overall N regional use efficiency increase of 4% (to 37%). Key in this process is that through combustion in modern plants N leaves the system as harmless N_2. NO_x can not be prevented 100%, but it can be reduced to very low levels (Lemmens *et al*, 2007) The flow of N_2 does not increase the nutrient use efficiency of the production but it diminishes the harmful N surplus, therefore, in this case, we have accounted the N_2 emission as a reduction of N surplus. Nitrogen use efficiency still increases on dairy and arable farms because the higher NFV compensates for the loss of N during combustion, causing a lower need for mineral fertilizers. However, the P use efficiency declines with 9%. This is due to the fact that P is left over after the combustion. This cannot be used, at the moment, as fertilizer because the material has to high concentrations of heavy metals. Therefore, if no other measures are taken (like e.g. phosphate mining (see par. 4.4.)), extra P fertilizer may be required.

4.2.2 Herd management

In Dutch herds, about one third of the animals is kept as young stock. As the young stock does not produce milk, they clearly lower total NUE. When weight gain is taken into account calves have a NitrogenUE of around 14% (De Wilde, 1995) while cows in maturity have a NitrogenUE of around 30%. A reduction of the amount of young animals implies that fewer cows reach maturity every year. As a result, either the amount of calves needs to be reduced to the amount needed for the replacement of milk cows or cows need to be kept longer in production in order to maintain total herd production. Jonker *et al* (2002) agree that strategies to increase production per cow appear to increase N utilisation efficiency the most. However, when it comes to increasing production at higher NUE breeding efforts are essential and these measures are dealt with in 4.5.2 Animal breeding efforts.

The replacement rate indicates the percentage of cows replaced yearly. The easiest measure is to reduce the amount of calves to the exact minimum needed. This measure can then be taken a step further by lowering the replacement rate and keeping cows for a longer period, but only when production levels remain constant. When less young stock is kept and/or when cows produce longer, less manure is produced increasing the overall NUE. In addition, less animal feed is needed.

On de Marke the replacement rate was reduced from 38 to 33% by keeping milk cows in production for a longer time (De Haan, 2000). However, in the top-10% biggest farms in the Netherlands the replacement rate is already 29%. At these farms a small amount of young stock is kept longer than strictly needed, e.g. five out of twenty calves are being sold off after two years. However, some flexibility is needed for selection and security purposes. Therefore, we conclude that in herd management there is hardly any room for NUE improvement; apart from breeding efforts that keep cows in production for a longer time (see 4.5.2).

4.2.3 No plowing for grassland renovation in dairy farming

Plowing and reseeding is a common activity in Dutch dairy farming. However, scientists state that reseeding is hardly needed except for calamities (Kasper *et al*, 2002). For environmental objectives no till dairy farming has many advantages. Grassland soils have a high potential for mineralization and subsequent nitrification and denitrification. Plowing grassland soils, consequently, often results in a high supply of mineral N, which causes serious N_2O and NO_3 losses (Aarts *et al*, 2002).

At the moment plowing and reseeding are popular because herbs and other malevolent species take over after long term grassland management. In addition, the field can become uneven. In no till agriculture, farmers need to handle grasslands more carefully. They will need to mow more judiciously and time the grazing more exactly. This will involve more knowledge and management time. However, the increased cost of management will, towards 2030, cancel out to the current costs of plowing and reseeding.

If grassland on sandy soils is renovated every six years, Aarts *et al* (2002) calculate a loss of 254 kg N ha^{-1} in the first year, compared to 96 kg N ha^{-1} yr^{-1} in the following years. Therefore 158 kg N lost ha^{-1} can be attributed to plowing for grassland renovation. An estimated 87 kg N is denitrified to harmless $N_{2,}$ 63 kg N is leached as NO_3 and another 8 kg N is emitted as N_2O (Aarts *et al*, 2002). For grassland on clay which is renovated every 10 years, 225 kg N

ha^{-1} is lost in the first year, compared to 135 kg N ha^{-1} yr^{-1} in the following years. 90 kg N ha^{-1} can be attributed to grassland renovation. An estimated 63 kg N is denitrified to N_2, 21 kg N is leached as NO_3 and another 6 kg N is emitted as N_2O (Aarts *et al*, 2002). For grassland on peat which is renovated every 20 years, 500 kg N ha^{-1} is lost in the first year, compared to 135 kg N ha^{-1} yr^{-1} in the following years. So, 365 kg N ha^{-1} can be attributed to grassland renovation. An estimated 310 kg N is denitrified to N_2, 25 kg N is leached as NO_3 and another 29 kg N is emitted as N_2O (Aarts *et al*, 2002).

After grassland plowing maize is often cultivated for a couple of years. Nevens and Reheul (2002) found that a system where grass and maize are rotated the optimal nitrogen gift is 30 kg N ha^{-1} less than when maize is cultivated continuously. However, the optimal nitrogen application they found (170 kg) for maize that is cultivated continuously is still 100 kg ha^{1-} lower than the average N gift of Dutch farmers on sandy soils. Therefore, we do not expect that shifting to continuous maize cultivation will necessarily affect nitrogen use efficiency of maize.

We conclude that no till dairy leads to less inputs per hectare. On a yearly basis this is: 26 kg N ha^{-1} on sandy soils, 9 kg N ha^{-1} on clay and 19 kg N ha^{-1} on peat. Overall, no till in dairy results in a 14 kg N/ha less inputs on farm level (this result is lower than the average of decreased inputs because not all dairy land is under grassland). The measure contributes to an increase of 1% NitrogenUE at zero additional costs at dairy farm level.

4.3 Currently known: End-of-pipe measures

The end-of-pipe measures comprise an extra category in this study. This type of measures is a bit extraordinary to the concept of nutrient use efficiency because extracted nutrients remain in the system. For the purpose of comparison we have set N and P extraction quantities as useful outputs that leave the system and thereby can contribute to an NUE increase. For the aim of simplicity we have clarified the measures below with average leaching values. For the measure's results we did use differentiated leaching values for all soil types (see Tables 7 & 8).

Table 7: Estimates of N leaching in the modeled region at dairy farms source: model calculations and Schröder et al, 2004***

	Clay	**Peat**	**Sand**
Soil N surplus (grass) kg/ha*	217	235	251
soil N surplus (maize) kg/ha*	120	214	139
Leaching fraction (grass)**	10%	3%	43%
Leaching fraction (maize)**	28%	10%	81%
Precipitation surplus (grass) mm**	266	242	329
Precipitation surplus (maize) mm**	387	350	434
N-leaching (kg N/ha) (grass)	8	4	53
N-leaching (kg N/ha) (arable)	29	15	83

Table 8: Estimates of N leaching in the modeled region at arable farms. Source: model calculations and Schröder et al, 2004

	Clay	**Sand**
Soil surplus (kg/farm)	15766	15 879
Soil surplus (kg/ha)	104	104
Leaching fraction	0.28	0.81
Precipitation surplus	266	329
N-leaching	29	85

4.3.1 Riparian buffer strips

Riparian buffer zones are strips of land along waterways without fertilizer input. Nutrients flowing through the strips in the subsurface water layers can be taken up by plants or be fixed in the soil. A distinction is made between dry and wet buffer zones.

The construction of dry buffer zones can be an effective measure to reduce N and P outflow to the surface waters if the flow takes place in shallow subsurface level (40 cm below field level). Nutrients can be extracted from the buffer strips through the harvesting of plants in the strips (Van Beek *et al*, 2003). Wet buffer zones are built at the same level as the surface water creating an anaerobic condition in the soils of the buffer zone. The advantage of wet buffer zones is that both the plants as the denitrification under anaerobic condition, remove nitrogen. Phosphates, however, become mobile under anaerobic conditions, which can lead to an increase in phosphate leaching to surface waters (Klok *et al*, 2003).

Van Beek *et al* (2003), citing a research from Orleans *et al* (1994), who modeled the efficiency of riparian buffer strips for different combinations of soil types and soil use, see Table 9. The results of the calculations demonstrate that buffer strips extract more N than P and that dry buffer zones are more efficient than wet buffer zones for P extraction as well as that wet buffer zones are more efficient for N extraction.

Table 9: Model results for different types of riparian buffer strips (3 m width). The results are the reduction of N and P outflow compared to a situation without a riparian buffer in % (Orleans et al, 1994). These results might not be representative for the Netherlands.

	Arable on clay		**Grass on sand**		**Maize on sand**	
Type of riparian buffer	N	P	N	P	N	P
Fallow	100	25.1	17.0	8.0	10.9	5.2
Grass buffer	100	33.3	17.0	8.0	15.6	5.9
Wet buffer	100	29.6	42.5	7.3	38.5	5.5
Forest buffer	100	13.2	17.0	4.0	15.6	3.8

With a width of 10 meters the dry riparian buffer has an efficiency of around 60% for the extraction of phosphates and 70% for the extraction of nitrogen. The efficiency reduces rapidly when the width is diminished with almost no effect when below 5 meters of width (Klok *et al*, 2003).

Assuming that one hectare of arable land is bordered at two sides with a dry riparian buffer zone of 10 meters through which 50% of the precipitation surplus passes. Given an average modeled soil surplus of 104 kg/ ha N for arable farms on both clay and sand and an assumed leaching fraction of 0.28 and 0.81 for clay and sand respectively (Schröder *et al*, 2004). Riparian buffers can trap 10 kg N ha^{-1} on clay and 30 kg N ha^{-1} on sand. The relation between phosphate surplus and leaching is more complex. Therefore we assumed P_2O_5 leaching to be 4 kg ha^{-1} on clayey soils and 8 kg ha^{-1} on sandy soils (Schröder & Corré, 2000), which leads to a P_2O_5 entrapment of 1 and 2 for riparian buffers on clay and sand respectively. The effects of the riparian buffers are also modeled for dairy farms.

The harvesting costs are assumed to be €240, corresponding with 4 hours work per year. Cost of land loss are more important, replacement costs of the land used is €2400 ha^{-1} (€48 000 ha^{-1} and a 5% return on land), resulting in a total cost of €2640 ha^{-1} arable land. This results in €88 and €264 per kg N on sand and clay respectively and €2640 and €1320 per kg P on clay and sand respectively. As with the manure processing measures costs are calculated for N and P separately indicating that total costs can be halved if efficiency improvements are sought on both nutrients. For the aim of comparison we have fixed the extraction of nutrients as a useful output that leaves the system, thereby increasing overall NUE.

For the construction of wet riparian buffer zones extra activities are necessary. The buffer zone has the same width as the dry buffer zone but the surface level has to be lowered to below water surface level to create the wet environment. The costs for the initial construction will be €96/y, assuming that 2 work days are necessary for the construction of these wet buffer zones and that it will last for 10 years after which reconstruction is necessary. Klok *et al* (2003) report an N & P extraction efficiency of 60-100% for wet riparian buffer zones. Using the same assumption as for dry riparian buffer zones, with an efficiency of 80%, the wet buffer zone will extract 34 kg N ha^{-1} y^{1}. The costs would then be €77 kg N^{-1} y^{-1} on sand. Costs per kg N as calculated by the model are different because here differentiated figures are used for nitrogen leaching for each of the separate soil types.

Overall wet riparian buffer strips are more effective in reducing pollution than dry riparian buffers. If applied to the entire region wet buffers decrease overall nitrogen pollution with 15 kg N ha^{-1} and phosphate pollution by 2 kg ha^{-1} at a cost of respectively €37 and €244 per kg reduction, making them a rather costly measure. Dry riparian buffers are even more expensive at €40 per kg nitrogen pollution decrease and €283 per kg phosphate decrease. The advantage of dry riparian buffers is that the nutrients are exported as usable products (grass or other crops) whereas in wet riparian buffers P and to a lesser extend N stays in the buffers and needs to be removed after a while.

Costs are high because riparian buffers result in a loss of land. They need to be constructed next to streams and ditches to be effective, which land is currently used for production. In our model this land needs to be compensated for by buying extra land.

4.3.2 Wetlands

Wetlands can pose opportunities for increasing the denitrification process, whereby being able to remove nitrogen from the system in harmless N_2 and harmful N_2O. Nitrate enters the wetland with drainage water from the agricultural drainage network (surface or subsurface). The nitrate moves into the sediment of the wetland primarily through diffusion. Once in the anaerobic portion of the sediment, nitrate is converted to nitrogen gas (N_2O and N_2). This results in a reduction in both nitrate concentration and load as the surface water moves through the wetland. Appelboom & Fouss (2006) conclude that the amount of nitrate denitrified in wetlands is influenced by the nitrate concentration in the water column, residence time, temperature, presence of denitrifying bacteria, available labile carbon, presence of vegetation and the water depth. The presence of vegetation is important to a wetland's ability to filter nutrients, but their uptake as a permanent path of nutrient removal is minimal, though plant uptake could be a permanent path of nutrient removal if the vegetation was harvested periodically (Day *et al*, 2004).

Appelboom and Fouss (2006) summarize that the average total nitrogen removal in wetlands ranges from 37% to 65%. In constructed wetlands using hedges, the hedges had an additional benefit of removing nitrogen (as much as an additional 18%) as the water seeped through them in the same manner as riparian buffers. There are some examples in the Netherlands of wetlands that treat surface waters from agricultural areas. The efficiency varies for nitrogen between 20 and 80% and for phosphates between 20 and 90% (Klok *et al*, 2003). Range varies according to the conditions under which the wetlands functions as mentioned above.

A general consensus, borne out of scientific studies, is that controlled wetlands remain effective (and indeed increase effectiveness) for up to 10 years (Forbes, 2004). The ten-year life span will be taken as a standard and below a cost indication will be given from different literature examples. The following parameters and assumption are used in further calculations. We assume that construction requirements for a wetland amounts to 10 man-days per hectare, adding an extra cost of 4800 €/ha and that no further work is needed for 10 years.

It is unknown whether wetlands have to be dredged after these ten years or whether they are a long-term C, N and P sink. Only if the latter is true wetlands can be considered a sustainable solution to N and especially P pollution from agriculture.

DeBusk *et al* (2004) cited in Forbes (2004) present that 78 m^2 are needed per kg N/y and 160 m^2 per kg P_2O_5/y. Using the assumptions made earlier, this results in €37 /kg N/y and €75 /kg P_2O_5/y. Costs included are the price of land and labor. Klok *et al* (2003) give examples from Mueleman (1999) for Dutch wetlands, where 60 ha are necessary with an inflow of 1000 m^3/d to filter water with an N concentration of 15 mg N/l and 70 ha are needed with the same inflow to filter water with a P_2O_5 concentration of 2 mg P_2O_5/l. The costs for these wetlands are €80 /kg N/y and €720 /kg P_2O_5/y. Given the excess rainfall data and using Klok's data, a rule of thumb about 66 ha would be needed to clean the water for each arable farm and about 114 for each dairy farm.

Another interesting result from Mueleman (1999, in Klok *et al*, 2003) is that wetlands are more efficient when lower inflow discharges are used. 10 wetlands constructed for a flow of 100 m^3/d need less area than 1 wetland for a flow of 1000 m^3/d. Mueleman's conclusion is that wetlands become too inefficient relative to the required area for flows larger than 1000 m^3/d. Although, smaller and more wetlands might need less space, too many small wetlands might put too much pressure on water management, making size a trade-off between wetland area and water management possibilities and costs, which can only be determined case specific.

In the model we calculated an example of wetland development for the peat areas of the Netherlands. The amount of wetlands created in the model example is sufficient to catch the nutrients from the remaining agriculture. Thirty percent of dairy farming on peat soils was converted to wetland to achieve this goal, creating a total amount of wetlands of 2884 ha. The cost of creating the wetlands was calculated using the information above, but for the acquisition of land we accounted €4 million per farm. Because dairy farming on peat soils is not profitable at the moment the relative loss in profits is small (from a loss of €821/ha to €1046/ha). This implies that, given the investments necessary, the cost-effectiveness is still relatively high: €6 /ha for each kg of N pollution abated or €46 /ha for reduced emission of P_2O_5 (kg).

It is clear that this measure not only has financial implications, but also political and societal. The assumption that peat farms are financially loss-making influences the outcomes to a large extent. The loss-making assumption is based on LEI figures that build on fixed interest rates on capital and a secured labor income. In our model, converting farmlands to natural wetlands or riparian buffers implies that farm income can be substituted by work outside of the farm and that only economic (profit-maximizing) behaviour is involved in decision-making. We acknowledge that this is a strong simplification of reality.

4.4 Future foreseen measures: Arable farming (crop breeding efforts)

Through genetic engineering more efficient crops can be bred. Genetic engineering applies constructed genes to improve some specific aspects of the N-uptake of plants. In *Arabidopsis* genetic engineering did result in a higher nitrite or ammonia concentration at the cellular level. The plants often did take up more N. Reduction of the nitrogen used in this photorespiratory pathway combined with extra photorespiratory activity led in laboratory conditions to seven-fold ammonium assimilation (Good *et al*, 2004). Oliveira *et al* (2002) state that these findings may hold for all C3-plants.

Obviously, other constraints reduce this figure. When nitrogen would be taken up so much more efficiently, one can expect to obtain similar yields with half the available nitrogen in the soil. However, this does not hold, because N is also needed for protein storage in seeds. Therefore economizing on resource use and especially N & P is highly limited (Raven *et al*, 2005). In the same field, cell biologists like Long *et al* (2006) expect that increasing the light use efficiency will allow a potential yield improvement of 50% in the coming years together with equal efficiency gains.

However, Wageningen crop systems biologists think that complex interactions within the plant will cause actual yield increases to be six times lower (Yin & Struik, 2006). This is supported by Britto & Kronzucker (2004) who argue, based on model outcomes, that acquiring maximum N-use efficiency requires over-expression of three enzymes (PEPcase, PPDK and GS). Over-expressing three enzymes can be considered an extremely complicated research effort. It is uncertain whether any of these efforts will have measurable impacts on increasing NUE in the near future, if so, it will be around 10% (Dobermann *et al*, 2003; Yin & Struik, 2006). In addition, breeding for NUE is not yet common. Most research efforts focus on yield and resistance to e.g. diseases, salt drought. Therefore, the feasibility of the above stated 10% NUE increase is highly dependent on the future importance of environmental policy.

For N input use the measure implies that a reduction of 21 kg N/ha is possible at an extra demand of 1 kg P_2O_5/ha for the entire arable sector because less animal manure is used (because of the model assumption that a fixed fraction of N fertilizer comes from manure). This would increase the arable NitrogenUE from 51% to 56%. The measure implies that less fertilizer is needed. Breeding has so far mostly been directed at improving yield potential or improving resistance to biotic and abiotic stress. When money is allocated for improving NUE, it cannot be allocated at the same time for improving yields. Synergy is not impossible, but nutrient use efficiency of most crops did hardly improve in the last decades, whereas yields increased very fast (Doberman *et al*, 2003). Therefore we considered the foregone benefits of a yield improvement of 10% as the cost of this measure.

This makes that crop breeding efforts will not automatically lead to a financial benefit. Subsequently, cost-effectiveness is estimated at a cost of €6 /kg N. For the region as a whole the effects are smaller: a NitrogenUE increase of 2% and an increased cost of €52 /kg P_2O_5/ha because manure now has to be (processed and) exported from the region.

4.5 Future foreseen measures: Dairy farming

4.5.1 Phosphate mining

In Dutch farming systems, vast amounts of manure have been applied over decades of time. This has caused a large accumulation of P in the soil which has the potential for P losses to the environment. Because much of the P in animal manure is soluble there is a direct risk for leaching to either groundwater or surface water. Different soils have different capacities of binding P. If the capacity is used for 25%, the soil is considered phosphate-saturated. This means that the concentration of P that leaches from the soil is, on a long-term average, higher than 0.1 mg/l, being the maximum for Dutch surface water (Koopmans *et al*, 2002). Even though phosphate mining has only been studied for sandy soils, as these soils are most severely P saturated, the measure can be applied to other soils too. Phosphate mining may take longer for deeper soils with a higher total P content.

P-mining is the process whereby soils are being kept under production, while adding as little P as possible to the soil, so that the amount of P will slowly diminish, as P is taken away as part of the harvest (Koopmans *et al*, 2004b). In order to harvest as much P as possible, there is probably a need to supply N and other elements. The measure can be implemented in two ways: i) a ban on all P fertilizer on the land (both organic and inorganic) or ii) a ban on artificial P fertilizer only. The first measure can only be implemented on sandy soils under grassland, because the yield effects on other soil types are yet to be studied. The second measure can be implemented on all sandy soils, both arable and dairy.

A ban on all P fertilizer is very costly, because it requires extra (artificial) N fertilization, because organic manure cannot be applied and thus has to be exported. Therefore this measure decreases the regional NitrogenUE from 33% to 31%, while improving PhosphateUE from 51% to 55%. With a ban on artificial P fertilizer better results can be achieved. For NitrogenUE this measure has no effect while PhosphateUE increases from 51% to 69%, while at the same time organic manure can still be applied. Of course, the measure only works on soils that are seriously P saturated and this will only hold for the first years after implementation.

The cost-effectiveness of a ban on artificial P fertilizer is high. The measure shows a win-win situation. On arable land €29 per hectare less inputs are needed for maize and wheat, and phosphate use efficiency increases on arable farm level to 149% (indicating P mining). On dairy farms results are less spectacular, but still substantial. On sandy soils PhosphateUE can increase (from 40%) to 46% at a profit of € 7/ha.

The first measure has been mainly worked out in experimental plots of Koopmans *et al* (2004ab) and therefore has been categorized as a future foreseen measure. However, recently the Flemish government has decided to include this measure in its new 'mest decreet'; only leaving room for derogation if farmers can prove that more P is needed. Farmers do not accept this measure easily due to a combination of factors amongst others: risk aversion and tradition. In addition, a total ban on P fertilizers comes at the cost of decreasing organic matter. Lastly, the measure does not hold for a long time because P reserves will be exploited at some point.

4.5.2 Nitrification inhibitors

Nitrification inhibitors (NI's) inhibit the activity of *Nitrosomonas* spp. bacteria, whereby they delay the oxidation of the ammonium present in the fertilizers into nitrate for a certain period of time. Because nitrate operates in a more mobile form (nitrate leaching, denitrification) compared to ammonium, and because nitrate is a product of the nitrification process, NI's can potentially block NO_3 and N_2O from leaching and volatilization. Much research has been carried out on NI's, especially in Germany, Spain and New Zealand, though mainly with the purpose of reducing N_2O emissions.

Results indicate that N_2O emissions can be reduced through the use of nitrification inhibitors. We conclude that both in mineral and slurry applications on average 40% less N is emitted in the form of nitrous oxide (Di *et al*, 2007; Menendez *et al*, 2006; Weiske *et al* 2001). However, results for NO3 are more blurred and it could not be concluded that nitrification inhibitors reduce N leaching to a similar extent in Dutch agriculture. In US conditions, where ammonium rich Urea is used more often, results are more explicit. De Klein *et al* (1996) researched the effects of NI's on slurry application and estimated an approximate 10 kg less emissions. Positive results of DMPP on organic manure fertilization are found in Spain too (Linaje *et al*, 2006). The result of the nitrification inhibitor is a 1% NUE improvement in dairy farming at a cost of €45 /ha.

More promising is the combination of manure separation with nitrification inhibitors. Nitrification inhibitors especially work well on liquid substances as urine and the liquid fraction of separated manure. Leaching of the applied liquid fraction can be reduced by 70% if applied together with nitrification inhibitors (Di and Cameron, 2004). This increases NitrogenUE with 6% on dairy farms to 30% and reduces nitrogen surplus with 112 kg N ha^{-1} at a small costs of €9 /kg N. However, as a result of this measure PhosphateUE decreases from 51% to 42% on a regional scale. This is due to the fact that the combustion of the solid fraction leaves behind the P fraction that cannot be used in agriculture (for the moment), wherefore extra P fertilizer is required.

New DMPP nitrification inhibitors are being developed that seem to be more successful than the older DCD inhibitors. Nitrification inhibitors are currently hardly being researched in the Netherlands. Only a review with laboratory experiments has been carried out recently (Dolfing *et al*, 2004). The experiences in the rest of the world evidence a more extensive research program on this topic, especially with respect to nitrate leaching.

4.5.3 Breeding efforts

Breeding efforts can help in producing cattle that can more efficiently transform N and P from fodder into useful products (meat and milk). If same research efforts that are currently undertaken for yield improvement are directed at improving nutrient use efficiency it is claimed that likewise gains can be achieved (Van Bruchem *et al*, 1999). Only recently some research efforts have started in the field of cattle selection (and breeding) for nutrient use efficiency (Herd *et al*, 2004). The results from this research outline great possibilities for selecting more efficient ruminants (Table 10).

It seems safe to extrapolate the data from the past, indicating an average annual rise of 1.25% in the trait directed for yield. A shift in traits is taking place, so that progress now can shift to a decline in N and P intake of 1.25% per year under stable milk yield. In 2030 this would mean a P and N intake at only 73% of present intake, assuming no change in the relative composition of the diet.

However, breeding purely for increased nutrient use efficiency comes at the cost of a decreased future milk yield. When comparing both projected situations: Breeding for yield and breeding for NUE, calculations show that while cost of feed drops to 46%, the amount of milk and meat produced drops by 26% (as compared to the autonomous yield improvement of 2030).

Table 10: Breeding efforts compared to breeding for production

Comparing 'breeding for production' to 'breeding for NUE'	Now	Breeding for yield	Breeding for NUE	Benefit breeding for NUE not breeding for yield
Food per cow (kg N)	28349	38555	20695	-46%
Yield per cow (kg N)	5784	7866	5784	-26%
NUE	0.20	0.20	0.28	37%

Breeding efforts can result in large increases of both NitrogenUE from 24% to 29% (on farm level) and PhosphateUE from 40% to 46%. These positive effects come at a financial benefit of 300 €/ha. This can be so, due to the fact that improved NUE leads to substantial savings in fodder and fertilizer, while the foregone costs on breeding for yield are restricted because more and more manure needs to be exported from the farm. This would imply that already at this moment it is profitable to start breeding for NUE instead of yield.

The example given is of course very hypothetical. In reality breeding efforts for yield, health and the environment can go hand in hand. As Jonker *et al* (2002) state: at increasing milk yields N utilization efficiency increases too. In addition, if there is to be improvement in traits other than milk yield and animal health, the breeding sector needs to put more emphasis upon structure and control (Bichard, 2002). Animal breeding has potential. This can already be seen in empirical research where NitrogenUE of 30% and higher are achieved when judicious feeding is applied (Tamminga, 1996). Here, we assume that similar results can be accomplished in animal breeding.

4.5.4 Fodder quality

In the conversion of animal feed to useful products the highest inefficiencies take place. More judiciously adapting the protein content of the feed to the cow's demand belongs to one of the most promising measures. Decreasing the crude protein content in fodder can improve NitrogenUE while at the same time maintaining whole milk production levels of 14.000 kg/ha/y (De Visser *et al*, 2001). It has been widely acknowledged that reducing N and crude protein in fodder can reduce N output at similar production levels (Yan *et al*, 2006; Ipharraguerre *et al*, 2005). De Visser *et al* (2001) state that the percentage of N in fodder can be decreased from about 2.8 till about 2.3 without compromising production.

Following calculations of Eastridge (2006), Lynch *et al* (2003) and de Visser *et al* (2001) improving fodder quality can on average increase NitrogenUE (fodder to milk and meat) from 21% to 23.3 %. Especially ammonia emissions are reduced in this way. Costs involve more quality control and measurements are needed during the entire chain of processes before feeding. This involves matching the own fodder with the bought fodder to such a quality that crude protein content is optimal. As technologies advance, the benefit of more efficient fodder use will outweigh the costs of these measures.

The effect of the measure is positive for NitrogenUE, on dairy farms NitrogenUE increases from 24% to 25%, while PhosphateUE does not automatically increase. At regional level the changes are similar (NitrogenUE from 33% to 34%). The measure comes at a benefit (win-win situation) because on-farm fodder production is better suited for purpose and less fodder has to be imported. Overall benefits are €135 /NUE% increase. Possible side effects include increased methane emissions due to the higher fibre content in manure. Negative CH4 emissions, however, fall without the scope of this research. This measure shows great potential but still needs more (applied) research before it can become fully operational and effective.

4.6 Future foreseen: End-of-pipe measures (bioreactors)

Permeable reactive barriers (PRB) are walls build into the ground to intercept chemicals in groundwater flow (e.g. Blowes *et al*, 2000). The groundwater that flows through them reacts with the barrier and in doing so it filters specific chemicals. It is imperative that the type of pollution is known as well as the flow direction of the water. Because it is inefficient to build PRBs everywhere, PRBs are more suitable for point source pollution. A bioreactor is a simple mix of 70% sand and 30% organic material like wood chips or sawdust. The abundance of energy rich carbon in the bioreactor strongly enhances the denitrification process and the in-line bioreactor is capable of extracting up to 90% of the nitrogen flowing through.

In agriculture, the main part of the pollution is from diffuse sources and flow directions are not always apparent. Therefore, a bioreactor is developed for the situation of tile-drained areas, where a significant part of the drained effluent flows through pipes to drain ditches. The bioreactor can be placed in line with the drain tiles where water flows through the bioreactor and consequently nitrogen can largely be intercepted.

Blowes (1994) suggested a design for an inline bioreactor with a volume of 8 m^3 that could handle 2.8 m^3/d with a residence time of 1 day. The mixture of 70% sand and 30% organic content would have a life expectancy of approximately 72 years if all the organic material would be available. Although a part of the organic material will be lost to other reactions and leaching from the tank, the life expectancy of one tank can still be measured in decades.

The surface necessary for the construction of the bioreactor is 8 m^2 for the bioreactor itself and 16 m^2 of a 1 meter safety zone around the bioreactor, amounting to a total of 24 m^2 which is a loss of productive area. Assuming the cost of 1 hectare of land to be around €42.000, the loss of land will amount to a cost of around €100. Furthermore, the bioreactor should be dug into the soil, and filled again with a mixture of sand and organic material. No lining of the bioreactor is necessary if built in relative impermeable soils like clay or fine silts. A farmer could let the hole be dug in half a day for a cost of around €60 per hour; totaling about €240. Filling the hole with the mixture of 70% sand and 30% organic material, will cost around €310 per bioreactor. In total it will amount to €650, rounding this up to a €1000 will also incorporate for unforeseen costs (like other materials needed for construction and possible maintenance costs) could be viewed as an indicative number. We assume that the bioreactor has a life expectancy of around 10 years, in which case the investment is €100/ha/y.

The bioreactor has a capacity of around 2.8 m^3/d, this is approximately half of the excess rainfall in the Netherlands per hectare (5.5 m^3/d). Assuming that only half of the excess rainfall does flow into the drainage tiles, one bioreactor of 8 m^3 has sufficient capacity per hectare. If only half of the excess rainfall does flow into the bioreactor, then also only half of the nitrogen leaching flows through the bioreactor. In the Netherlands there is an average soil surplus of nitrogen of 104 kg N/ha per year on maize, about 29 kg N/ha (28%) of that will leach, half of this will be filtered with an efficiency of 90%, resulting in a nitrogen extraction of around 13 kg N per hectare. For the aim of comparison, we assume that the extracted nitrogen is transferred to outside the model area, partly by denitrification and partly by replacing the bioreactor after ten years. Overall, the bioreactor can be a cost-effective measure. Applied on a regional scale the bioreactor can decrease N pollution with 4 kg ha^{-1} at a cost of €11 kg^{-1} ha^{-1}. The measure does not have an effect on PhosphateUE.

Currently research and development is going on in the field of PRBs. However, because their use is limited to point source pollution, the development of PRBs is mainly focused on extraction of heavy metals from known point sources of industrial plants. In Dutch agriculture, a PRB like the bioreactor can only be applied cost effectively in areas that are tile-drained. However, in such areas they can strongly diminish diffuse pollution of nitrogen. PRBs might affect the speed of drainage; this side affect should be studied in further research on PRBs in the Netherlands.

4.7 Combination of measures

Here we combined a selection of measures of which we think that their functioning is independent of the implementation of other measures. We made two combinations, each with two variants. Combination A1 consists of the measures 1) catch crops after maize, potato and winter wheat, 2) site specific fertilizer application on potato, 3) improved NUE by crop breeding of all arable crops, 4) improved animal NUE by breeding 5) no-tillage on grassland. Combination A2 consists of the same measures but here manure use in agriculture is fine tuned to maximize the sum of nitrogen and PhosphateUE. In A2 the fraction manure N of total applied N is again used to maximize the sum of the two nutrient use efficiencies. Combination B1 is the same as A1 but in B1 the measure manure separation and the burning of the thick fraction is included as well. In B2, like in A2 the fraction of N applied from manure in arable farming is changed to maximize the sum of NitrogenUE and PhosphateUE.

In terms of nitrogen use efficiency improvement and nitrogen pollution abatement combination B1 shows the best performance. The big increase in nitrogen use efficiency is because manure N is used more efficiently in this scenario than in the A-combinations and less manure is used than in B2. The large reduction in N pollution as compared to the other scenarios is caused by the burning of the solid manure fraction. In B2, this effect is counterfeited by a higher use of relatively inefficient manure use in arable agriculture.

In terms of PhosphateUE B1 performs worse because of the unusable slack that is produced during the burning of solid manure. In B2 this effect is counterfeited by a higher use of manure in arable farming which reduces P fertilizer imports to the model region. The A combinations are cost negative. This is caused by the breeding for more efficient dairy cows' measure.

4.8 Land use scenarios

The effect of three scenarios on nutrient use efficiency (NUE) and profitability were explored: i) a doubling of dairy farming at the expense of arable agriculture; ii) a large growth in biofuel crop cultivation; and iii) a large expansion of nature areas in the Netherlands. Furthermore three land use adjustments were tested on their effect on NUE. The latter include a 50% reduction of dairy production, a 50 % reduction of pig production and an NUE optimization of land use.

4.8.1 Dairy for arable

The quota system is likely to be abolished in 2015. This will allow Dutch milk production to grow. In combination with a global dietary change (China doubled its milk import the last 10 years) towards more animal produce, including dairy, this might well imply a 3% annual productivity increase, resulting in a doubling of milk production in 2030. This scenario is based on the Veeneklaas & Van der Ploeg scenario (2000).

Dairy farming will become more efficient, fodder to milk and meat efficiency is expected to rise to 40 percent for both N as P. However the efficiency increase is less than the expected productivity increase per cow of 50%. Dairy farming production will double at the cost of arable farming. Dairy expansion will start on clay soils and then start occupying sandy areas, leading to a big change in the Dutch landscape. All fodder production from arable farming will be used for feed. Pig production will keep constant.

Dairy farms are less nutrient use efficient than arable farms, hence an increase in the number of dairy farms at the cost of arable farms will reduce nutrient use efficiency. This is only partly compensated by the expected rise of NUE of cows (from 0.22 to 0.30). In addition, future dairy farms will become more intensive and manure needs to be exported. More dairy farming will increase the demand for fodder and as there will be less arable farms, more fodder needs to be imported. However, in this scenario grazing will approach 0% which is beneficial to NUE because no manure is dropped uncontrolled in the meadow and the NFV of manure increases.

A shift from arable to dairy farming will only happen when there are political or economical drivers. Therefore, we assume that milk prices will double to €0.30/l. Furthermore, fodder use efficiency and zero grazing will lead to lower costs, but fodder costs are expected to rise with 50%.

In this scenario the overall NitrogenUE on dairy farms will increase from 24% to 35%, while PhosphateUE will rise from 40% to 53%. On a regional scale this will have a smaller beneficial effect on NUE: NitrogenUE rises from 33% to 38% and PhosphateUE from 52% to 56%. However, because dairy farms in general create bigger nutrient surpluses the losses increase by 16 kg N/ha and 3 kg P_2O_5/ha regionally. However cost do not outcompete benefits, therefore effectiveness is low for NUE (win-loose) and double negative for losses.

4.8.2 Increased biofuel cropping

Currently demand for biofuels is increasing because of political stimulation combined with high oil prices. The so-called second generation biofuels which include liquid fuels made from waste and agricultural produce is said to be competitive at oil prices over US$60 per barrel (Boerigter, 2006). At present oil prices are at US$66 per barrel.

A promising feedstock of so called Biomass-to-Liquids plants, but as well other biomass to energy installations is switch grass (Bakker *et al*, 2004). Switch grass (*Panicum virgatum*) is a warm season perennial herbaceous (C4) grass that is established from seed. It develops rhizomes and is also deep rooting, often more than 2 m. It grows 50-250 cm tall depending on the variety and climatic conditions. Switch grass produces on average 14 (ranging between 10 and 22) ton DM per hectare on northern European farming conditions and slightly higher in experimental settings (Sharma *et al*, 2002; Bakker *et al*, 2004; Parrish & Fike 2005). Nutrient input is modest (60 kg N, no P_2O_5 in Northwest Europe) (Parrish & Fike 2005) and production costs in the Netherlands are about €62 /ton (Christian *et al*, 2004). Compared to tree energy crops like willow, switchgrass is cheaper to produce, compared to other energy grasses like miscanthus or elephants grass, switchgrass is easier established and less risky (Christian *et al*, 2004).

We simulated a scenario in which switchgrass will be cultivated on one fourth of the land of arable farms. Drivers for adoption of biofuels are the low labor demand, a lack of alternative profitable crops, and an increase in interest in biofuel crops because of political reasons. In northwest Europe the advised nutrient application to switchgrass is only 60 kg N/ ha and no phosphate fertilization is needed in the medium long run (0-10 years). This is low compared to other crops that are commonly grown in Europe. Nutrient removal is also low in comparison to other crops (70 - 98 kg N/ha, 7-10) (Christian *et al*, 2001; Elbersen *et al*, 2003) but overall NUE is still high.

Table 11: Comparison of advice nutrient application to food/fodder crops and the energy crop switchgrass

Application type	**N (clay)**	**P_2O_5 (clay)**	**N (sand)**	**P_2O_5 (sand)**
Sugar beet advice	158	40	150	0
Potato advice	208	85	187	0
Wheat advice	117	0	103	0
Maize advice	235	85	259	0
Switch grass	60	0	60	0

Switchgrass is not yet cultivated commercially in the Netherlands. We do not expect that switchgrass will be a real money-maker for farmers. So, we assume that farm gate prices are marginally higher than farm production costs. However, as opportunity costs of cultivating other crops are sometimes negative, farmers' financial situation may improve.

An increase in soil organic matter is a likely side effect of widespread cultivation of perennial energy grasses like switchgrass and miscanthus. Furthermore food and fodder prices might go up, resulting in more expensive animal produce. Although Patzek & Pimentel (2005) state that the production of most biofuel crops costs more energy than it produces, this is rejected by a number of other studies (reviewed in Greene & Roth, 2006).

Switching one fourth of arable land to switchgrass improves NitrogenUE substantially. NitrogenUE increases from 51% to 61%, while on the other hand PhosphateUE decreases from 52% to 49%. The scenario comes at a cost of €15 per NUE% indicating a €3 cost per kg N reduction. At regional level the effects are negligible due to the fact that the measure is only applied to less than 10% of the region.

4.8.3 Nature

In the coming decades it can be expected that one third of Dutch arable land will be converted into nature. This shift of land use is not neutral to N & P emissions. In this section we show that it does matter which parts of the Netherlands are converted into nature. First, we will describe a scenario in which all nature is realized on sandy soils, followed by an example in which nature is spread over the major soil types of the Netherlands and lastly we will give an example of smart nature development.

Nature on sand

1/3 of arable and grazing land is transformed into nature, but all of these lands are located on sandy soils. This causes a steep decline in agricultural land use on sand. Only 10 % of farming is done on sand in this scenario. Dairy farming, as currently being most common on sandy soils is reduced. Only 44% of the farm holdings are dairy farms, 26% less than the current situation. As dairy farms have a lower NUE than arable farms this relative change to arable farms implies an increase of regional nutrient use efficiency. Besides that, the model farms (both arable and dairy) on sand perform worse in terms of NUE than farms on clay (0.52 & 0.25 vs 0.51 & 0.24 for arable and dairy farms on clay and sand respectively). Aarts *et al* (2005) observed the same in a study that included many dairy farms. This also causes a modest increase in NUE. Nature itself is expected to be neutral on N & P in the long term. This NUE gain, however, comes at a great cost. Based on the LEI database the value of dairy farms is estimated at €4 million and the value of arable farms at €3 million. The annual cost of buying these farms equals the interest rate of state bond. We did not add cost for nature development.

Nature spread on all soil types

If nature development is equally spread on all soil types, the relative use of different soil types by farming remains unaltered. On the other hand, farm type distribution changes, because currently farm types are not evenly spread over the soil types. As can be observed this will especially have an impact on arable farmland. This development has a negative effect on regional NUE because arable farms are more efficient in their nutrient use than dairy and pig farms. Cost calculation of this scenario was done in the same way as the nature on sand scenario.

Smart nature development

Smart nature in this context is nature that has not only a biodiversity or nature purpose but also an environmental function for cleaning surface water. This can be done by creating wetlands and by letting agricultural waters flow into the wetlands. In current belief, Dutch nature has to be nutrient poor. Therefore, currently almost no agricultural affected waters are allowed to intrude nature areas because of a fear of nutrient enrichment and hence loss of species. The use of nature and wetlands in particular to clean waters, therefore, needs a change in ideas about nature in the Netherlands, which might not be easy. However, this type of multifunctional nature does not imply that there is no space left for nutrient-poor nature. First of all wetlands cannot be created on sandy soils, and secondly using compartmentalization techniques, zones can be created within nature areas with different nutrient levels. In this way biodiversity and the environment can both prosper (Table 12).

The costs of turning land into nature are high while NUE gains are relatively low. Changing agricultural land into nature may be a good idea for nature, but not necessarily for the environment as regional nutrient use efficiencies stay constant or diminish. However, especially the smart nature scenario shows the biggest decrease in N pollution (indicated by an N surplus decrease) against limited costs. Spreading nature on all soil types reduces nitrogen pollution less than the other scenarios. The development of smart nature on all soil types in the Netherlands performs best on reducing both N and P pollution.

Table 12: The amount of farms after nature creation, the amount of wetlands needed for mitigation of leaching from the farms, the area that is available for wetland creation, the amount of created wetlands which is the minimum value of the latter two, and the percentage of newly created nature that has to be converted to wetland.

	Nr of farms	**Swamp needed to mitigate leaching (ha)**	**New nature area available for wetland creation (ha)**	**Created wetlands (ha)**	**% Swamp of nature**
Dairy farms on clay	108	3954	3146	3146	80%
Dairy farms on peat	83	2759	3146	2759	100%
Dairy farms on sand	108	4736	0	0	0%
Arable farms on clay	29	1927	3192	1927	100%
Arable farms on sand	29	2384	0	0	0%

4.8.4 50% reduction in dairy production

Compared to insects, birds and to a lesser extent pigs, cows are a very energy and nutrient inefficient species (e.g. Nakagaki & DeFoliart, 1991). Theoretically this would not matter in terms of NUE of the entire system if the re-use efficiency of manure was 100%. In reality, this is not the case. Therefore, replacing dairy farming by arable farming in our model causes a predicted increase in regional nutrient use efficiency of 6%. Partly banning dairy farming does increase the NUE of production inside the region but it does not increase the nutrient use efficiency of milk. On a larger level therefore, this kind of measures are ineffective as long as consumption patterns are not changed.

4.8.5 50% reduction in pork production

Although pigs are nutrient inefficient as compared to plants or insects, the nutrient use efficiency of our modeled pig farms (0.36 for N and 0.38 for P_2O_5) is not much lower than that of the region (0.33 for N and 0.51 for P_2O_5). This causes NUE to be rather constant when pork production is reduced in the region. A 50% reduction of pork causes an insignificant decrease in NitrogenUE and a small increase in PhosphateUE (2%). Like with the previous example this adjustment has no effect on the efficiency of pork production itself.

4.8.6 NUE optimization of land use

In this adjustment agricultural production was changed in the region in order to maximize the sum of phosphate and nitrogen use efficiency. The physical geography of the region was fixed, and all land had to be used for agriculture (not for nature). Furthermore, peat could not be used for arable farming. The fraction of N from manure in arable farming was allowed to change as well. The solution was found using MS solver^{TM}. The resulting land use (Table 13) shows a big shift to arable farming and reduction, but not elimination of intensive pig farming. This adjustments yield a NitrogenUE gain of 9% and a PhosphateUE gain of 4% on regional level.

Table 13: Adjustments in agricultural production to maximize the sum of NitrogenUE and PhosphateUE.

Farm type	**Change in holdings**
Dairy clay	-98%
Dairy peat	0%
Dairy sand	-100%
Arable clay	145%
Arable sand	148%
Intensive pig	-79%

5 Results and discussion

5.1 Overview

Table 14 gives a qualitative overview of the results of this study. The table portrays the mechanisms, state of development and effects of the different measures. The results can be grouped in four categories: i) reducing N inputs; ii) increasing fodder to milk/meat conversion; iii) manure processing and iv) end-of-pipe measures.

Reducing nutrient inputs seems a logical first measure to increase NUE. Both P mining and site and time specific management have the potential for decreasing fertilizer applications. A ban on mineral P fertilizer in some P saturated (sandy) areas of the Netherlands looks, overall, as the most feasible measure to increase phosphate use efficiency. Also from a policy perspective this measure can easily be implemented, as is shown in Flanders. An additional advantage is that the measure does not put more pressure on the national manure market.

In dairy farming greatest NUE improvements can be achieved in the fodder to milk-meat conversion section of the farm. Either by breeding efforts or improving feed quality NUE (both N and P) can be increased. For the short term more emphasis on tailor-made animal feeding operations have potential, while in the longer run specifically breeding for NUE holds promise.

Table 14: Overview of measures and their effects applied to the relevant sector (dairy, arable or both)

Measure	**Mechanism**	**State of development**	**Potential effect**	
			N	**P**
Catch crops	Nutrient retention in winter	In use	medium	low
Site and time specific management	Adjusting N supply to N demand	In progress	medium	none
Controlled release fertilizers	Adjusting N supply to N demand	In use	none	none
Manure processing **	Increasing NFV and emission of harmless N_2	In use	low	negative
Herd management	Lowering cattle stock	In use	none	none
Riparian buffers ***,*****	Nutrient removal	In use	none	none
Wetlands *****	Nutrient removal	In progress	none	none
No grassland plowing for grassland renovation	Nutrient retention through permanent pasture	In use	low	none
P mining ****	Lower P inputs	In progress	none	high
Nitrification inhibitors	Adjusting N supply to N demand	In progress	none	none
Crop breeding efforts	Increasing NUE in plants	Hypothetical	low	none
Animal breeding efforts	Increasing NUE in animals	Hypothetical	medium	medium
Improved feeding	Adjusting protein supply to animal demand	In progress	medium	medium
Bioreactors *****	Nutrient removal	In progress	none	none

* Effects assessed on the basis of application for sector (arable, dairy or region):
>0-2 ΔNUE%=low, 3-6 ΔNUE%=medium >7 ΔNUE%=high

** The most successful technique is used here: manure separation and combustion of the solid fraction

*** The most successful variant is used here: the wet riparian buffer

**** The most successful variant is used here: a ban on artificial P fertilizer

***** Have effect in terms of NUE but do have pollution reduction effect

Manure processing has been a popular instrument in current debates on sustainable agriculture. From an NUE (N) perspective, however, not the anaerobic digestion of manure but the subsequent separation and combustion of the solid fraction looks promising. Both fractions (liquid and solid) reduce nitrogen emissions: the liquid fraction through its increased Nitrogen Fertilizer Value (NFV), which diminishes the need for artificial fertilizer and hence increases NUE, and the solid fraction because it can be combusted and leave the system in harmless N_2. The latter does not increase NUE but does decrease nitrogen pollution. The solid fraction can also be used for methane production. Challenges still exist in making the remaining P a useful resource. At the moment heavy metal concentrations in the combusted leftovers are too high.

Lastly, end-of-pipe measures, though expensive, are powerful instruments to extract nutrients from the system. These measures do not contribute to any increase in tradable output per kg nutrient used. Therefore, we distracted N_2 outputs from the end of pipe structures from the N surplus for comparing the end-of-pipe measures with the other measures. In this respect the researched measures of wetlands and riparian buffers both look successful. When combined with nature conservation ('smart nature') wetlands can become multifunctional environmental buffers for N and P leaching.

5.2 Aggregated measures

The described measures can be aggregated to assess the overall potential of NUE. Four packages of measures have been made that highlight the possibilities for the arable and dairy sector. In package A the measures of catch crops, crop breeding, animal breeding and no plowing for grassland renovation during grassland renovation have been combined. The difference between A1 and A2 is the amount of manure from pig and dairy farms that is used in arable farming. In A2 this figure is optimized (and decreased) for NUE and PUE. In the B scenarios the manure is separated in a solid and liquid fraction and the solid fraction is combusted. In B2, like in A2 the fraction of N applied from manure in arable farming is changed to maximize the sum of NUE and PUE (Table 15 & 16).

Table 15: Overview of the performance in terms of nitrogen of four combinations with two types of fine tuning. A1 consists of the measures catch crops, site and time specific management, crop breeding, animal breeding, no grassland innovation with ploughing. A2 consists of the same measures but here manure use in arable agriculture is optimized to maximize the sum of NitrogenUE & PhosphateUE. In A2 the fraction manure N of total applied N in arable farming is 0.21 while it is 0.30 in A1. Combination B1 is the same as A1 but contains manure separation and the burning of the solid fraction as well. In B2, like in A2 the fraction of N applied from manure in arable farming is changed to maximize the sum of NitrogenUE and PhosphateUE. In B2 this fraction is 1.

Combi-nation	**Change in N surplus (kg/ha)**	**NitrogenUE old**	**NitrogenUE new**	**NitrogenUE change**	**Cost €/ha^{-1}**	**Cost-effectiveness (€/ NUE% /ha)**	**Cost-effectiveness per kg N (€/ha)**
A1	-60	33%	41%	8%	€ -88	-11*	-1*
A2	-62	33%	41%	8%	€-84	-10*	-1*
B1	-101	33%	43%	10%	€ 443	46	4
B2	-94	33%	41%	8%	€ 411	49	4

* indicating a benefit (win-win)

Table 16: Overview of the performance in terms of PhosphateUE improvement and phosphate pollution for the four combinations of measures. The combinations are the same as in Table 15.

Combination	Change in P_2O_5 surplus (kg/ha)	PUE old	PUE new	PUE change	Cost (€/ha)	Cost-effectiveness (€/ PUE%/ha)	Cost-effectiveness per kg P (€/ha)
A1	-3	51%	52%	2%	€ -88	-55*	-31*
A2	-3	51%	52%	2%	€ -84	-53*	-30*
B1	10	51%	46%	-5%	€443	-92	-46
B2	-4	51%	53%	2%	€411	187	107

* indicating a benefit (win-win)

The highest possible nitrogen use efficiency and nitrogen surplus improvement can be achieved using the B1 mix of measures. The B1 combination of measures performs badly in terms of phosphate management because of the manure separation and combustion which turns manure P into a waste product. This effect can be partly reduced by increasing the amount of manure that is applied in arable farming. But when 100% of the arable nitrogen need is derived from the liquid fraction of manure the phosphate use efficiency increase is slim compared to that of nitrogen. Furthermore it will be hard to substitute all artificial fertilizer by manure. The A scenario's in which the manure separation is excluded, show the same nutrient use efficiency improvement but a much lower nitrogen pollution reduction.

5.3 Cost-effectiveness of measures in arable farming at farm level (Nitrogen)

Site and time specific management will be the most cost-effective measure in arable farming in terms of NitrogenUE. Matching theoretical research findings with farmers' needs seems to be the issue here. Catch crops in arable agriculture are still quite expensive and as stated before controlled release fertilizers do not have an effect at all (Table 17).

Table 17: Cost-effectiveness of measures for arable farming (nitrogen) at farm level, average of all soil types

	Ninput change	NUEold	NUEnew	NUE change	Cost (€/ha)	Cost-effectiveness (€/NUE%/ha)	Cost-effectiveness (€/kg N/ha)
Time and site specific management	-14	51%	54%	3%	€ 12	4	1
Catch crops	-18	51%	55%	4%	€ 60	15	3
Crop breeding	-21	51%	56%	5%	€ 274	55	13
Controlled release fertilizers	0	51%	51%	0%	€ 200	NA	NA

5.4 Cost-effectiveness of measures in dairy farming at farm level (Nitrogen)

Table 18 shows that in dairy farming still possibilities exist for win-win. The negative figures at cost-effectiveness indicate that these measures both increase NUE, while at the same time come at a profit. For animal breeding efforts this is still hypothetical, but for improved breeding and no grassland renovation using ploughing experimental research already points in this direction. In addition, manure processing (separation and combustion) also has potential, though at the moment is relatively expensive.

Table 18: Cost-effectiveness of measures for dairy farming at farm level (nitrogen), average of all soil types

	Change in N surplus (kg N)	NUEold	NUEnew	NUE change	Cost (€/ha)	Cost-effectiveness (€/NUE%/ha)	Cost-effectiveness (€/kg N surplus/ha)
Improved feed	-13	24%	25%	1%	€ 124-	135-	10-
Animal breeding	-62	24%	29%	5%	€ 300-	57-	5-
No plowing for grassland renovation	-14	24%	25%	1%	€ 12-	11-	1-
Manure processing	-106	24%	29%	5%	€ 986	184	9

5.5 Cost-effectiveness of measures in arable farming (Phosphate) at farm level

In arable farming we did not fund measures that improve PhosphateUE. The already high relative PUE does not necessitate much research in this field and room for PhosphateUE improvement seems small (Table 19).

Table 19: Cost-effectiveness of measures for arable farming (phosphate) at farm level, average of all soil types

	P_2O_5surplus change	PUEold	PUEnew	PUE change	Cost (€/ha)	Cost-effectiveness (€/PUE%/ha)	Cost-effectiveness (€/kg P_2O_5/ha)
Crop breeding	0	68%	68%	0%	€ 274	NA	NA
Time and site specific management	0	68%	68%	0%	€ 12	NA	NA
Catch crops	0	68%	68%	0%	€ 60	NA	NA

5.6 Cost-effectiveness of measures in dairy farming (phosphate) at farm level

In dairy farming, on the other hand, there is still room for improvement. Especially a ban on mineral P fertilizer has a large effect on PUE. This measure is also easy to implement. Again long term efforts on animal breeding and improved feeding pay off. Manure processing comes at a double loss, both in terms of costs and PUE. This is due to the fact that extra P needs to be imported to the farm, because the leftover P after combustion can at the moment not be used (due to excess heavy metals) (Table 20).

Table 20: Cost-effectiveness of measures for dairy farming (phosphate) at farm level, average of all soil types

	P_2O_5 surplus change	PUEold	PUEnew	PUE change	Cost (€/ha)	Cost-effectiveness (€/PUE%/ha)	Cost-effectiveness (€/kg P_2O_5/ha)
Animal breeding	-12	40%	46%	6%	€ 300	€ 53	€ -26
Ban op P fertilizer	-12	40%	46%	6%	€ 7	€ -1	€ -1
No P manure	-15	40%	47%	7%	€ 18	€ 2	€ 1
No plowing for grassland renovation	0	40%	40%	0%	€ 12	NA	NA
Manure processing	25	40%	31%	-9%	€ 986	€ -112	€ -40
Improved feed	0	40%	40%	0%	€ 587	€ -124	NA

5.7 Cost-effectiveness of all measures at regional level (nitrogen)

For increasing NitrogenUE win-win measures are available in the short and long run. In the short run both no till of grassland and improved animal feeding can benefit farmers by increasing NitrogenUE and reducing costs. In the longer run breeding efforts will contribute too, though this is less certain. In animal breeding other factors play a role too: yield and animal health (Table 21).

Site and time specific management does still perform well and only cost €2/kg N/ha reduction. In addition, the end-of-pipe measures wetlands and bioreactors have a positive effect on N surplus at a relative low cost. As has been indicated in the measures chapter, the results of these measures heavily depend on the model assumptions. In this research LEI data of the 10% biggest farms were used. Dairy farms on peat performed particularly economically bad. If farming comes at a loss, alternative like wetland nature becomes more competitive. As has been indicated too, other arguments than economic play a role here (social, political). Manure has a small potential of increasing NUE, but a relatively big potential of decreasing N surplus.

Other results are that a total ban on P manure and fertilizer is counter-effective for nitrogen. If no organic manure can be applied, N has to be imported and overall NitrogenUE decreases.

Table 21: Cost-effectiveness of all measures at regional level (NitrogenUE)

	NUE change	**N surplus change (kg/ha)**	**Cost (€/ha)**	**Cost (€/ NUE%/ha)**	**Cost (€/ kg N/ha)**
Improved feed	1%	-9	€ 84-	-91	-10
Animal breeding	5%	-42	€ 203-	-40	-5
No plowing for grassland renovation	1%	-10	€ 8-	-8	-1
Crop breeding	2%	-14	€ 80	52	6
Site and time specific management	0%	-3	€ 4	14	1
Bioreactors	0%	-4	€ 40	NA	11
Wetlands	0%	-22	€ 125	319	6
Catch crops	1%	-6	€ 24	34	4
Manure processing	4%	-76	€ 821	184	9
Riparian wet buffer	0%	-15	€ 547	NA	37
Riparian dry buffer	0%	-13	€ 528	NA	40
Nitrification inhibitors	0%	0	€ 17	461	48
P fertilizer prohibition	0%	0	€ 14-	NA	NA
P mining	-3%	29	€ 18	-6	-1

5.8 Cost-effectiveness of all measures at regional level (Phosphate)

Table 22 shows an overview of the costs of each measure and its P effects. All measures have been aggregated to regional level. The table shows that especially the manure processing and end-of-pipe measures are still relatively expensive. The breeding efforts, on the other hand, show win-win opportunities: increasing NUE at a profit.

Table 22: Ranking of all measures on cost-effectiveness (€/PUE%/ha)

	PUE change	**P_2O_5 surplus change (kg/ha)**	**Cost (€/ha)**	**Cost-effectiveness (€/PUE%/ha)**	**Cost-effectiveness (€/kg P_2O_5/ha)**
Animal breeding	5%	-8	€ 203-	-42	-26
Ban on mineral P	18%	-24	€ 14	-1	-1
No P on grass	5%	-8	€ 11	2	1
Wetlands	0%	-3	€ 125	355	46
Crop breeding	0%	1	€ 80	137	74
Improved feed	0%	0	€ 84	NA	NA
Riparian wet buffer	0%	-2	€ 547	NA	244
Riparian dry buffer	0%	-2	€ 528	NA	269
No plowing for grassland renovation	0%	0	€ 8-	NA	NA
Nitrification inhibitors	0%	0	€ 17	NA	NA
Bioreactors	0%	0	€ 40	NA	NA
Site specific fertilisation	0%	1	€ 4	-10	-5
Catch crops	0%	1	€ 24	-48	-26
Manure processing	-10%	22	€ 782	-77	-35

From the end-of-pipe measures only wetlands show a relative cost-effective P surplus decrease. Other end-of-pipe measures are either very expensive or do not have an effect at all. In the case of bioreactors this was not the intention in the first place. Subsequently, combining N and P effects, wetlands seem more effective than bioreactors because they have an effect on both N and P. Because cost-effectiveness is calculated for N and P separately, a combined effect is underrated.

5.9 Land use scenarios (nitrogen)

Shift to dairy performs best in terms of NUE improvement, though this scenario had some very positive efficiency assumptions. However as costs are increasing more rapidly than profits this scenario scores weak on cost-effectiveness. Reduction of dairy production (without the positive environmental assumptions of the shift of dairy production scenario) and the NUE maximization have a big NUE potential as well. The nature scenarios do not improve NUE, as they do not affect productivity. However, especially the smart nature scenario shows the biggest decrease in N pollution (indicated by an N surplus decrease) against limited costs. So, replacing dairy farming on peat soils by wetlands has potential from an overall environmental and economic perspective. The other nature scenarios perform worse and biofuels also do not have great potential in terms of NUE. A decrease in pig production does not have a big impact. This is mainly because the NUE of our modeled pig farms (36%) is just in between the NUE of arable and dairy farms (Table 23).

Table 23: Effects of land use scenarios (NitrogenUE)

	NUE change	**N surplus change (kg/ha)**	**Cost (€/ha)**	**Cost-Eff (€/ NUE%/ha)**	**Cost-Eff (€/kg N /ha)**
NUE maximization of land use	9%	-92	€ 87	-10	-1
½ decrease of dairy production	6%	-48	€ - 91	-16	-2
Shift to dairy	5%	16	€ 1023	210	-64
Biofuel	2%	-8	€ 51	33	7
½ decrease of pig production	0%	-18	€ 2	-7	.1
1/3 Nature on sand	0%	-60	€ 349	920	7
Smart nature	-1%	-74	€ 479	-863	6
1/3 Nature equally distributed	-1%	-53	€ 400	-719	8

5.10 Land use scenarios (phosphate)

From a PhosphateUE perspective results are similar. Scenarios that include a more efficient livestock keeping (shift to dairy) or a change from dairy keeping to arable farming show an increase in PhosphateUE, whereas the nature scenarios show a decrease in PhosphateUE, but a decrease in P surplus. Also here smart nature has large effects on P surplus (Table 24).

Table 24: Effects of land use scenarios (PhosphateUE)

	PUE change	**P_2O_5 surplus change (kg/ha)**	**Cost (€/ha)**	**Cost-Eff (€/ PUE%/ha)**	**Cost-Eff (€/kg P_2O_5/ha)**
1/3 Nature on sand	-1	-10	€ 349	-306	45
Smart nature	-3%	-19	€ 479	-181	26
1/3 Nature equally distributed	-3%	-8	€ 400	-151	49
Biofuel	-2%	-2	€ 51	-27	-25
½ decrease of dairy production	9.4%	-14	€ - 91	-10	-7
NUE maximization of land use	10%	-19	€ -87	-9	-5
½ decrease of pig production	2.1	-8	€ 2	0	0
Shift to dairy	4%	3%	€ 1023	199	-814

6 Implications and reflections

Taking nutrient use efficiency as a point of departure proves useful in clarifying and distinguishing the greatest challenges for Dutch agriculture. Seen from an overall global perspective, only an increase in efficiency of nitrogen and phosphate can improve the increased demand for agricultural products while at the same time reducing environmental losses. Subsequently, further studies should try to expand on our findings and also try to include efficiencies of imported products, as well as include other environmental indicators as energy efficiency.

We found that a combination of technological measures can yield high Nitrogen Use Efficiency gains (8%) towards 2030, without creating more pollution at other levels. Till 8% this efficiency gain can come at a financial gain as well. From this point onwards great investments have to be undertaken to increase Nitrogen Use Efficiency further. The proposed combination of measures can improve phosphate use efficiency by 2%. Phosphate Use Efficiency can temporarily be further increased by a ban on artificial fertilizer.

Overall we see that highest nutrient use efficiency gains can be achieved in the dairy sector. At the moment dairy has a nitrogen use efficiency of 24% and the arable sector of 51%. This is of great importance, especially because dairy farming occupies two-thirds of Dutch agricultural land. Particularly in the conversion of animal feed to useful products, efficiencies are low and increasing them implies environmental as well as financial gains. The animal sectors convert a large amount of nitrogen in imported fodder into nitrogen in manure that is currently inefficiently used. The most logical way of improving this is by reducing the fodder required for producing milk and meat. Breeding efforts to improve NUE in cattle and fodder quality improvements provide opportunities for increasing NUE are promising examples of doing this. The combined result of both measures can improve regional NUE and PUE from respectively 24% to 34% and 51% to 56%. These measures imply that new technologies come available in the course of the next twenty years and that breeding efforts are directed towards more nutrient use efficient cows. Policy can put pressure on this development by reducing N and P application standards on grassland.

Practices that have been tested on experimental dairy farms also provide win-win opportunities. Results from experimental farms and vanguard farms prove that no plowing for grassland renovation has positive, though small, gains in terms of NUE and profitability.

From a phosphate use efficiency (PhosphateUE) point of view only a few measures show promising results. We conclude that, from the currently available measures, P mining, improved feeding and animal breeding have potential. In addition, end of pipe measures confirm positive results on PUE. Especially a ban on artificial P fertilizer can have a great absolute influence on overall PUE and should be considered by policy makers as a realistic measure to improve PUE. A drawback of this measure is that the PUE gain is acquired mostly in arable farming on clay whereas the problem is worse on dairy farming on sand.

In addition, the construction of wetlands, especially in peat areas, is quite a cost-effective measure, both from N and P pollution perspective. In peat areas dairy farming is less profitable than in other areas and NUE is low. Subsequently, it is relatively easy to create wetlands in these areas. Within the context of both the water framework directive and nature management policy, smart, multifunctional nature (wetlands) provide possibilities for synergies.

Subsequently, new smart filtering technologies portray promising results. The inclusion of bioreactors in tile drained areas can to a very large extent reduce nitrogen discharge to surface waters. The relatively low cost and great N filtering potential of this measure supports more research efforts in this field. Especially practical, experimental research is needed on the composition of the reactors and applicability in Dutch tile drained areas. This measure is particularly beneficial in the light of a future, more productive agriculture while at the same time higher losses. Especially in high productive clay areas filtering measures can provide a solution to high N losses to surface waters.

In the plant section breeding efforts can improve NUE too, however, efficiency gains are more difficult to achieve. Efforts focused at time and site specific nutrient management ('geleide bemesting') are promising and should be stimulated. There is a need to make low-tech instruments available for farmers whereby nutrient supply can be adjusted more judiciously to nutrient demand.

Manure processing, popular at this moment as a panacea for energy production, does not look promising from an overall NUE perspective. Most manure processing techniques do not improve the nitrogen utilization coefficient and therefore hardly provide any NUE improvement. As a matter of fact, most measures show negative NUE results. Only the measure of manure separation into a liquid and a solid fraction has a positive effect on nitrogen use efficiency and especially nitrogen pollution. This is due to the fact that the liquid fraction has a higher nitrogen working coefficient and the solid fraction can be combusted, whereby harmless N_2 leaves the system. However, combustion leaves behind an ash of P rich material that (currently) cannot be applied to agriculture. Therefore, on a regional scale more P inputs are needed and PUE decreases.

A popular manure processing measure at the moment is anaerobic digestion. We conclude that anaerobic digestion is not a solution for greatly increasing NUE. Especially, when other materials than manure need to be added to maintain proper energy levels, the measure is counter-productive and produces more material with a relatively low nutrient working co-efficient.

Autonomous trends in Dutch land use predict a shift from arable to dairy farming, a shift from agriculture to nature, and a possible increase in the cultivation of biofuel crops. The shift from arable to dairy does not have to be negative per se. Especially, if dairy farming keeps on improving yields and if the overall efficiencies of NUE and PUE can be remained equal or even increase, compared to current figures. Less promising are the nature management plans. If one third of current agriculture is converted to nature NUE and PUE will decrease at a high costs (a loss-loss situation in terms of both nutrient use efficiency and cost-effectiveness). However, this scenario also inhabits opportunities for so-called smart nature: nature that at the same time converts nutrient losses to plant biomass (e.g. wetlands). The latter strategy will need a proper rethinking of the current bias on oligotrophe nature. In the smart nature scenario a shift is needed towards multifunctional, nutrient rich nature. The average household preference for nutrient rich forests shows a promising trend in this direction. The increase of biofuels in crop rotations will have a negligible effect on nitrogen use efficiency and a small negative effect on phosphate use efficiency, because less animal manure can be applied.

Significant reductions in N & P pollution do not come for free. The most cost-effective measures have a relative small scope of improving NUE (less than 5 %). Once this low hanging fruit has been picked, real financial sacrifices have to be made to further reduce pollution from agriculture.

More research is needed on the following topics:

- Clear input-uptake curves for both N and P fertilization are of utmost importance. At the moment these curves are ambiguous are contradictory. This is a great obstacle for model building and practical advices.
- Upscaling of regional level to European and global level.
- Research on animal breeding for NUE is needed. Already a shift can be observed, away from breeding for yield towards breeding for resistance. The next step should be towards breeding for NUE.
- Research is needed on further adjusting fodder quality to cattle demand.
- The implementation of smart end of pipe solutions is, also within the context of the water framework directive, a pathway that shows potential. In this light the attention on bioreactors is justified. However, bioreactors should be adjusted to the Dutch situation.
- Nitrification inhibitors (NI's). Outside of the Netherlands hopeful results are achieved with applying NI's to grazed pastures and the mixing of NI's with urine. Research is needed how to fine-tune NI's to Dutch conditions and the applicability on ploughed grasslands.

The used methodology, with a simple model and extensive measure description, proves useful. Greatest sensitivities were found in the measures, not in the model. This implies that for explanatory modelling measure descriptions and assumptions need to be treated carefully. In addition, we found it very useful to differentiate in a category of 'currently known' and 'future foreseen', clarifying different stages of certainty.

In retrospect, we observe that much research on abatement measures is still performed at the level of experimental plots. Evidence is lacking on a higher scale level (farm, region). This study has been useful in upscaling experimental research to farm and regional level. However, higher scale level evidence is needed to empirically test our results.

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