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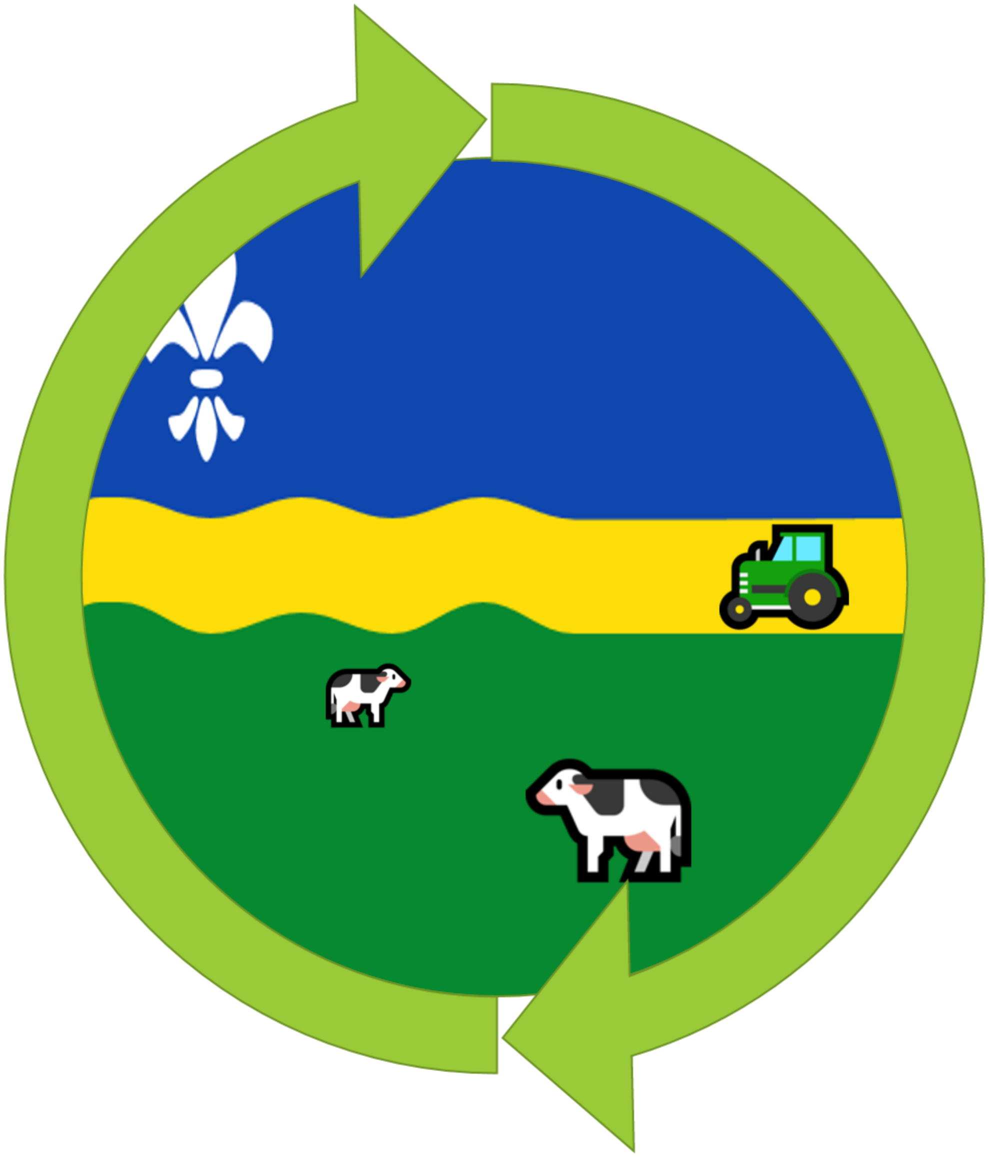
A bio-economic modelling case study of Flevoland



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MSc Thesis Plant Production Systems
July 2019

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Correct citation: Riechelman, W.H., 2019, Can regional integration of arable and dairy farms through land exchange contribute to the Dutch vision of circular agriculture?, MSc Thesis Wageningen University, 49 p.

Contact office.pp@wur.nl for access to data, models, and scripts used for the analysis

Abstract

Potential economic and environmental benefits of land and manure exchange were studied with a bio-economic regional model using mixed integer linear programming for the province Flevoland (Netherlands). Aditionally, the role of land exchange in integrating arable and dairy farms regionally was examined. As this is a potential method to transform an intensive and specialised agricultural system into a circular one.

Data of the Dutch census bureau, scientific papers, and extension services was used to accurately approximate biophysical and economic parameters of the region. Simulated interactions between arable and dairy farms was limited to renting of land with fixed prices for arable and dairy land, and transfer of at most 25% of a dairy farms manure to arable farms.

Four scenarios were written and simulated. In the reference scenario, land exchange was disabled and regional profit was maximised (NO). In the second scenario, land exchange was enabled and regional profit was maximised (MAX). In the third scenario, land could be exchanged and the smallest increase in profits due to enabling land exchange, was maximised, equitably distributing profits of land exchange (EQUIT). In the fourth scenario, exchangeable dairy land was limited, resulting in more realistic cropping patterns (MAX2).

Calculated potential profit increase through land exchange was of up to 36.3% for arable farms and up to 13.9% for dairy farms. However, in the current model it was not possible to distribute profits equitably among arable and dairy farms~~.~~

Land exchange led to more artificial P use but less artificial N fertiliser use and a reduction in soil organic matter inputs from both crops and manure. Suggesting that land exchange may affect environmental impact of agriculture and is detrimental to soil fertility in the long term. However, differences between scenarios in nutrient use and organic matter inputs were primarily due to shifts in crop frequencies. Therefore, simulations with other crops may give different results.

Regional circularity indicators: fraction exported manure and imported livestock feed, performed worse with more land being exchanged. However, the recipients and suppliers of manure and feed were not included in the modelled system and may be located within the province. So, the present findings do not proof that land exchange impairs regional circularity.

To better understand to which degree land exchange is profitable, environmentally detrimental, and useful in regional circularity, the following things need to be considered for future studies:

- Include additional farm-farm interactions to 1) facilitate equitable distribution of additional profits and to 2) better capture rescource flows between farms such as manure, feed, labour, and money.
- Include non-farm actors that deal with manue and feed in the modelled system as these would likely occupy a role in regional circularity.

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Abbreviations

BEFM	Bio-Economic Farm Model
BEM	Bio-Economic Model
BERM	Bio-Economic Regional Model
CAP	Common Agricultural Policy
CBS	Centraal Bureau voor de Statestiek (Dutch statistics bureau)
CH	Chicory
CP	Consumption potato
DVE	Darm Verteerbaar Eiwit (Dutch unit of digestible protein for milk production)
EFA	Ecological Focus Area
EOM	Effective Organic Matter
FA	Fallow
GP	Grass permanent
GT	Grass temporary
h	hour
LHC	Livestock holding capacity
LU	Livestock unit
MiPr	Milk Production
MS	Maize silage
PE	Green peas
SB	Sugar beet
SO	Seed onion
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SP	Seed potato
VEM	Voeder Eenheid Melk (Dutch energy unit for milk production)
WC	Winter carrot
WO	Winter wheat + Oil radish
WW	Winter wheat
y	year

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1. Introduction

1.1. Background

Intensive agriculture in the Western World is able to obtain high yields per hectare and produce agricultural products at a low cost price. There are however serious concerns about the impact of agriculture on the environment and finite resources (Bieleman, 1999; Ehrlich and Ehrlich, 2013).

In the Netherlands, one of the countries with the most intensive agriculture, agricultural impacts have been on the policy agenda for decades especially with regards to manure (Backus, 2017; Henkens and Van Keulen, 2001). In September 2018 the Dutch minister of agriculture presented a vision for the development of the agricultural sector. Dutch agriculture should transform from a linear to a circular system where nutrients are used more efficiently, (food) waste is reduced, and the welfare of rural society, animals, and producers is improved. The ministry did not delineate how this transformation should be accomplished and gives room for societal actors to initiate change (Ministerie van Landbouw Natuur en Voedselkwaliteit, 2018).

An unanswered questions with regards to circular agriculture is on which integration level agriculture should be circular: farm, region, national, European, or global? Circularity, in terms of nutrients can be found at farm level in mixed arable-livestock system. However, during the last decades these systems have mostly been replaced by specialised, capital, and knowledge intensive farms that focus on either livestock or specialty crops (de Wolf et al., 2017; Leterme et al., 2019).

1.2. Current solutions

Reversing specialisation and introducing new agricultural activities on a farm is hard because it requires large investments, for example, in machinery and infrastructure (de Wolf et al., 2017; Martin et al., 2016; Regan et al., 2017). An alternative to combining crops and livestock on one farm, is to combine the two on a regional level (Asai et al., 2018; Martin et al., 2016; Regan et al., 2017; Russelle et al., 2007). Potential benefits of integrating dairy and arable farms include: higher nutrient use efficiency, better distribution of manure on cultivated land, increased soil organic matter (SOM) input on arable soils, lower artificial fertiliser use, lower import of concentrates, decreased crop protection use, longer and less intensive crop rotations, or more profitable and more intensive crop rotations (de Wolf et al., 2018b, 2018a; Regan et al., 2017).

Yet, these benefits have not all been observed in experiments and there are drawbacks as well. Regan et al. (2017) did not find significant reduction in pesticide use in a case study in Winterswijk and de Wolf et al. (2018a) found increased glyphosate use because grassland was converted to arable land more often, using glyphosate. Farmers have to make good arrangements when integrating their farms to control pests, rotate crops properly, and built trust for a lasting co-operation (Bos and van de Ven, 1999; de Wolf et al., 2018b, 2018a)

A relatively simple way for arable and dairy farms to cooperate is by exchanging land and manure. For example, an arable farm gets a hectare of grassland to cultivate potatoes and in exchange the arable farm allows the dairy farm to spread manure on arable land (Regan et al., 2017). A dairy farm may also get some arable land to cultivate grass or silage maize to compensate lost feed production from the hectare lent to the arable farm. It is also possible that the arable farm performs some land work for the dairy farm, saving the dairy farm labour and the need to own certain machines.

Even a seemingly uncomplicated cooperation between farms such as exchanging land or manure, has many aspects that need to be considered by the farmers. The amount of land or manure that is transferred, soil management, timing of manure application, which crops to cultivate, how much fertilisers, or crop protection to use, are all example of decisions that can affect both farmers. Cooperation can benefit both farmers but careful deliberation is required to make sure both parties do in fact benefit. Sometimes, farmers cooperate largely on basis of trust, communicating operational decisions by phone and discussing more important issues in person, without writing up contracts (Asai et al., 2018; Regan et al., 2017).

A previous study into economic and environmental impacts of land exchange using bio-economic modelling found a positive economic effect on arable farms in Flevoland (Nakasaka, 2016). Environmentally, that study found a reduction in effective organic matter (EOM) inputs and both increases and decreases in nitrogen use, depending on the modelled scenario. However, the study was not aimed at studying regional cooperation between farms, merely on economic and environmental consequences for arable farms. Hence, it ignored consequences of land exchange on dairy farms as well as their behaviour.

1.3. Bio economic modelling

Bio-economic models (BEM) can be developed for different integration levels, such as farm (BEFM) or regional (BERM) level (Janssen and van Ittersum, 2007). There are also different classes of BEM. In this study a mechanistic normative BERM was used, meaning that the regional farming system as a whole was simulated based on what it looks like in reality, and that it looks for an optimum distribution of resources amongst different constraints (Janssen and van Ittersum, 2007). Such models allow for future predictions outside the range of observations, and can assess alternative policies, technologies, and farm configurations (Antle and Capalbo, 2001; Janssen and van Ittersum, 2007).

Explained briefly, linear programming models have an objective function for which the objective value is optimised. Optimisation is done by calculating the optimal values of decision variables. Most variables are subject to one or more constraints based on biological, legal, policy, or heuristic limits. The decision variables themselves can also be interesting outputs as these determine what is required to obtain the optimal objective value.

1.4. Description of the region

The region studied is the Dutch province Flevoland. Flevoland consists of three large polders reclaimed between 1944 and 1968; the Noordoostpolder, Oostelijk Flevoland, and Zuidelijk Flevoland (Bieleman, 2000; Janssen, 2017) (Figure 1). The latter two are collectively referred to as the Flevopolder. Over 70% of the land in Flevoland is used for agriculture of which roughly 70%

is arable and 20% is dairy farming (CBS, 2018a). Most urban area is found in the cities Almere and Lelystad. Other people live in urban centres spread throughout the remaining municipalities, or live on farms scattered in the landscape.

Flevoland has the highest land rent prices in the country (RVO, 2019a) as well as some of the highest yields of the Netherlands (CBS, 2019a). Common crops are: seed potato (*Solanum tuberosum*), consumption potato (*Solanum tuberosum*), summer barley (*Horderum vulgare*), seed onion (*Allium cepa*), sugar beet (*Beta vulgaris*), and winter wheat (*Triticum aestivum*) (Smit and Jager, 2018). Farms in Flevoland differ in size, economic intensity, orientation, availability of family labour, efficiency and farm plan and can be classified accordingly (Mandryk et al., 2014).

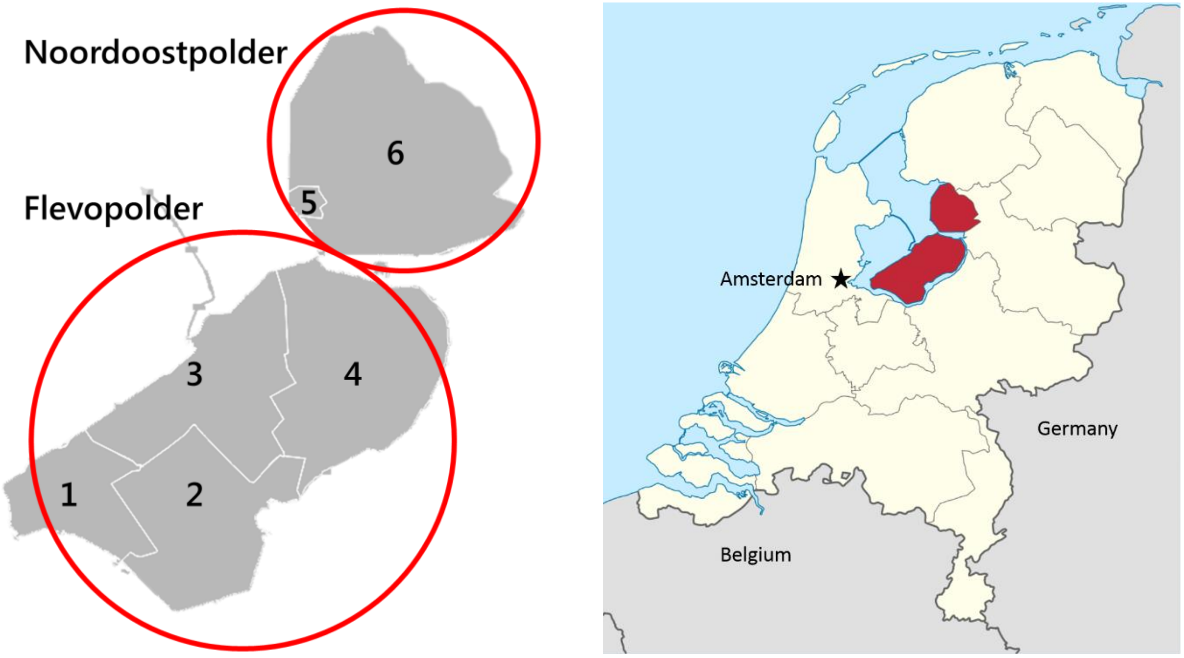

Figure 1. Map of Flevoland. The Flevopolder consists of two polders Oostelijk Flevoland and Zuidelijk Flevoland (both not drawn). The numbers indicate municipalities: (1) Almere, (2) Zeewolde, (3) Lelystad, (4) Dronten, (5) Urk, (6) Noordoostpolder. The polder Noordoostpolder encompasses the municipalities Urk and Noordoostpolder. The map on the right indicates the location of Flevoland within the Netherlands.

1.5. Greening payments

The common agricultural policy (CAP) has played a role in transforming Dutch agriculture into its present form. The CAP has changed over the years, from focussing on supporting production to supporting farm livelihood, environment, and rural areas to curb negative impacts of agriculture (European Commission, 2019; Hodge et al., 2015). Currently, Dutch farmers can get a payment per area under cultivation, if the farm meets certain criteria with regards to their farm plan. The first is: farms over 15 ha have to have 5% of their land as ecological focus area (EFA) (RVO, 2018a). This can be certain (catch) crops, fallow land, or specific landscape elements. A farms shortage on EFA reduces the area over which greening payments are paid out in tenfold. The second condition is aimed at crop diversity, depending on the cultivated area of a farm, the area of the single or two largest crop(s) is limited (RVO, 2018a). What counts as a crop in terms of crop diversification, is mainly determined by the plants species. So, while fodder beet and sugar beet may be different crops, they are of the species *Beta vulgaris* and considered as one crop for crop diversification (RVO, 2018b). The allowed size of the largest crop or crops depends on the size of the farm. Farms under 30 ha can allocate at most 75% of their land to one crop. In addition to this, farms over 30 ha can allocate at most 95% of their area to the two largest crops combined (RVO, 2018b).

1.6. This study

In this thesis, the model developed by Nakasaka (2016) was extended to include dairy farms', crops, livestock, and objectives. This enables the study of arable-dairy farm cooperation on a regional level. The objective of this study was, to assess whether cooperation can contribute to transferring Dutch agriculture to a circular system. The research questions revolve around the effects of land exchange. How does land exchange affect:

- profits of arable and dairy farms
- manure use
- use of artificial N and P fertilisers
- amount of imported cattle feed
- effective organic matter inputs (EOM)

Section 2 describes the model, Section 3 lists data sources and describes the setup of calculations. Section 4 presents the models results. In Section 5, an interpretation of model outputs is given. Section 5 also discusses several opportunities to improve modelling studies into circular agriculture. A synthesis of this thesis is written in Section 6. Included in the appendix is additional information to supplement information in Sections 2, 3 and 4.

2. Model description

The basic mixed integer linear programming bio-economic regional model proposed by Nakasaka (2016) was extended, to quantitatively assess the financial and environmental benefits of land exchange in Flevoland.

The model was written and executed in FICO Xpress 8.5. The full model script can be found in supplemented materials. First, a list of indices, variables, and parameters are presented, followed by a description of the models objective function and constraints. Section 3 describes the set up of calculations, some assumptions made in the calculations, and sources of parameters.

2.1. Model description

In the following tables the indices (Table 1), variables (Table 2), and parameters (Table 3) used in the model are listed, together with a brief description.

Table 1. Set indices used in the model

Index	**Description**
c	Index of crops
f,k	Indices of farms
t	Index of farm types
$s,s1,s2$	Indices of plant species
i	Index of fertiliser inputs
m	Index of main crops
v	Index of concentrates
r	Index of feeding regimes
n	Index of nutrients in fertilisers

Table 2. Variables used in the model.

Variable	**Description**	**Unit**
Area_f	Area of land owned by farm f	ha
$AGPay_f$	Area over which greening payments are paid out to farm f	ha
$ARL_{f,k}$	Land rented out from farm f to farm k	ha
$ARL_{k,f}$	Land rented out from farm k to farm f	ha
$ASpec_{s,f}$	Area of species s on farm f	ha
$CSpec_{c,s}$	Matrix of binary variables used to determine whether a crop is regarded as a certain species for greening payments	-
$FC_{f,c}$	Amount of crop c on farm f fed to livestock	ton/y
$FMProd_f$	Manure produced on farm f	kg
$GSanc_f$	Sanction reducing greening payment area, for not meeting all greening requirements	ha
$isExemt_f$	Binary variable that exempts farms from compliance with greening payment conditions	-
$LabH_f$	Labour hired on farm f	h
$LC1_f$	Area of the largest crop on farm f	ha
$LC2_f$	Combined area of the two largest crops on farm f	ha
$LU_{f,r}$	Livestock units under regime r on farm f	-

MEx_f	Manure of farm f exported outside the region	kg
$MImp_f$	Manure imported on farm f from outside the region	kg
$MSell_{f,k}$	Manure transferred from farm f to farm k	kg
$MSell_{k,f}$	Manure received on farm f originating from farm k	kg
$Muse_f$	Manure used on farm f	kg
$PenDiv_f$	Area penalty for not meeting crop diversification requirements of farm f	ha
$PenEFA_f$	Area penalty for not meeting Ecological Focus Area requirements on farm f	ha
RGP	Relative gross profit	-
$TGPF0_f$	Total gross profit of a farm in base scenario	€
$TGPF_f$	Total gross profit of an individual farm	€
$TGP0$	Total gross profit of the region in base scenario	€
TGP	Total gross profit of the region	€
$UArea_f$	Area cultivated by farm f	ha
$XCr_{c,f}$	Area of crop c on farm f	ha
$XI_{f,i}$	Amount of fertiliser i used on farm f	kg
$XV_{f,v}$	Amount of concentrate v fed to livestock on farm f	kg/y

Table 3. Parameters used in the model.

Parameter	***Description***	***Unit***
$Area_f$	Area of land owned by farm f	ha
$bigN$	A large number used to make constraints unbinding	-
$CMApply$	Cost of applying manure on arable land	€/kg
$CMEx$	Cost of exporting manure	€/kg
$CMImp$	Cost of importing manure	€/kg
CMP_r	Milk price of milk from livestock in regime r	€/l
CM_r	Milk produced per livestock unit in regime r	l
$CMTran$	Cost of transporting manure	€/kg
$Cost_{c,t}$	Production cost of crop c on farms of type t excluding fertiliser cost	€/ha
CrE_c	Energy content of crop c	VEM/kg
CrE_c	Protein content of crop c	DVE/kg
CrS_c	Structure value of crop c	-
$CrSV_c$	Saturation value of crop c	-
$distA_{f,k}$	Distance between farm f and farm k	km
$ForN_c$	Maximum amount of nitrogen that may be applied on a ha of crop c	kg/ha
$ForP_c$	Maximum amount of phosphorous that may be applied on a ha of crop c	kg/ha
$FT_{f,t}$	Array of binaries used to tell whether a farm f is farm type t	-
$GPay$	Greening payment	€/ha
$HLabC$	Cost of hiring labour	€/h
$ICost_i$	Cost of fertiliser i	€/kg
$isDairy_f$	Array of binaries used to tell whether a farm f is a dairy farm	-
$isM_{c,m}$	Array of binaries used to tell whether a crop c is a main crop m	-
$LabA_f$	Annual available labour on farm f	h/y
Lab_c	Annual required labour to cultivate crop c	h/ha/y
$LabLU_r$	Annual required labour per livestock unit in regime r	h/LU/y
$LFUC_r$	Livestock feed uptake capacity of livestock in regime r	kg/LU/d
LUC_r	Not feed related cost of livestock in regime r	€/LU
$MAXLU_f$	Maximum livestock units on farm f	-
$MaxMNUse$	Maximum use of N originating from manure	kg/ha

MP_c	Market price of crop c	€/ton
$MProd_r$	Manure produced by livestock in regime r	m^3
MTD	Maximum distance over which land can be exchanged between two farms	km
$MTDM$	Maximum transfer distance of manure	km
$NutCont_{i,n}$	Nutrient n content of fertiliser i	kg/kg
$NutContM_n$	Nutrient n content of manure	kg/kg
$PARLD$	Rent price dairy land	€/ha
$PARL$	Rent price arable land	€/ha
RE_r	Required energy for livestock in regime r	VEM/LU
$ROTAM_m$	Rotation constraint frequencies of main crops m	-
RP_r	Required protein for livestock in regime r	DVE/LU
VC_v	Cost of concentrate v	€/kg
VDM_v	Dry matter content of concentrate v	g/kg
VE_v	Energy content of concentrate v	VEM/kg
VP_v	Protein content of concentrate v	DVE/kg
VS_v	Structure value of concentrate v	-
VSV_v	Saturation value of concentrate v	-
$WEFA_c$	Weighing factor for Ecological Focus Area of crops	-
YC_r	Young stock in regime r	-
YE_r	Energy required for young stock in regime r	VEM/young stock
YE_r	Protein required for young stock in regime r	DVE/young stock
$Yield_{c,t}$	Yield of crop c on farms of type t	ton/ha

2.2. Objective function

While farmers have multiple objectives (Mandryk et al., 2014), in this study it was assumed that farmers maximise profits. Central to the objective of the simulations in this study, is total gross profit (TGP), the sum of all farm profits minus costs of production

$$
\max \left\{
\begin{aligned}
&\sum_{\substack{f,c,t\\ FT_{f,t}=1}} \big((XCr_{c,f} * YIELD_{c,t} - FC_{f,c}) * MP_c\big) - \big(XCr_{c,f} * Cost_{c,t}\big) + \sum_{f} AGPay_f * GPay \\
&\quad - \sum_{f,i} ICost_i * XI_{f,i} - \sum_{f} LabH_f * HLabC \\
&\quad + \sum_{\substack{f,k\\ distA_{f,k} \le MTD}} \Big((1 - isDairy_k) * PARL * ARL_{f,k} + isDairy_f * PARLD \\
&\quad * ARL_{f,k}\Big) - \Big((1 - isDairy_f) * PARL * ARL_{k,f} + isDairy_f * PARLD * ARL_{k,f}\Big) \\
&\quad + \sum_{f,r} \big(LU_{f,r} * CM_r * CMP_r * 365\big) - \big(LU_{f,r} * LUC_r\big) \\
&\quad - \sum_{f} MEx_f * CMEx - MImp_f * CMImp \\
&\quad - \sum_{f,k} \big(MSell_{f,k} * distA_{f,k} * CMTran\big) + \big(MSell_{f,k} * CMApply\big) \\
&\quad - \sum_{f,v} XV_{f,v} * VC_v
\end{aligned}
\right\} \tag{1}
$$

Where $(XCr_{cuff}*YIELD_{c,t}\text{-}FC_{f,c}*MP_c)\text{-}(XCr_{c,f}*Cost_{c,t})$ is the crops harvested minus the crops fed to cattle, times the market price, minus the cost of producing crops per ha excluding fertiliser costs. $AGPay_f * GPay$ is the greening payments paid out to farms. $ICost_i * XI_{f,i}$ is the cost of fertilisers. $LabH_f * HLabC$ is the cost of hiring labour. $\Big((1 - isDairy_f) * PARL * ARL_{f,k} + isDairy_f * PARLD * ARL_{f,k}\Big) - \Big((1 - isDairy_f) * PARL * ARL_{k,f} + isDairy_f * PARLD * ARL_{k,f}\Big)$ is the income from renting out land minus the cost of renting in land, PARL being the price of arable land rent and PARLD for dairy land.

$(LU_{f,r} * CM_r * CMP_r * 365) - (LU_{f,r} * LUC_r)$ describes the annual profit from milk minus the maintenance cost of livestock. $MEx_f * CMEx - MImp_f * CMImp$ are the costs of exporting or importing manure. $MSell_{f,k} * distA_{f,k} * CMTran$ is the transport cost of manure per km when manure is transported from one farm to another. $MSell_{f,k} * CMApply$ is the cost of applying transferred manure on arable land. $XV_{f,v} * VC_v$ are the costs of purchasing feed for livestock.

2.3. Constraints

2.3.1. Labour

A farms own labour ($LabA_f$) and hired labour ($LabH_f$) had to be equal or larger than the labour required for crops ($XCr_{c,f}$* Lab_c) and livestock ($LabLU_r$*$LU_{f,r}$)

$$\sum_c XCr_{c,f} * Lab_c + \sum_r LabLU_r * LU_{f,r} \leq LabA_f + LabH_f \qquad \forall(f) \qquad (2)$$

2.3.2. Land

All simulated land needed to be covered by a crop, including fallow:

$$\sum_{f,c} XCr_{c,f} = \sum_f Area_f \qquad (3)$$

Per farm, the area of crops ($XCr_{c,f}$) was constrained by Utilised area ($UArea_f$) (eq. (4) which itself was defined by the farm area ($Area_f$) and the Area Rented Land ($ARL_{f,k}$ rented from f to k, $ARL_{k,f}$ rented from k to f) (eq. (5)

$$\sum_c XCr_{c,f} \leq UArea_f \qquad \forall(f) \qquad (4)$$

$$UArea_f = Area_f + \sum_k ARL_{(k,f)} - \sum_k ARL_{(f,k)} \qquad \forall(f) \qquad (5)$$

Farms were also restricted in the amount of land they could rent out, to avoid more land being rented out than available, and to avoid land being rented in and out several times:

$$\sum_k ARL_{f,k} \leq Area_f \qquad \forall(f) \qquad (6)$$

2.3.3. Greening payments

The size of the greening payments were limited by the area over which greening payments are paid ($AGPay_f$) and the height of the per ha payment (*GPay*). $AGPay_f$ was constrained by:

$$AGPay_f \leq UArea_f - PenDiv_f - 10 * PenEFA_f - GSanc_f + isExemt_f * bigN \qquad \forall(f) \qquad (7)$$

$$AGPay_f \leq UArea_f \qquad \forall(f) \qquad (8)$$

Where $PenEFA_f$ and $PenDiv_f$ are penalties for not meeting Ecological Focus Area (EFA), or crop diversification conditions, and $GSanc_f$ an additional sanction. In the constraints, an exemption ($isExempt_f$ =1*)* makes the first constraint unbinding by adding a large number (*bigN)* to the right hand side of the constraint (RVO, 2018b, 2018a). A farm can get exempt from complying with these conditions by cultivating a given area of crops which are listed for exemption.

The first of the two green payment conditions is that a farm needs to have 5% of its area under cultivation as ecological focus area (EFA). In reality, a variety of options are available to fill in this EFA, such as ponds, tree rows, single trees, cover crops, flower rows, each with its own weighing factor (RVO, 2018a). However, in the simulations farms could only fulfil their EFA requirement by cultivating crops with certain EFA Weights ($WEFA_c$) (Table A 2).

$$0.05 * UArea_f - \sum_c XCr_{c,f} * WEFA_c - PenEFA_f \leq 0 \qquad \forall(f) \qquad (9)$$

The second condition, called crop diversification (*PenDiv*$_f$), limits the size of the largest, or largest two crops species, depending on the size of the cultivated area. Legislation differentiates crops based on their plant species, so the area of crops was converted to area of species.

$$ASpec_{s,f} = \sum_c CSpec_{c,s} * XCr_{c,f} \qquad \forall(f,s) \qquad (10)$$

Where *ASpec*$_{s,f}$ is area cultivated with a plant species on farm f and *CSpec*$_{c,s}$ is a matrix with binary values to convert area crops to area species. The area of the largest (*LC1*$_f$) and two largest (*LC2*$_f$) was determined by:

$$ASpec_{s,f} \leq LC1_f \qquad \forall(f,s) \qquad (11)$$

$$ASpec_{s1,f} + ASpec_{s2,f} \leq LC2_f \qquad \forall(f, s1, s2 | s1 <> s2) \qquad (12)$$

For farms utilising small than 30 ha, *PenDiv*$_f$ was calculated according to equation (13), while for farms utilising larger than 30 ha, *PenDiv*$_f$ was calculated according to equation (14), reflecting current legislation (RVO, 2018b).

$$PenDiv_f = \left(LC1_f - 0.75 * UArea_f\right) * 2 \qquad \forall(f) \qquad (13)$$

$$PenDiv_f = LC1_f - 0.75 * UArea_f + 5 * \left(LC2_f - 0.95 * UArea_f\right) \qquad \forall(f) \qquad (14)$$

Where

$$LC1_f - 0.75 * UArea_f \geq 0 \qquad \forall(f) \qquad (15)$$

and

$$LC2_f - 0.95 * UArea_f \geq 0 \qquad \forall(f) \qquad (16)$$

Calculation of $GSanc_f$ depends on the size of *PenEFA*$_f$ and *PenDiv*$_f$ (Table 4).

Table 4. Calculation of *GSanc*$_f$ depending on the size of (10* PenEFA$_f$ + PenDiv$_f$) in relation to *UArea*$_f$. Where *UArea*$_f$ is the utilised area of farm f,*PenEFA*$_f$ penalty ecological focus area, *PenDiv*$_f$ the penalty crop diversification, and *GSanc*$_f$ an additional sanction imposed on top of the penalties.

10* PenEFA$_f$ + PenDiv$_f$.	***GSanc$_f$ =***
= 0	0
$< 0.2 * UArea_f$	$\frac{2 * (PenDiv_f + 10 * PenEFA_f)}{4}$
$> 0.2 * UArea_f < 0.5 * UArea_f$	$\frac{UArea_f - (PenDiv_f + 10 * PenEFA_f)}{4}$
$> 0.5 * UArea_f$	$\frac{UArea_f}{4}$

2.3.4. Crop rotation

Many crops are cultivated in a rotation to reduce yield losses inflicted by soil borne pests and diseases. While this model only simulated a single year, crop rotation was simulated by limiting the percentage of cultivated area a specific crop can have on a farm. For example, wheat can be cultivated once every two years, so only 50% of the cultivated area is allowed to be wheat. It was assumed that land rented from dairy farms had previously been maize or grass, and therefore would not need crop rotation. The constraint was formulated as:

$$\sum_{c} XCr_{c,f} * isM_{c,m} \leq \left(UArea_f - \sum_{\substack{k \\ isDairy(k)=1}} ARL_{k,f} \right) * ROTAM_m + \sum_{\substack{k \\ isDairy(k)=1}} ARL_{k,f} \qquad \forall(m,f) \quad (17)$$

Where *isM_{c,m}* is an array of binaries checking whether a crop C is main crop M, as some distinct crops can be regarded as a the same crop with regards to crop rotations. Such as sugar and fodder beets, or wheat with, and without catch crop. *ROTAM_m* is a number between 0 and 1, determining the maximum fraction of a farms area that can be cultivated with main crop M.

Farmers take care not to cultivate root and tuber crops too often as this is detrimental to soil structure. To reflect this, a root and tuber rotation constraint was added with a value of 0.7 (Mandryk et al., 2014).

$$\sum_{c} XCr_{c,f} * isRT_c \leq \left(UArea_f - \sum_{\substack{k \\ isDairy(k)=1}} ARL_{k,f} \right) * 0.7 + \sum_{\substack{k \\ isDairy(k)=1}} ARL_{k,f} \qquad \forall(f) \quad (18)$$

2.3.5. Livestock

To account for young stock required to rejuvenate the dairy herd, livestock units (LU) were used (Louhichi et al., 2010). The number of LU per farm was restricted as:

$$\sum_{r} LU_{f,r} \leq MAXLU_f \qquad \forall(f) \qquad (19)$$

Where $LU_{f,r}$ is the number of LU on farm f fed ration r and MAX_LU_f is the cow holding capacity of farm f.

Cattle requires a certain amount of energy (expressed in VEM, a Dutch net energy value for lactating cows), digestible protein, (expressed in DVE, a Dutch measure for digestible protein) and structure, in their feed. In the model, annual VEM and DVE requirements were simulated with the following constraints:

$$\mathbf{365} * \sum_r LU_{f,r} * \left(RE_r + (YC_r * YE_r)\right) \leq \sum_c FC_{f,c} \ * 1000 * CrE_c + \sum_v XV_{f,v} * VE_v \qquad \forall(f) \tag{20}$$

$$\mathbf{365} * \sum_r LU_{f,r} * \left(RP_r + (YC_r * YP_r)\right) \leq \sum_c FC_{f,c} \ * 1000 * CrP_c + \sum_v XV_{f,v} * VP_v \, \forall f \qquad \forall(f) \tag{21}$$

Where $LU_{f,r}$ is the farms livestock units fed ration r, Rx_r the nutritional requirement (E for VEM and P for DVE) per dairy cow, YC_r the number of young stock per LU, and Yx_r the nutritional requirement per young stock. $FC_{f,c}$ is the quantity of crop c used as fodder on farm f in tons, its multiplied with 1000 to transfer the quantity into kg's, *CRx* is the nutritional content of crop c. Added to the nutrition from fed crops is the amount of concentrate v ($XV_{f,v}$) multiplied by its nutritional content Vx_v.

Besides sufficient energy and protein, a feeding ration also requires enough structure. The required structure value (SV) of the ration is assumed to be higher than one (Federatie Nederlandse Diervoederketen, 2016). Thus a restriction for SV was formulated:

$$\frac{\left(\sum_c FC_{f,c} * 1000 * CrS_c + \sum_v XV_{f,v} * VDM_v * VS_v\right)}{\left(\sum_c FC_{f,c} * 1000 + \sum_v XV_{f,v} VDM_v\right)} \geq \mathbf{1} \qquad \forall(f) \tag{22}$$

Where VDM_v is the dry matter content of concentrate (V) and S is the specific structural value of the fed crop (CrS_s) or concentrate (VS_v). The DM content of fed crops is not explicitly in this constraint because the yield for fodder crops (maize and grass) was given in kg DM ha^{-1}.

The maximum amount a cow can eat depends on the saturation value of the ration and the feed uptake capacity of the cow.

$$\sum_c FC_{f,c} * 1000 * CrSV_c + \sum_v XV_{f,v} * VDM_v * VSV_v \leq \sum_r LFUC_r * 365 * LU_{f,r} \qquad \forall(f) \tag{23}$$

Where dry weight of fed crops ($FC_{f,c}$) and concentrates ($XV_{f,v}$ * VDM_v) multiplied by crop or concentrate specific saturation values ($CrSV_c$ or VSV_v) on the left side must be smaller than the livestock feed uptake capacity ($LFUC_r$) multiplied by the number of days in a year and the number of livestock units of every regime ($LU_{f,r}$).

2.3.6. Manure

Besides milk, dairy farms produce manure depending on the number of LU on the farm and the applied feeding regimes:

$$FMProd_f = \sum_r LU_{f,r} * MProd_r * 1030 \qquad \forall f \tag{24}$$

Manure production is expressed in kg. Since, the regime specific manure production ($MProd_r$) per LU is expressed in cubic meter, $MProd_r$ is multiplied with 1030 to convert m^3 to kg. Dairy farms need to get rid of their manure which they can do either by applying it on their land as fertiliser ($Muse_f$), selling it to a local arable farm k ($MSell_{f,k}$), or exporting their manure outside the region

(*MEx*$_f$). While the manure arable farms apply on their land, has to come from either a local dairy farm (*MSell*$_{k,f}$) or has to be imported from the external manure market (*MImp*$_f$). These sources and sinks of manure are expressed in a single constraint for all farms:

$$Muse_f + MEx_f + \sum_k MSell_{f,k} = FMProd_f + \sum_k MSell_{k,f} + MImp_f \qquad \forall f \qquad (25)$$

Arable farms were disabled from selling or exporting manure (26), while dairy farms were disabled from importing or buying manure from a nearby farm (27).

$$\sum_{\substack{f \\ isDairy(f)=0}} MSell_{f,k} + MEx_f = 0 \qquad (26)$$

$$\sum_{\substack{f \\ isDairy(f)=1}} MSell_{k,f} + MImp_f = 0 \qquad (27)$$

2.3.7. Fertilisation

Farm nutrient use was constrained by a range determined by the sum of minimum nutrient requirement of the farms crops (lower bound) and the sum of the legal maximum nutrient application (upper bound). The lower bound NPK application per crop were set per farm type:

$$\sum_{\substack{c,t \\ FT_{f,t}=1}} XCr_{c,f} * NutReq_{c,n,t} \leq \sum_i XI_{i,n} * NutCont_{i,n} + Muse_f * NutContM_n \qquad \forall (f,n) \qquad (28)$$

Where *NutReq*$_{c,n,t}$ is the required amount of nutrient *n* for crops on farms of type *t*, *XI*$_{f,i}$ the amount of fertiliser *i* used on farm *f*, and *NutCont*$_{i,n}$ the nutrient content *n* of fertiliser *i*.

The upper bounds for N and P were constrained as:

$$\sum_i XI_{f,i} * NutCont_{i\text{"N"}} + Muse_f * NutContM_{\text{"N"}} \leq \sum_c ForN_c * XCr_{c,f} \qquad \forall (f) \qquad (29)$$

$$\sum_i XI_{f,i} * NutCont_{i\text{"P"}} + Muse_f * NutContM_{\text{"P"}} \leq \sum_c ForP_c * XCr_{c,f} \qquad \forall (f) \qquad (30)$$

Where *ForN*$_c$ and *ForP*$_c$ are the amount of N or P that a farm can use per ha of crop.

3. Setup of calculations

3.1. Simulation overview

Due to lack of memory, Flevoland as a whole could not be simulated at once. Therefore, separate optimisations were performed, separating the province into its two polders level (i.e. Flevopolder, Noordoostpolder) (Table 5). The Flevopolder contains the municipalities Dronten, Lelystad, Zeewolde, and Almere (unsimulated), while the Noordoostpolder consists of the municipalities Noordoostpolder and Urk (unsimulated). The two polder have roughly the same number of farms (≈780), but different numbers of dairy farms (Flevopolder=162, Noordoostpolder=90). The difference in arable:dairy farm ratio also allowed for analysis of the importance of dairy farm sparsity. The Noordoostpolder also has a higher farm density compared to the Flevopolder.

Table 5. Overview of which municipalities and scenarios were included in each simulation, as well as the value for MIPRELSTOP that was used.

Simulated region	Municipalities	Scenarios	MIPRELSTOP
1: Flevopolder	Dronten, Lelystad, Zeewolde	NO, MAX, EQUIT, MAX2	0.03
2: Noordoostpolder	Noordoostpolder	NO, MAX, EQUIT, MAX2	0.03

3.2. Scenario set up

Each simulation had four scenarios (Table 6). In the first, NO, land exchange was disabled. This scenario was used as reference-scenario. The objective in NO was to maximise TGP while land exchanged is disabled. In scenario two (MAX), TGP was also maximised, but, with land exchange enabled. To remove redundant land exchange (that did not contribute to increasing TGP), a constraint was added (31) to fix the objective value after maximising TGP, followed by minimising land exchange.

$$TGP \geq TGP0 \tag{31}$$

$$min\left\{\sum_{f,k} ARL_{f,k}\right\} \tag{32}$$

Scenario two maximises regional profit, disregarding the goals of individual farmers, so an increase in regional profit may be distributed unequally amongst farms. In reality a farmer will not exchange land if this is perceived as financially unbeneficial. To better reflect this behaviour of individual farmers, a third scenario was developed (EQUIT). Scenario three, first maximised regional gross profit without land exchange. Then a constraint was added stating that the gross profit of each farm (*TGPF$_f$*) should be at least that farms gross profit when land exchange was disabled (*TGPF0$_f$*).

$$TGPF_f \geq TGPF0_f \qquad \forall(f) \tag{33}$$

Thereafter, land exchange was enabled and the relative gross profit (RGP) was maximised using a max-min approach. This way the smallest increase in farm profit is maximised, resulting in a more equitable distribution of increased profits amongst farms. This better reflects how farmers decide whether to exchange land than maximising profits for the region.

$$max\{RGP\} \tag{34}$$

Where:

$$\frac{TGPF_f - TGPF0_f}{TGPF0_f} \geq RGP \qquad \forall(f) \tag{35}$$

In this scenario redundant land exchange was also removed by fixing the objective value and minimising land exchange according to equation (32).

Preliminary results of the first three scenarios indicated a wide gap between scenarios MAX and EQUIT, both of which did not appear to be fully representative of reality. In MAX crop rotation constraints seemed to be violated regionally and in EQUIT little land exchange occurred. Therefore, a fourth scenario was used attempting to approach reality. This scenario (MAX2) was the same as MAX in all but one constraint:

$$\sum_k ARL_{f,k} \leq AREA_f * 0.2 \qquad \begin{matrix}\forall(f)\\ \text{isDairy(f)=1}\end{matrix} \tag{36}$$

This constraint (44) restricted a dairy farms land available for rent to arable farms. The associated assumption is that all dairy farms apply for derogation and have 80% of their land as grassland, leaving them with 20% to rent out or cultivate maize.

Table 6. Overview of scenarios used in this study listing their objectives and to what degree land exchagne was enabled.

Scenario	**Objective**	**Allowed land exchagne**
NO	Maximise regional profit	no
MAX	Maximise regional profit	yes
EQUIT	Maximise minimum increase of farm profit compared to NO	yes
MAX2	Maximise regional profit	Exchangeable land of dairy farms was limited to 20%

3.3. MIPRELSTOP

Maximisation of the objective function was done using a simplex algorithm. Because simplex only works with continuous variables, a branch and bound method was applied. First, the objective value was maximised assuming all variables are continuous, this gives a maximum value. Then, one by one, the variables that should be integer, were made integer and simplex was used repeatedly with different combinations of integer values set as constraints. This way, the algorithm looked for an integer solution as close to the continuous solution as possible. When there are many integer variables, it can take a long time to find and test all integer solutions. To reduce this time, we set MIPRELSTOP to 0.030. Consequently, if an integer solution was found that was 97.0% of the continuous solution, we accepted this integer solution as optimal and stopped searching.

3.4. Farm distribution and location

Flevoland (Figure 2 A), was considered to be composed of four municipalities: Dronten, Lelystad, Noordoostpolder, and Zeewolde. Almere and Urk were left out because they have little agricultural land (Appendix II Farm distribution, Table A 5). Using Google Maps, the latitude (north-south, or Y-axis) and longitude (east-west, or X-axis) of the four municipalities was estimated. Based on this estimation and the area of each municipality retrieved from CBS, four-sided municipalities were created in a plot. Then, all farms were randomly assigned an X and Y coordinate within the ranges of their respective municipality. The coordinates of Lelystad where adjusted to exclude nature and urban areas in the west of the municipality, from locations where farms could be, to have a more accurate farm density. Simulated farm locations were then visualised by plotting them in a scatterplot (Figure 2 B)

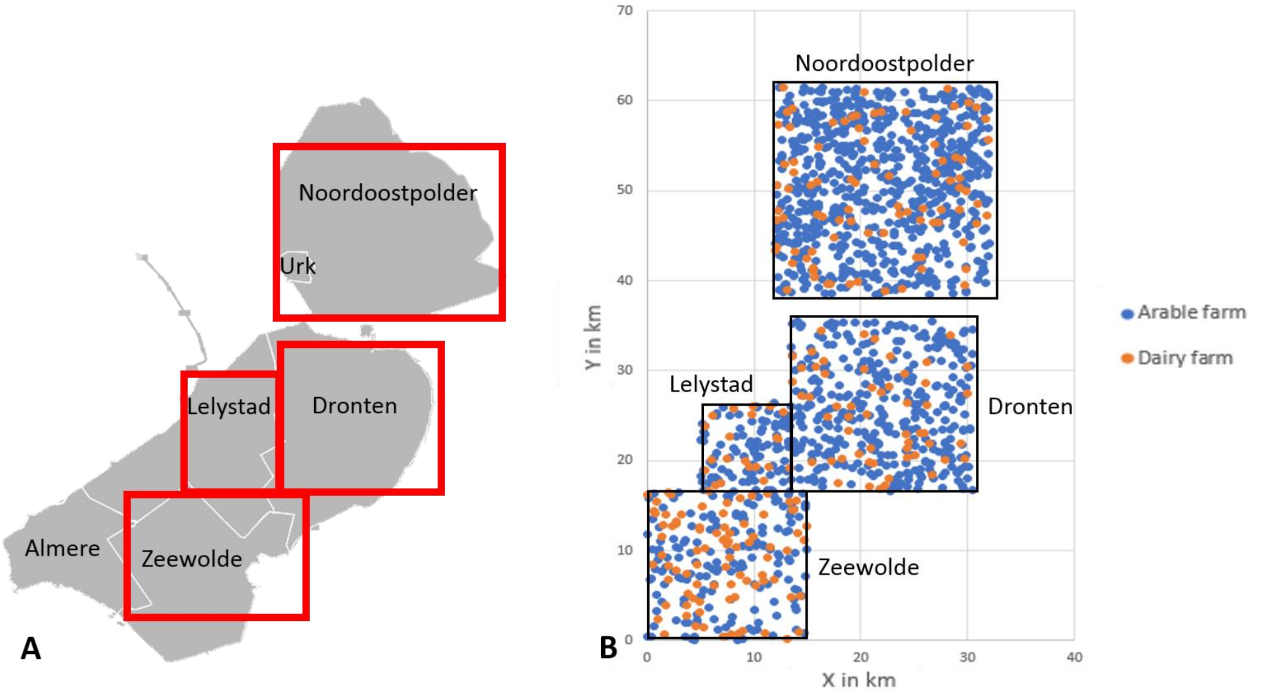

Figure 2. A) Map of Flevoland with municipal borders. The red squares approximate the dimensions of the simulated municipalities in B. B) Simulated distribution of farms in Dronten, Lelystad, Noordoostpolder, and Zeewolde.

3.5. Farm types

Based on the total number of arable farms and number of farms in each farm type, described by Mandryk et al. (2012) and Nakasaka (2016), the frequency of each arable farm type was determined. These frequencies were multiplied with the current number of arable farms to determine the current number of farms for each farm type in Flevoland (Appendix II Farm distribution, Table A 5,Table A 6).

In this study eight farm types are discerned: seven arable and one dairy type (D). The arable farm types are differentiated based on their orientation (**P**roduction, **E**ntrepreneur, **N**ature), size in terms of gross income (**M**edium, **L**arge), and intensity as gross income per hectare (**M**edium, **H**igh) (Mandryk et al., 2012; Nakasaka, 2016). Arable farm types in this model are: PMM, PMH, PLM, PLH, EMM, ELM, and NLM (Table 7).

Table 7. Description of farm types used in this thesis. The arable farm types (PMM, PMH, PLM, PLH, EMM, ELM, and NLM) are based on Mandryk et al. (2012) and Nakasaka (2016)*. The numbers of farms are based on census data of 2017* (CBS, 2018b)*, and the average labour available on dairy farms (D) is an estimated guess supported by* Valacon (n.d.).

	Orientation	Size	Intensity	Number this thesis	Average size (ha)	Average available labour (h/year)
PMM	production	medium	medium	426	28.9	915.2
PMH		medium	high	121	24.0	1056
PLM		large	medium	418	80.8	2860
PLH		large	high	198	71.7	3300
EMM	entrepreneur	medium	medium	43	39.7	1600
ELM		large	medium	72	68.4	5000
NLM	nature	large	medium	27	85.1	4080
D				252	55.3	5000

Due to lacking access to more detailed data, it was assumed that arable farm types are distributed equally throughout the province. The number of farms of each type per municipality was determined by multiplying the total number of farms of a type with the municipal fraction arable farms. The number of dairy farms in each of these municipalities was set to the number of dairy farms in 2017 (CBS, 2018b). Definitive number of farms per farm type are included in Appendix II Farm distribution (Table A 5).

3.6. Farm resource endowment

Based on their farm type, each arable farm was assigned an area and amount of family labour randomly assigned from a normal distribution with the mean as identified by Mandryk et al. (2014) with a standard deviation 5% of the mean after Nakasaka (2016). For dairy farms, area and labour assignment was done similarly, but instead using the average size of dairy farms in Flevoland as mean for area allocation and assuming average annual labour to be 5000 hours. 5000 hours was based on the average available labour for ELM farms which are most similar in size, and 5000 hours is close to the average labour on average dairy farms in the Netherlands (Valacon, n.d.). The livestock holding capacity (LHC), or maximum number of cows, was set to zero for arable farms. For dairy farms, the LHC was generated per farm with a municipality dependent mean and a standard deviation 5% of this mean. Mean LHC per municipality was retrieved from CBS (2018d) (Table A 7).

3.7. Labour

It was assumed that available labour and required labour are spread equally throughout the year. Labour for dairy activities, excluding land work, depended on the number of LU (Valacon, n.d.). Annual required labour for crops was based on data in van der Voort (2018) and are listed in Table A 1. Cost of hiring labour was also based on van der Voort (2018), assuming hiring of an all-round employee and pay according to collective wage agreements.

3.8. Land

To reduce computation difficulty, the maximum distance over which two farms could exchange land was restricted to 8km (Nakasaka, 2016):

$$\sum_{\substack{f,k \\ distA_{f,k}>MTD}} ARL_{k,f} + \sum_{\substack{f,k \\ distA_{f,k}>MTD}} ARL_{f,k} = 0 \qquad \forall(f) \quad (37)$$

To avoid unrealistic changes in cultivated area of single farms, $UArea_f$ was capped at 500 ha.

$$UArea_f \leq 500 \qquad \forall(f) \quad (38)$$

To simplify the rules for greening payments, the minimum cultivated area per farm was set to 15:

$$UArea_f \geq 15 \qquad \forall(f) \quad (39)$$

Rent price of dairy land was set to €1174 per ha, rent price of arable land was set to €587 per ha to be comparable with Nakasaka (2016). This reflects that dairy land has more value to arable farms as they can freely cultivate potatoes or carrots on this land. While it does not matter for dairy farms whether they cultivate grass or maize on their own land or on arable land.

3.9. Greening payments

CAP greening payments were simulated as these may affect farmers' decision making with regards to crop choice and exchanging land. For each simulated farm, the area over which greening payments were paid out was calculated based on rules described by RVO (2018a). Farms with less than 15 ha under cultivation are normally exempt from EFA conditions (RVO, 2018a). Farms with less than 10 ha under cultivation are exempt from crop diversification requirements (RVO, 2018b). The complexity of these exemptions was left out of the model by constraining the minimum area under cultivation per farm to 15 ha. Farms could also be exempt from both conditions by cultivating more than 75% grassland, fallow, and or green peas (RVO, 2018b, 2018a).

The greening payment per hectare was set equal to the real payment, €113/ha (Esselink, 2019a).

Preliminary simulations showed that farms always comply with diversification requirements. To safe some computation time, the following constraint was added:

$$\sum_{f} PenDiv_f = 0 \qquad (40)$$

3.10. Crop rotation

Table 8. Main crops from set M and their corresponding Crop(s) from set C as well as their rotational frequency ($ROTAM_m$). Rotational frequency of Seed potato, Carrot, Onion, Sugar beet, Chicory, Wheat, and Potato are based on Mandryk et al. (2014). The frequency of Temporary grass is based on recommendations by de Wolf et al. (2018), who stated that conversion of temporary grassland older than three years to arable land results in high leaching of nutrients. This leaching is due to a large built up of organic matter which mineralises after conversion and arable crops are unable to take up all mineralised nutrients.

Main crop (M)	**Crops (C)**	**Rotation frequency ($ROTAM_m$)**	**Scientific name**
Seed potato	Seed potato (SP)	0.25	*Solanum tuberosum*
Carrot	Winter carrot (WC)	0.17	*Daucus carota*
Onion	Seed onion (SO)	0.17	*Allium cepa*
Consumption potato	Consumption potato (CP)	1[1]	*Solanum tuberosum*
Sugar beet	Sugar beet (SB)	0.2	*Beta vulgaris*
Chicory	Chicory (CH)	0.25	*Cichorium intybus*
Green peas	Green peas (PE)	0.17	*Pisum sativum*
Wheat	Winter wheat (WW), Winter wheat + oil seed radish (WO)	0.5	*Triticum aestivum* and *Raphanus sativus*
Fallow	Fallow (FA)	1	-
Permanent grass	Grass permanent (GP)	1	*Lolium perenne*
Temporary grass	Grass temporary (GT)	0.75	*Lolium perenne*
Maize	Maize silage (MS)	1	*Zea mays*
Potato	Seed potato (SP), Consumption potato (CP)	0.33	*Solanum tuberosum*

[1] Consumption potatoes cannot be cultivated continuously as CP is also subject to the Potato rotation constraint with a rotation frequency of 1/3.

3.11. Crop parameters

Market price, and production cost parameters were based on data in van der Voort (2018) and are listed in Table A 3. Crop yields per ha per farm type were taken from Mandryk et al. (2014) when possible. Values for other crops were based on van der Voort (2018), except for grass temporary and grass permanent. For these crops the average dry matter (DM) production per ha was based on Schils et al. (2018). A complete overview of yield data in this thesis and in Nakasaka (2016) can be found in Appendix I, Table A 4.

Annual effective organic matter contribution of crops was based on Conijn and Lesschen (2015), with the exception of Winter carrot and Chicory which are based on Nakasaka (2016) (Table A 13).

Fodder properties of permanent grass, temporary grass, and maize were based on Productschap Diervoeding and CVB (2016). (For an overview see: Appendix I Crop parameters, Table A 1)

3.12. Livestock

A livestock unit in Flevoland typically consists of 0.7 young animals 0-2 years of age and 1 dairy cow (Appendix III Livestock units, Table A 7).

Federatie Nederlandse Diervoederketen (2016) was used to determine the required energy, protein, and structure per milk production level per farm. Assuming young stock grows according to advised growth, a farm requires on average: 5603.8 VEM, 345 DVE and 5.6 kg dry matter (DM) per young animal per day (Federatie Nederlandse Diervoederketen, 2016; Remmelink et al., 2018).

For mature cows it was a little harder to determine the required amounts of energy, protein, and structure in the diet, as rationing determines milk production (MiPr: kg's fat and protein corrected milk per day per cow). For milk production and maintenance a dairy cow requires:

- $5323+440*MiPr+0.73*MiPr^2$ VEM
- $115.5 +1.396*33*MiPr+0.000195*MiPr^2$ DVE

Because the model cannot square decision variables such as MiPr and to simplify the model, several dairy activities (R) were introduced, each with their own milk production, VEM, and DVE requirement, per LU (Table A 8). This way milk production, VEM and DVE requirements became parameters of a farm level decision variable $LU_{f,r}$, number of LU fed ration R. By using dairy activities one could also set activity specific milk prices or adjust the portion of young stock per LU. For all current activities it was assumed that dairy cows weigh 650kg, milk has 3.3% protein and 4% fat, cattle is fed indoors, and that the milk price is standard and stable over the year at €0.355/kg milk (Table A 8) (Blanken et al., 2018).

The SV of a diet is determined by a feed specific SV and the portion of that feed in the total diet. SV of feeds range roughly from -0.4 (cheese whey or molasses) to 4.3 (straw or hay).

Dry matter uptake was assumed to be 14.9 kg for dairy cows and 5.6 kg for young stock (Federatie Nederlandse Diervoederketen, 2016). The saturation values were taken from Federatie Nederlandse Diervoederketen (2016).

3.13. Manure

Selling of manure was restricted to 25% of the manure produced on a dairy farm and limited to farms located within a 10 km radius (*MTDM*). These two restrictions are two of the conditions for *boer-boer*[1] transport, a form of manure transport exempt from extensive weighing and sampling (RVO, 2019b). Unlike actual *boer-boer* transport, simulated dairy farms were not obliged to be able to place 75% of their manure on own land. Cost of weighing and sampling are variable and to keep things simple, only *boer-boer* transport was allowed.

$$\sum_{\substack{f,k \\ distA_{f,k}>MTDM}} MSell_{f,k} = 0 \tag{41}$$

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[1] Literally farmer-farmer transport, direct transport from one farm to a close neighbour.

$$\sum_{k} MSell_{f,k} \leq 0.25 * FMProd_{f} \qquad \begin{matrix}\forall(f) \\ \text{isDairy(f)=1}\end{matrix} \qquad (42)$$

The amount of manure a farm can apply per ha was limited to 170 kg's N from manure per ha for regular farms or 250 kg's N from manure for farms with derogation (*MaxMNUse*)(RVO, 2019c), with a manure N content of 4g/kg (*NutContM*$_{"N"}$) (van Schie-Rameijer et al., 2019). In the model, manure use was constraint as:

$$Muse_{f} * NutContM_{"N"} \leq MaxMNUse * UArea_{f} \qquad \forall(f) \qquad (43)$$

Only dairy farms could get derogation, if they comply with two conditions. First, 80% of the cultivated area is grassland, and second; no artificial P fertiliser is used on the farm (RVO, 2019c, 2019d).

Preliminary simulations resulted in dairy farms only cultivating maize and thus forgoing derogation. This does not reflect reality, as there are grasslands and dairy farms with derogation in Flevoland (CBS, 2018b; RVO and NVWA, 2018). The national average percentage dairy farms with derogation of total dairy farms in 2019 was roughly 82%[2]. The fraction of dairy farms that apply for derogation is lower in Flevoland than the national average (RVO and NVWA, 2018). It was assumed that all farms applied for derogation as 100% is closer to reality than 0%

The price of exporting manure was set to €0.012/kg, importing manure costs €0.0038/kg, transferring manure to a local arable farm to €0.00026/kg/km, and the application cost of manure on arable land was set to €0.0035/kg (van Dijk and Galama, 2019). It was assumed that transfer and application costs were paid by the dairy farm.

3.14. Fertilisation

The lower bound nutrient requirement for crops was based on Mandryk et al. (2014), by adding NPK use from artificial fertiliser and manure together.

Mandryk et al. (2014) did not include grass, maize, or wheat followed by oilseed radish. Therefore, minimum nutrient requirement values were taken from other sources for these crops, assuming there are no differences in nutrient application for these crops between farm types. NPK requirements for maize was based on van der Voort (2018) and of oilseed radish cultivated after winter wheat was calculated as the sum of winter wheat (Mandryk et al., 2014) and oil seed radish (van der Voort, 2018). Advised N fertilisation of grassland is 354 kg N/ha/y assuming grass is mown and that soil N supply during the growing season is 110 kg/ha (van Schie-Rameijer et al., 2019) which is average for soils in Flevoland (Bokhorst and van der Burgt, 2012). This is however higher than legally allowed on temporary grassland. Therefore, the N requirement for temporary grass was set to the legal maximum of 310 kg N/ha/y (RVO, 2017). P fertilisation recommendation of grassland in the Netherlands depends on both the PAL and the P-$CaCl_2$ value as well as the amount of P extracted during the growing season. With an assumed PAL value between 27-50 and an median P-$CaCl_2$ value of 2 of grassland in marine clay areas (PBL, 2017), P fertilisation for

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[2] There were 21753 farms with grassland in 2018 (CBS, 2018d), in 2019 about 17904 farms opted for derogation (Braakman, 2019).

the first cut is 0 (van Schie-Rameijer et al., 2019). For healthy and productive cows, the P content of grass should be 3.5 g/kg DM. Assuming a farmer fertilises to maintain soil P content, the same amount of P should be applied as is taken from the field during harvest. This means that with grass yields of 10800 kg DM a year, at least 37.8 kg P should be applied annually. An overview of nutrient requirements per crop per farm type can be found in Table A 10.

N and P application per farm was limited by the N and P utilisation space[3], or maximum N or P application. N utilisation space depends on the cultivated area of each crop and the crop specific N norms (RVO, 2019e, 2017). P utilisation space depends on the cultivated area and the phosphate status of the soil (RVO, 2018d, n.d., n.d.). Assumptions were made to arrive at P utilisation space parameters. It was assumed that the phosphate status of arable and grassland soils was classified as neutral, meaning that arable soils were assumed to have a Pw-value between 36 and 55; and grasslands were assumed to have a PAL value between 27 and 50. Therefore, farms' P use space increased by 60 kg per additional ha cropland and 90 kg per additional ha grassland (RVO, 2018d).

N content from manure was assumed to be 0.004 kg N/kg manure (van der Voort, 2018) and corrected with a working coefficient of 0.6 (RVO, 2018e). An overview of N and P norms used in this thesis, is supplied in Table A 9.

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[3] NL: gebruiksruimte. The amount of N or P a farm is allowed to apply on its cultivated land.

4. Results

The following paragraphs describe differences and similarities between scenarios and regions in terms of obtained profits, cultivated crop areas, manure use, fodder use, nutrient use, organic matter, and greening payments.

4.1. Economic effect of land exchange

Land exchange (MAX) increased total regional profits by 28.5% in the Flevopolder and 21.6% in the Noordoostpolder compared to no land exchange (NO). In the Flevopolder arable profits increased by 36.3% while dairy profits decreased by 2.8%. In the Noordoostpolder arable profits increased by 22.2% and dairy profits by 13.9% (Figure 3).

When comparing the scenario where profits from land exchange were distributed equally (EQUIT); in the Flevopolder total, arable and dairy profits increased by 0.3% In the Noordoostpolder total profits increased by 1.7%, arable profits by 1.7% and dairy profits by 2.6%. So, in both polders land exchange enabled farms to increase their profit, even when equitably distributing profits. In both polders and both scenarios, allowing land exchange increased the area cultivated by arable farms at the expense of area cultivated by dairy farms

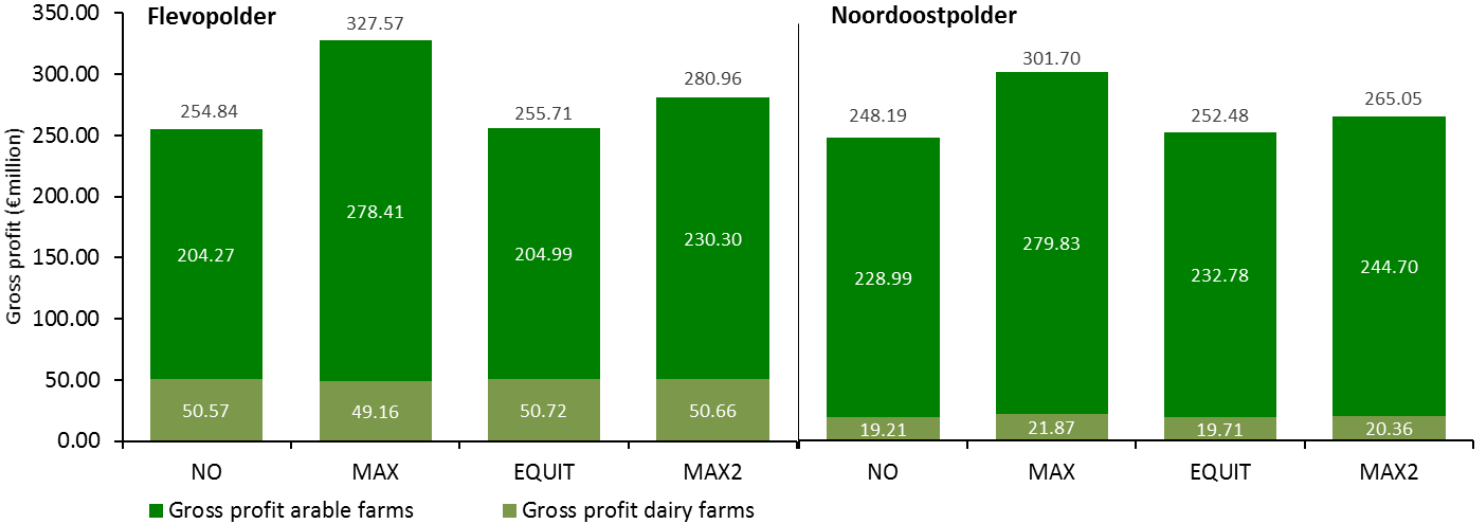

Figure 3.Gross profits obtained in the four scenarios in Flevopolder (left) and Noordoostpolder (right). The number above the columns indicates the total gross profit of the area.

In MAX2, regional profit in the Flevopolder increased by 10.2%, arable profits by 12.7%, and dairy profits by 0.2% compared to NO. In the Noordoostpolder, total and arable profit was 6.8% higher and dairy profit was 6.0% higher than NO. Hence, the availability of dairy land for rent, directly affects potential income of arable farms.

Both scenario MAX and MAX2 suggest that land exchange allows for the region to make a higher profit, while EQUIT indicates little space for development of income. Since, EQUIT maximises the increase in profit of the farm with the lowest increase in profits, it is possible that there is still room to improve profits but that the model has no way to distribute these profits to the farms that benefit the least and thus stops maximising income. In reality, there may be ways to distribute increased income.

Regardless of farm type, farms in this model need more land to improve their individual income. Arable farms can mainly improve their income by cultivating more, or more profitable crops (Figure 3 and Figure 4). For more crops, a farm needs more land. For more profitable crops, a farm needs more land or land without crop rotation constraint (dairy land).

Dairy farms however, could only increase profit by decreasing cost, since the maximum milk production was already attained in NO (Table 10, p.33). Reducing costs can be done in two ways; first, by feeding more crop and buying less fodder, which requires land. Second, by exporting less manure, which is more costly than applying manure or transferring manure to an arable farm. Since the transferable amount of manure was already maximised, the only current way for dairy farms to increase their profit is by cultivating more land, reducing feeding and manure export costs.

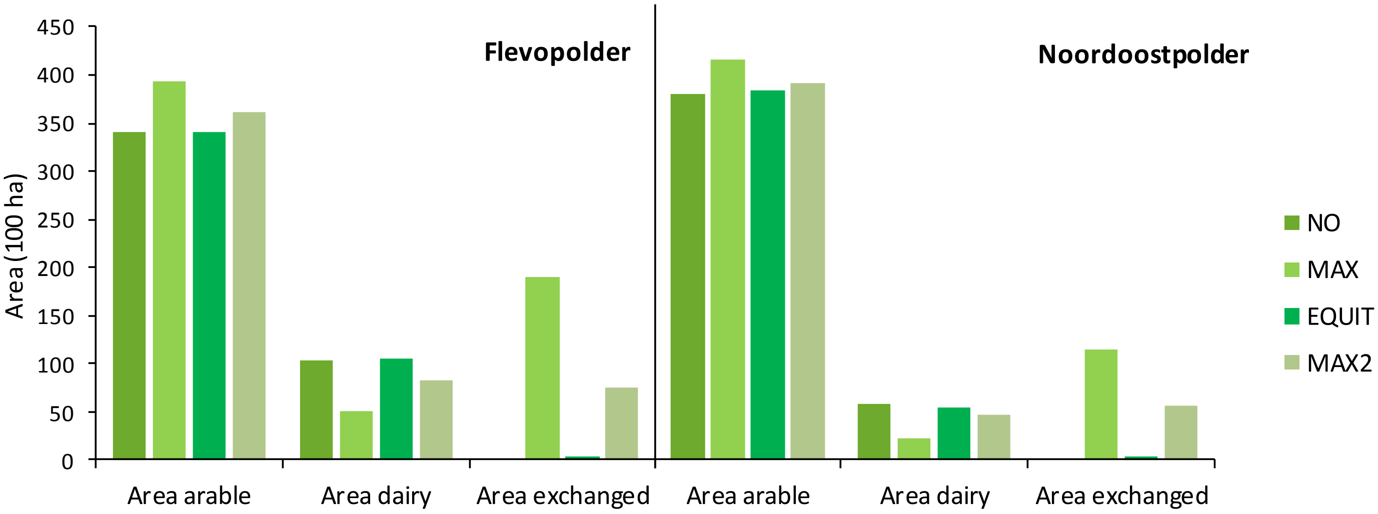

Figure 4. Areas cultivated per farm group and the total area exchanged land for each scenario. Note that land can also be exchanged among arable farms.

Farm types ELM and PMM seem to be the arable farm types that are able to benefit most from land exchange in terms of cultivated area, why this, is not entirely clear (Figure 5). PMM has similair yields (Table A 4), production costs, and available labour as most other farm types (Table 7) and ELM has relatively high fertilisation cost (Table A 10). ELM does have a higher available labour to owned land ratio (Table 7); hence, renting land to ELM might make better use of the labour available on these farms, decreasing the amount of labour that has to be hired regionally. Alternatively, PMM and ELM farms could coincidentally be located close to several dairy farms, giving these farms better access to dairy land.

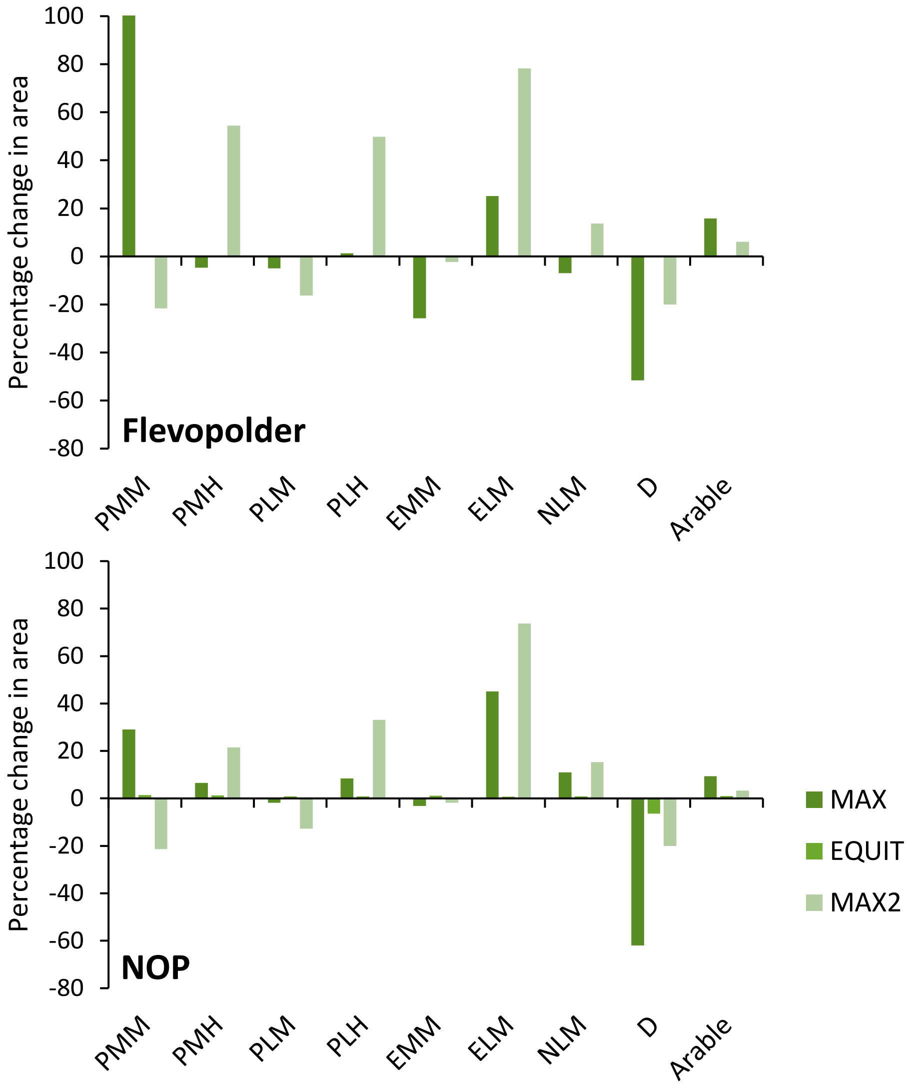

Figure 5. Relative change in cultivated area compared to NO of dairy farms (D), sum of arable farms (Arable) and per arable farm type (PMM, PMH, PLM, PLH, EMM, ELM, NLM).

4.2. Crop production

In scenario MAX, the cultivated area in both polders of seed potato (SP), winter carrot (WC), green peas (PE), and temporary grassland (GT) increased while the cultivated area of seed onion (SO), consumption potato (CP), chicory (CH), winter wheat (WW), fallow (FA), winter wheat followed by oil seed rape (WO), permanent grassland (GP), and maize (MS) decreased. The area sugar beet (SB) was unaffected (Figure 6). MAX2 had almost the same changes as MAX but the changes were smaller. The allocation of crops per polder per scenario is presented in Figure 7, while the corresponding additional data is supplemented in appendix Table A 11.

MAX violates crop rotation constraints on a regional level (Figure 7). For example, SP with a maximum crop rotation frequency of 0.25, clearly covers more than 25% of the regions area. This is allowed within the model because crop rotation constraints are set per farm, not regionally. Arable farms are able to rent a lot of land from dairy farms and this land is not rotationally constrained because it was assumed that dairy farms would always have a "fresh" plot of (grass) land for arable farms to use. This would not be the case if the cropping pattern in MAX would be used in several consecutive years.

In part to circumvent regional crop rotation constraint violation, exchangeable dairy land was restricted to 20% of total dairy land in MAX2. This reduced the area SP to within the 25% limit but did still violate WC and PE constraint of 17% in the Flevopolder with both crops covering 18% of the polders agricultural area. Considering that crop rotation constraints are in reality often more guidelines than hard laws, makes that MAX2 a more realistic scenario than MAX.

Table 9. Provincial crop areas of the reference-scenario (NO) and of Flevoland (average 2013-2017) (CBS, 2019b). Aggregate crop groups are included in the table to compensate for the limited number of crops used in the calculations and directly correspond with CBS categories.

	NO (ha)	%	Flevoland (ha)	% of total area arable and grass/feed crops
SP	18019	18	8686	11
WC	12253	12	3235	4
SO	3167	3	9147	11
CP	5463	5	10139	12
SB	0	0	9173	11
CH	11552	11	2113	3
PE	12253	12	713	1
WW	630	1	13016	16
FA	1448	1	432	1
WO	7723	8	-	-
GP	12935	13	4116	5
GT	0	0	9711	12
MS	2804	3	3253	4
Sum	88246	100	73735	90
Aggregate				
Potato	23482[1]	27	18894	23
Vegetables	39225[2]	44	17448	21
Sugar beet	0	0	9173	11
Cereals	8352[3]	9	15716	19
Fallow	1448	2	432	1
Grass	12935[4]	15	14832	18
Fodder crops	2804[5]	3	5097	6
Sum	88246	100	81592	100

[1] SP+CP, [2] WC+SO+CH+PE, [3] WW+WO, [4] GP+GT, [5] MS

Table 9 indicates pronounced differences in crop areas between the reference scenario and reality. When crop areas are aggregated in more general groups to compensate for the limited number of simulated crops, there are still differences between the reference and reality. Simulated area of vegetables is a lot larger than reality, while the simulated area cereals is a lot smaller than reality. In reality farmers are likely more prone to cultivate cereals than peas. Furthermore, this model does not take into account that vegetable cultivation requires knowledge and machinery, it is assumed that all simulated arable farms have this.

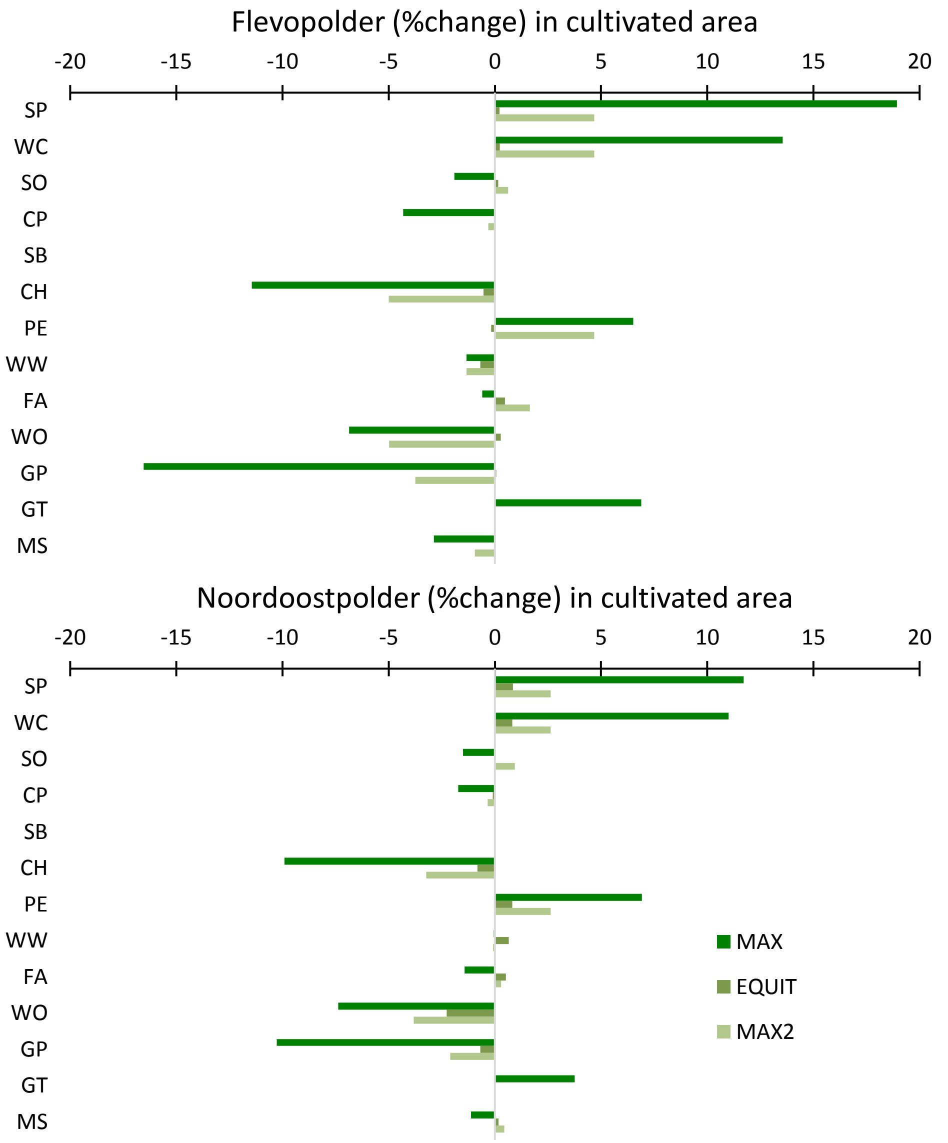

Figure 6. Change in crop area compared to NO as percentage of total area in the Flevopolder (TOP) and the Noordoostpolder (BOTTOM).

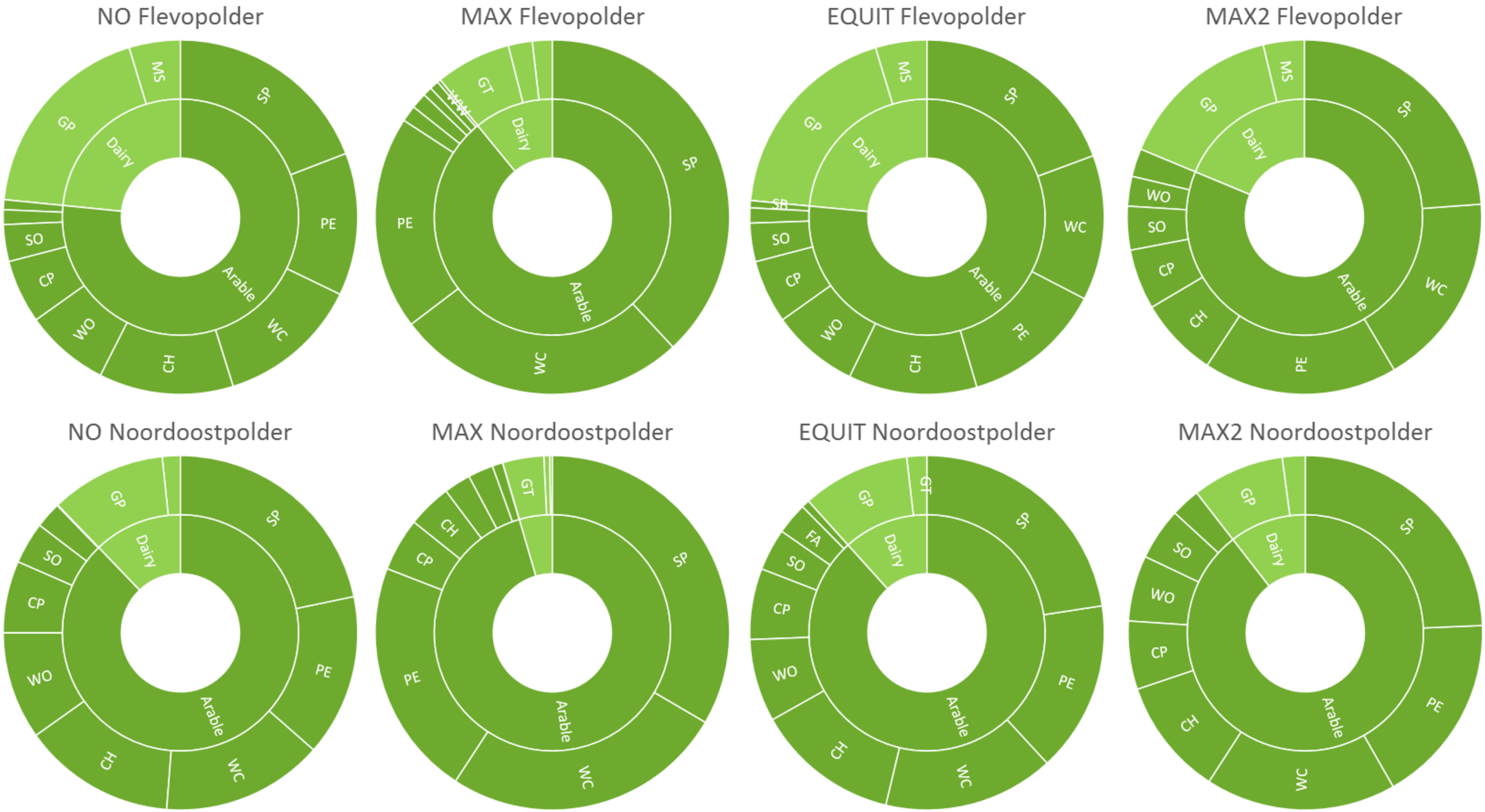

Figure 7. Crop areas per polder and per scenario.

4.3. Manure

Manure was mostly applied on land cultivated by dairy farms themselves. In scenario MAX, more manure was exported compared to the other scenarios (Figure 8). In this scenario, manure production was lower in the Flevopolder due to a decrease in LU. In the Flevopolder, close to the maximum allowed manure was transferred to arable farms in all scenarios (25% of farm production), while the potential for manure transfer was not always fully used in the Noordoostpolder. Restricting exchangeable dairy land (MAX2) mitigated the increase in manure export and decrease in LU due to land exchange

No manure was imported from outside the modelled system. Note that imported and exported manure could be traded with a party within the province but outside the modelled system.

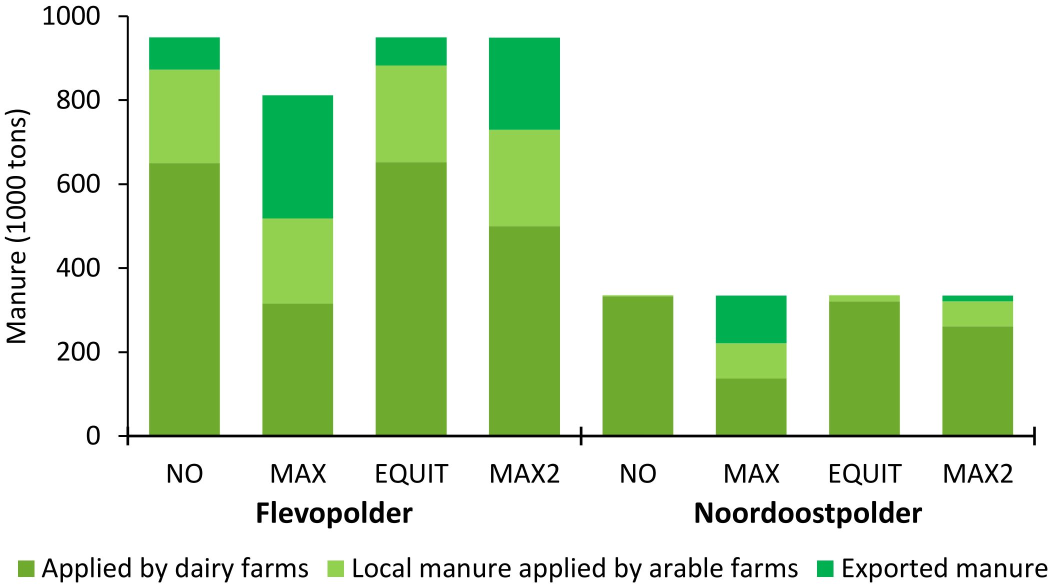

Figure 8. Manure flows. Local manure applied by arable farms was transferred from a local dairy farm to that arable farm. Exported manure is manure moved from a dairy farm to a party outside the modelled system. No manure was imported to arable farms from outside the modelled system.

Table 10. Livestock units (LU) per region and per scenario. R1-R3 are feeding rations with increasing milk production and feed requirements per LU. LU holding capacity is the maximum number of LU that can be housed in the region.

		NO	MAX	EQUIT	MAX2	LU holding capacity
Flevopolder	**R1**	0	0	0	0	24612
	R2	0	0	0	2	24612
	R3	24612	21051	24612	24597	24612
Noordoostpolder	**R1**	0	0	0	0	8701
	R2	0	0	0	0	8701
	R3	8701	8677	8701	8682	8701

4.4. Fodder

Compared to NO, a lot less crop is used as cattle feed in MAX (Figure 9). Because the area used to produce feed is replaced by arable crops (Figure 4). In the Flevopolder this decrease in fodder production is largely and in the Noordoostpolder completely, compensated with concentrates (Figure 9). This means that on a regional level, it is more profitable to cultivate arable crops than to produce fodder for livestock. The reduction in total feed use in Flevopolder MAX and MAX2 is due to a significant reduction in livestock units (Table 10). In the Noordoostpolder, the total number of LU decreased less in MAX and MAX2 than in the Flevopolder (Table 10). The higher proportion concentrates in the Flevopolder compared to the Noordoostpolder is caused by higher stocking rates (Table A 7).

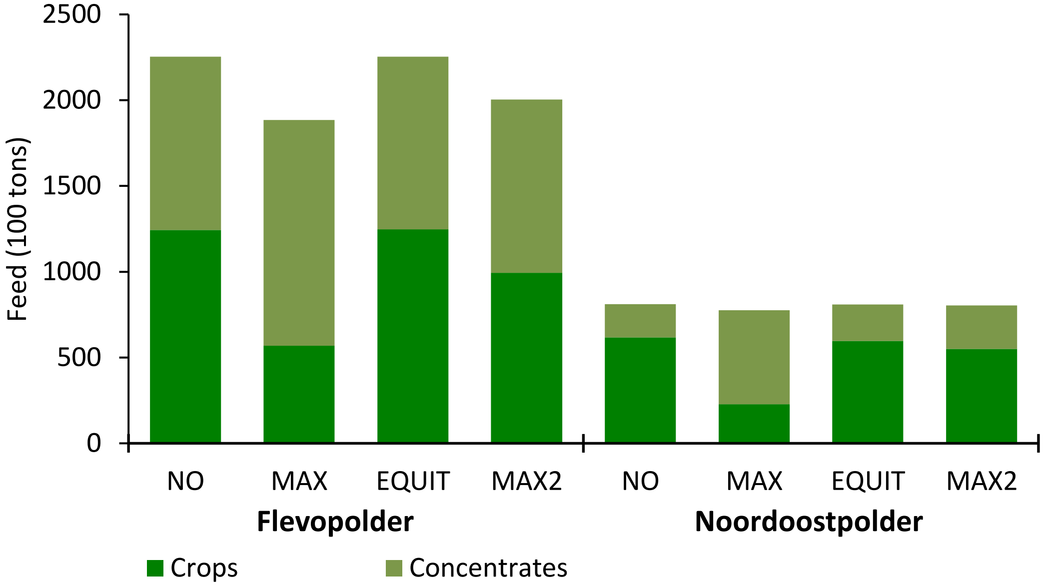

Figure 9. Feed used by dairy farms in 100 tons.

4.5. Nutrients and organic matter

Required application of N and P and effective organic matter (EOM) inputs from crops are dependent on the cropping pattern. Therefore, crop specific EOM input and minimum nutrient application per ha set in this model are listed and scored in Table 11. For example, SP has below average EOM input (score=0.7) and N requirement (score=0.7). Hence, if SP is cultivated more frequently at expense the of WW, which has above average scores, regional EOM inputs from crops and required N use decline.

In the following three sections, differences in nutrient use and EOM inputs between NO and the other scenarios are presented. These differences are primarily due to most crops, especially grass and wheat, being cultivated less frequently in favor of peas, winter carrot and seed potato (Figure 7).

Table 11. Crop effective organic matter (EOM) input, average N and P requirement parameters, and EOM and N scores. The scores are the crop's value for EOM or N divided by the mean value of either all crops or all arable crops. A number below 1 indicates the crop scores below average, a number higher than one is a score above average.

	EOM input (kg/ha)	EOM score arable crops	EOM score all crops	Mean N requirement for all farm types (kg/ha)	N comparison to average arable crops	N comparison to all crops	Mean P requirement for all farm types (kg/ha)
Mean	1457			140			34
Mean arable crops[1]	1174	1	0.8	129	1.0	0.9	36
SP	875	0.7	0.6	95	0.7	0.7	60
WC	150	0.1	0.1	124	1.0	0.9	60
SO	500	0.4	0.3	117	0.9	0.8	60
CP	875	0.7	0.6	265	2.0	1.9	60
SB	1275	1.1	0.9	126	1.0	0.9	60
CH	650	0.6	0.4	57	0.4	0.4	0
PE	650	0.6	0.4	71	0.5	0.5	60
WW	2630	2.2	1.8	206	1.6	1.5	0
FA	500	0.4	0.3	0	0.0	0.0	0
WO	3630	3.1	2.5	233	1.8	1.7	0
GP	3975	3.4	2.7	165	1.3	1.2	37.8
GT	2575	2.2	1.8	200	1.5	1.4	37.8
MS	660	0.6	0.5	160	1.2	1.1	0

[1] Excluding GP, GT, and MS

4.5.1. Nitrogen

In MAX, EQUIT, and MAX2, total nitrogen inputs were lower than in NO. Most N from organic sources (manure) was applied by dairy farms, whereas arable farms applied the majority of artificial N fertilisers (Figure 10). While the majority of decreased N application is due to a decrease in organic N applied by dairy farms, cropping patterns with more seed potato, winter carrots, and peas also required less artificial N fertilisers on arable farms. Seed potato, winter carrot, and green peas have low N requirements compared to grasses and wheat.

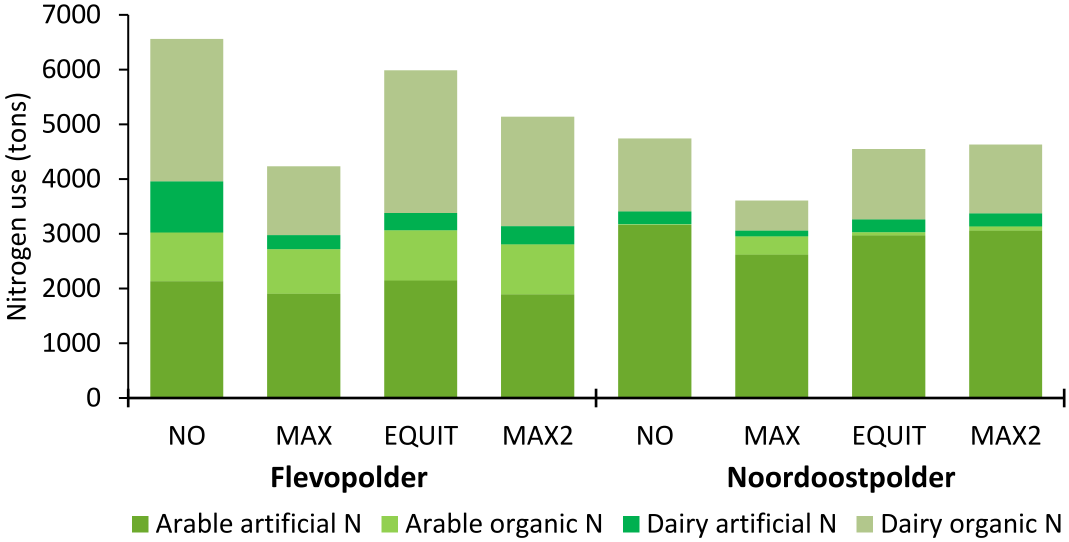

Figure 10. Total N application per scenario, per polder. Organic N application was not corrected for N working coefficient.

4.5.2. Phosphorous

Overall, land exchange slightly increased application of P fertilisers, ranging from +0.6% (MAX2, Noordoostpolder) to +14.2% (MAX, Noordoostpolder). Mainly due to higher use of artificial P fertilisers, despite a reduction in organic P application (Figure 11). In the Noordoostpolder, there was little difference in P use between NO and MAX2, while this was not the case in the Flevopolder.

Note that dairy farms were not allowed to apply artificial P fertilisers as this is one of the conditions to get derogation and all dairy farms in these scenarios were constrained to have derogation.

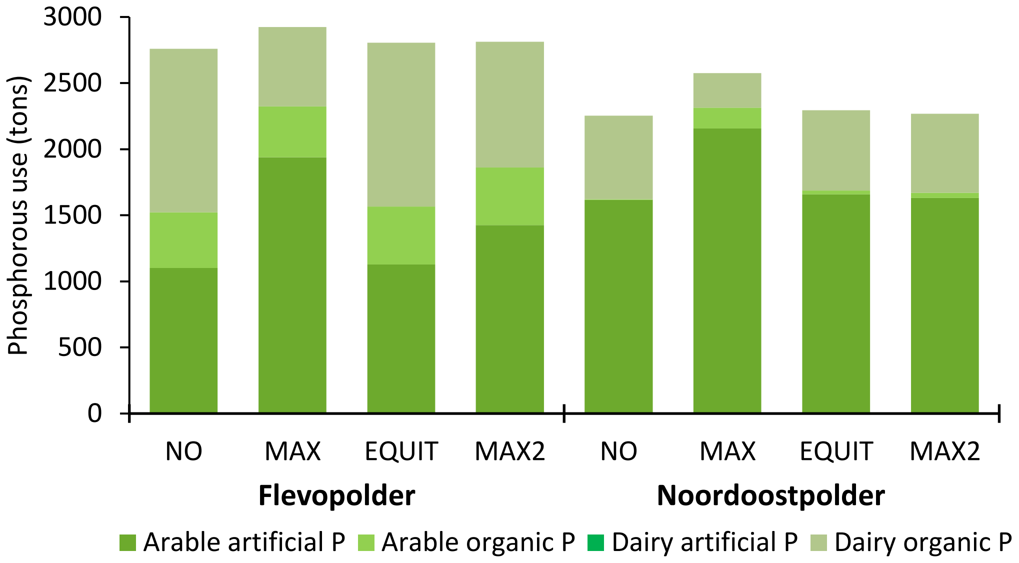

Figure 11. Total phosphorous application in tons per scenario, per polder. Dairy farms were not allowed to apply artificial P fertilisers as condition for derogation which was mandatory in these scenarios.

4.5.3. Organic matter

In both polders and in all scenarios, the majority of effective organic matter (EOM) inputs originates from crops (Figure 12), especially grasses.

Maximum land exchange led to a decrease in regional EOM inputs, especially because of a reduction in arable and dairy crop EOM input (Figure 12). Additionally, less manure was being applied and exported instead (Figure 8). The reduction in dairy crop EOM input is due to a large reduction in the area cultivated by dairy farms (Figure 7). Because grass cultivated by dairy farms has a large EOM input (Table 11), a reduction in dairy area leads to a large decrease in regional EOM input. The same phenomena is observed in MAX2 but to a lesser degree than MAX.

Cultivated area of most arable crops declines and is replaced by seed potatoes, green peas, and winter carrot. Winter carrot and peas have a relatively low EOM input, their increased frequency explains the low EOM input from arable crops in scenario MAX (Table 11).

Differences in EOM inputs between NO and EQUIT are very small as the cropping patterns differ little (Figure 7).

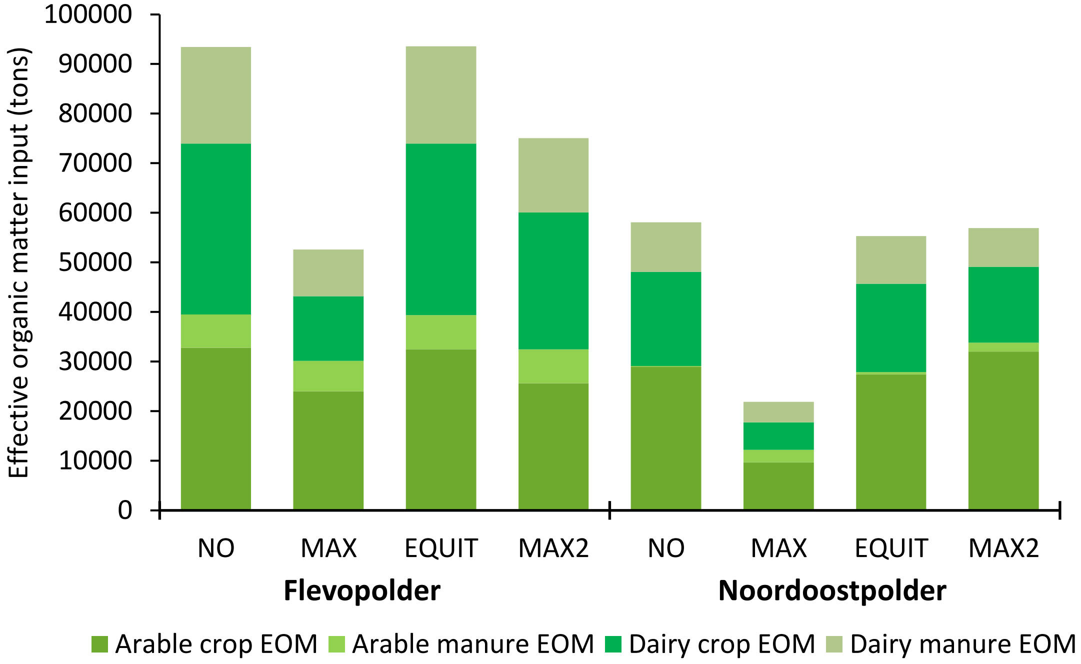

Figure 12. Effective organic matter (EOM) inputs from crops and manure per scenario and per municipality.

4.6. Greening payments

In scenario NO, all farmers in the Noordoostpolder complied with the EFA and crop diversification requirements or were exempt from meeting these requirements by having 75% of their land under cultivation of peas, grass, or fallow (Figure 13). While In the Flevopolder, some farms did not meet EFA requirements. In scenario MAX, area greening payments was smaller than in NO in both polders. While in EQUIT, the Flevopolder had more greening payments compared to NO. In the Flevopolder MAX2 had less area penalties. Dairy farms had exemption in all scenarios and both polders because they had over 75% of their land under grass cultivation.

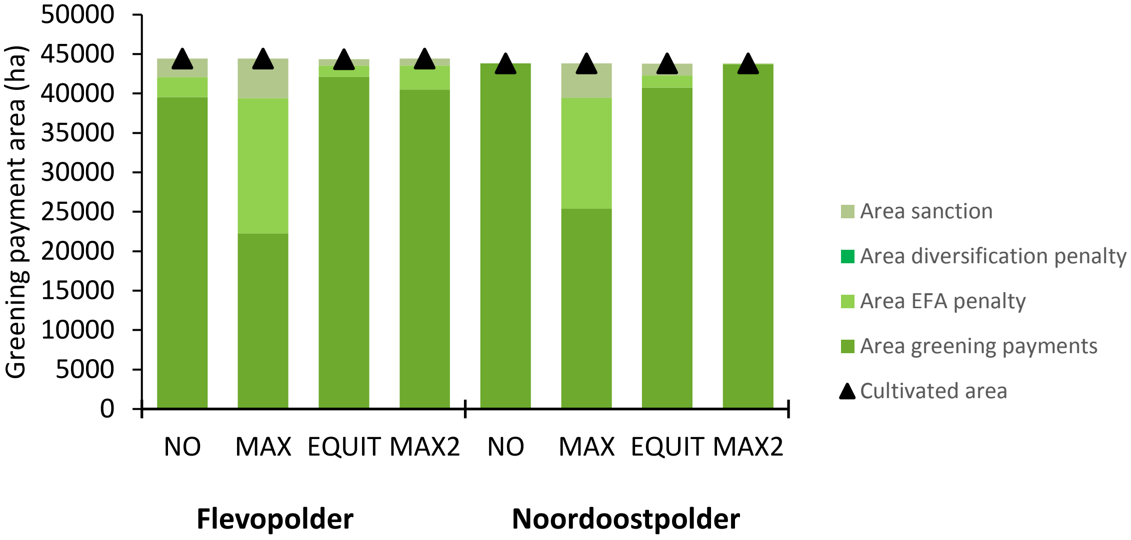

Figure 13. Over the cultivated area, greening payments can be paid out. If a certain condition is not met, a penalty is imposed in the form of a reduction in payment area as well as a sanction depending on the degree to which the requirement was not met.

5. Discussion

5.1. Economic effect of land exchange

To study whether land exchange can be financially beneficial to farms, four scenarios were run for the Flevopolder and Noordoostpolder. When compared to a scenario without land exchange (NO), the scenario with maximum land exchange (MAX) reveals that there is potential to improve regional profits by allowing the most efficient farms to conduct the most lucrative activities and make the best use of land, labour, and crop rotation resources. However, farmers do not cooperate to maximise regional profits, but presumably to maximise their own profits. Scenario EQUIT was an attempt to simulate this, by stringing together several optimisation steps and constraining lower bounds for individual farm profits. This way, benefits of land exchange were distributed more equally. In scenario MAX2, rentable dairy land was restricted to 20% of a dairy farms area to curb unrealistically large changes in cropping patterns due to land exchange.

Nakasaka (2016) did a similar study on Flevoland and also found an increase in total regional profits when no land exchange was compared to maximum land exchange but only of 5.4% as opposed to the 28.5% and 21.6% increase found in this thesis. However, these values reported by Nakasaka (2016) were closer to the limited land exchange scenario in this thesis (10.2% and 6.8%). Nakasaka (2016) assumed all farms had 5% of their area as fallow to serve as ecological set aside, while such a set-aside (greening payments) was optional in this thesis and could also be partially received. This second approach is less restrictive to farms and leaves more room to cultivate lucrative crops instead of setting aside land. Furthermore, more land could be rented from dairy farms in MAX than in Nakasaka (2016). Where Nakasaka (2016) restricted rentable dairy land to 30% of a dairy farms area, such a restriction was not in place here. In MAX, at least halve of all dairy farm land was rented by arable farms which increases the area that can be cultivated with potato or carrot. Nevertheless, when land rentable dairy land was restricted to 20% in this thesis, increases in profits compared to no land exchange were still higher than in Nakasaka (2016). Together, the different methods of simulating subsidy legislation and the difference in how much dairy land could be rented, can explain why Nakasaka (2016) found a lower increase in his second scenario than I did.

When comparing no land exchange with equitable land exchange (using a max-min approach), Nakasakas (2016) value of 3.5% is higher to 0.3% and 1.7% found in this thesis. This may be because Nakasakas (2016) simulations did not take into account the profit and objectives of dairy farms. In other words, arable farms in Nakasakas model could rent land from dairy farms regardless of the dairy farms' profit, while arable farms in this thesis could not. Furthermore, the inclusion of dairy farms increases the number of farms that need to benefit from land exchange, which makes optimising for relative gross profit more complicated. On top of this, dairy farms are less able to benefit from land exchange because they do not benefit from the release of crop rotation constraint the way arable farms do. This makes it more difficult to maximise the increase in profit of dairy farms. Together, dairy farms having a harder time benefiting from land exchange and the increase in the number of farms, provide an explanation for the different values found here and by Nakasaka (2016).

Some Dutch farmers work with informal agreements on prices and quantities of exchanged goods and land (Asai et al., 2018; Regan et al., 2017). Three options to simulate this behaviour were considered: the first was crop specific land rent prices, the second was crop independent variable land rent prices, and third a variable financial transaction from one farm to another. The first option does not work because the crop that will be cultivated on rented land is unknown. The second does not work because one cannot multiply two decision variables such as (*area land rented*)*(*money paid per ha*). The third one was abandoned after realising that allowing a monetary transaction from one farm to another, could very easily result in farms transferring money to farms that they do not really interact with just so regional profits can be distributed equally. There was insufficient time to device, test, and run simulations with direct monetary transactions.

Equitably exchanging land resulted in minor increases in profits because the potential increase in profits of dairy farms was limited. Clearly, a max-min approach where only manure and land can be exchanged is insufficient in distributing gains amongst arable and dairy farms. Simulating ways for dairy farms to benefit from cooperation with an arable farm could improve profits in an equitable scenario. This might be achieved by means of monetary transactions between farms or forcing arable farms to cultivate fodder crops for the dairy farms they cooperate with. This compensates dairy farms for their decrease in feed production.

5.2. Environmental impact of land exchange

Besides studying the effect on farm profit, the model in this study also allows for analysis of how land exchange affects effective organic matter (EOM) inputs and both organic and inorganic application of N and P. It was expected that land exchange affects regional cropping pattern and manure application. Because crops have specific EOM inputs and N and P requirements, the cropping pattern largely determines nutrient application and EOM inputs.

The low EOM inputs in these simulations give the impression that soil organic matter (SOM) stocks will decrease over time when land exchange is allowed, while soil organic carbon (SOC) concentrations in Dutch arable soils have been stable or slightly increasing in past decades (Reijneveld et al., 2009). However, the fact that the overall EOM inputs are lower when land is exchanged, does not necessarily mean that land exchange reduces soil organic matter (SOM) contents. Firstly, because this model does not take into account what parcel a crop is cultivated on. If grassland is rotated evenly, the EOM input may not change much for the average field. Only parcels where continuous grass was cultivated would see a reduction in overall EOM inputs when these fields are torn to cultivate carrots, peas, or potatoes. Secondly, this model does not currently take into account that arable farmers monitor and manage their SOM content (Mandryk et al., 2014; Reijneveld, 2013) and apply organic fertilisers such as compost or champost to maintain or even increase their SOM content.

Both aspects can be studied with a model; the first by introducing discrete parcels that can be transferred among farms, the second by adapting the objective function to also optimise for other farm objectives. The first method is probably hard to compute on a provincial scale but would be valuable on a smaller level. The second method could be done largely within the current model, adjusting the objective function to include multiple objectives and using objective weights identified for Flevoland farmers by Mandryk et al. (2014) and introducing organic fertilisers such as compost.

Even if the model is adapted to take into account farmers' value of SOM, it remains to be seen whether the decrease in EOM inputs when land is exchanged, is mitigated. Hijbeek et al. (2018) found that costs of organic materials and the difference in gross margin between root/tuber crops and cereals, as well as legislation, are perceived as constraining increase in SOM contents.

In MAX, N fertilisation was lower compared to NO in both polders. This reduction is mainly due to a decrease in organic N input caused by a lower manure application and marginally due to decreased artificial N input. In contrast, Regan et al. (2017) reported that cooperation through land and manure exchange, reduced artificial N fertiliser use on arable farms by substituting artificial N fertilisers with manure. Such a substitution was not found in this study because the amount of manure arable farms could receive from dairy farms was close to the maximum in all scenarios. Furthermore, the differences in crop rotations that were compared are larger in this study than in Regan et al. (2017). Instead of cooperation resulting in longer crop rotations with fewer potatoes reported by Regan et al. (2017), land exchange in this study resulted in shorter crop rotations.

Total P fertilisation was somewhat higher in MAX than in NO. In MAX a lot more artificial P fertiliser was used on arable farms while the input of organic P was lower. The increase in P fertiliser use is due to the dominant crops in MAX (SP, WC, and PE) requiring above average P inputs (Table 11).

Whether the observed changes in fertiliser use due to land exchange is a net positive or negative shift for the environmental impact of agriculture is unclear. Furthermore, other crops such as in other parts of the world, have different nutrient parameters. Therefore, the observed effects on fertiliser use do not necessarily extend to other agricultural systems.

5.3. Circularity

The aim of this thesis is to find out whether land exchange between arable and dairy farmers can contribute to a circular farming system on a provincial or municipal level. Indicative of this would be reduced artificial N and P use, manure export, and fodder import. Under the assumption that farms only maximise income, less artificial N fertilisers but more artificial P fertilisers were used by arable farms. Additionally, more manure was exported rather than applied on arable land, and more external concentrates were imported. This may give the impression that land exchange is detrimental to circular agriculture because it increases farms' use of external inputs and export of by-products.

However, the models system boundaries only include what comes in and goes out farm gates, the suppliers, and outlets of concentrates, manure, and fertilisers are not specified. Neither were dairy farms able to acquire concentrates such as wheat or peas from local sources. The raw materials used to make concentrates may be sourced and processed within the province, arguably still fitting within a provincially circular agricultural system. Likewise, exported manure may be processed locally and sold as a replacement for artificial fertiliser or separated in different fractions which may be more suitable for arable crops (Verloop et al., 2013). Especially the thick fraction from manure might be interesting for arable farms if their rotation needs more P. Because this fraction contains a lot of P, which dairy farms need to get rid of. The solid fraction also contains more EOM compared to slurry (Verloop et al., 2013). The region still has plenty of nutrients from the manure that is produced, which could substitute some of the artificial fertilisers that were used. To gain a better understanding of the role of land exchange within circular agriculture, one requires a more comprehensive model that includes manure, raw resources, and feed flows from and to concentrate and manure processing plants.

Writing code to include such flows is not too difficult. However, feed processors are not eager to share data on their resource and output fluxes (Toon te Poele, personal communication; 12-06-2019). Furthermore, processing manure to a fertiliser replacement product is a new technology for which data may also be hard to obtain (Esselink, 2019b). Data on manure seperation is available (van Dijk and Galama, 2019).

The economic viability of manure processing is largely determined by the cost price of processing and transporting manure as well as the price of artificial fertilisers (van Dijk and Galama, 2019; Verloop et al., 2013). Van Dijk and Galama (2019) concluded that separation of manure is not economically sensible unless one gets added value for EOM (€0.20/kg). If a more comprehensive provincial model is made, it would be interesting to assess the effect of valuing EOM at 20 cents per kg.

In addition to including manure and feed processors in the system, direct transfer of manure and feed between farms in the region can be extended. Extension of manure transfer could be done by allowing for other forms of manure transport that somewhat more complicated with regards to legislation and cost calculation than *boer-boer* transport. A simpler alternative could be relaxing the 25% limit on *boer-boer* transport, allowing more direct manure transfer. This would also serve as a policy exploration, informing manure policy makers. Transfer of feed from arable farms to dairy farms could be modelled by allowing production and sale of feed crops by arable farms or forcing arable farms to cultivate feed crops for dairy farms as part of the cost of renting land. Enabling feed production by arable farms and transfer of feed from arable to dairy farms might compensate dairy farms for their reduction in feed production observed in land exchange scenarios, possibly making equitable distribution of profits more feasible.

5.4. Amount of peas

Modelled provincial pea area ranged roughly from 11 thousand ha to 17 thousand ha (Table A 11), while in reality Flevoland only had 713 ha peas on average (CBS, 2019b). The probable reason that arable farms in this model cultivate so much pea is that it is the most profitable non-root/tuber arable crop after deduction of production and fertiliser costs (Table 12). The restriction on root/tuber crop frequency =0.7 was binding so peas where the most profitable after root/tuber crops. In reality farmers may prefer winter wheat over peas because winter wheat inputs more EOM (Table A 13) and may have a less elastic price, being a more abundant global commodity than peas. Meaning that the price of peas may decrease a lot more than that of wheat when Dutch farmers increase their production. Farmers in reality also have other vegetable crops to choose from.

*Table 12. Average arable crop profit per ha, differentiating between root/tuber crops and non-root/tuber crops. Profit was calculated as sales price of crops * average yield per ha - general production cost - fertilisation cost when Urea, triple super P, and Kali 60 were used.*

Crop	Profit (€/ha)	Is root or tuber crop
SP	8948	yes
WC	7014	yes
SO	3032	yes
CP	4441	yes
SB	2559	yes
CH	5304	yes
PE	2186	no
WW	737	no
FA	0	no
WO	529	no

While such a large area under pea cultivation is not representative of the current situation, cultivating more peas may fit very well in a circular agricultural system. Firstly because it is a nitrogen fixing plant, potentially reducing the required artificial N fertiliser amount (Fustec et al., 2010). Secondly because it is a source of protein for livestock and could replace imported feed stocks. Local production fits in the ministries vision on circular agriculture (Ministerie van Landbouw Natuur en Voedselkwaliteit, 2018). However, some argue that arable land should primarily be used to produce food for human consumption and only feed livestock with grass, by-products, and other organic materials humans cannot or will not eat (de Boer and van Ittersum, 2018; Van Zanten et al., 2018).

5.5. Greening payments

Results show that it is more profitable for simulated farms to grow lucrative crops such as seed potato than to cultivate the required area wheat with oil radish or fallow[4], if this is possible within the limits of crop rotation constraints. Considering that a 100 ha farm needs almost 17 ha WO or 5 ha of fallow to comply with EFA requirements and get €11300 in greening payments, that 5-17 ha would make more money with a root or tuber crop (Table 12). Gaudino et al. (2018) also concluded that intensive farm tend to forgo their greening payments because the payments do not outweigh reduced income caused by compliance.

In reality, farmers have more options to comply with EFA requirements than presented in this model. These include: other catch crops and landscape elements such as trees, hedges, or ponds

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[4] Wheat followed by oil radish has an EFA weight of 0.3. Fallow has a EFA weight of 1. Meaning that 1 ha of wheat followed by oil radish counts as 0.3 ha EFA.

(RVO, 2018f). Furthermore, in reality farmers generally pursue multiple goals, besides profit maximisation which may persuade them to use a farm plan in compliance with EFA requirements (Mandryk et al., 2014).

Given the large difference in profitability between root/tuber crops, peas, and wheat (Table 12), greening payments (currently €113/ha) are unlikely to affect modelled cropping patterns. Unless the influence of greening payments is specifically studied, it seems fair to assume farmers find a way to get their greening payments regardless of their cropping pattern. This way future models assessing land exchange in relation to integrating arable and dairy farms regionally, could be simplified.

5.6. Comparison Flevopolder and Noordoostpolder

In the Flevopolder, where there were more dairy farms per arable farm, potential regional profit from land exchange was higher than in the Noordoostpolder. This was mainly due to arable farms benefitting more from land exchange in the Flevopolder than in the Noordoostpolder. From comparing MAX and MAX2, one can conclude that the availability of rentable dairy land is an important factor in increasing potential regional profit. Since there is more dairy land rentable in the Flevopolder, it is likely that this is the reason why potential regional profits are higher in the Flevopolder than in the Noordoostpolder.

Dairy farms themselves were better able to benefit from land exchange in the Noordoostpolder than in the Flevopolder. In reality, this might be explained by the fact that when dairy farms are scarce, they have more bargaining power when cooperating with arable farms. This does not hold for the model, because the rent prices of land are the same in both polders. A more likely explanation is that the Noordoostpolder had a higher farm density (Figure 2). With more arable farms close by, dairy farms in the Noordoostpolder have more options to find a profitable cooperation. Another possibility, is that the higher stocking rates in the Flevopolder, made the importance of land for a dairy farm higher, compared to the Noordoostpolder (Table A 7). Making it less profitable to rent out land.

5.7. Validity of reference scenario

Crop areas of Flevoland in NO and reality were compared. In the simulation, the total cultivated area was overestimated. This might be due to overestimation of farm sizes in setting up the calculations. Furthermore, the simulated province had a higher percentage area of seed potato, winter carrot, chicory, and green pea and a lower percentage of seed onions, consumption potato, sugar beet, as well as a slightly underestimated area grass and fodder crops. The crops used for the calculations make up roughly 90% of the area arable and dairy land.

The differences in potato are probably due to the model optimising for income; seed potatoes are worth more than consumption potatoes. Together the simulated area of potatoes is closer to the actual area. The model does not take into account that seed potato cultivation requires more expertise, making it more difficult to actually cultivate this crop. The difference in sugar beet and seed onion area could be caused by underestimating the profitability of these crops when setting up parameters of calculations.

An explanation for the difference in cereal cultivation between the reference scenario and reality is that cereals play a key –non financial- role in crop rotations. Other functions of cereals such as improving soil structure or organic matter content are taken into account by simulated farms.

Disregarding sugar beet, the reference scenarios cropping pattern is quite representative of reality, if one takes into account that the model optimises for short term profit.

5.8. Model assumptions

5.8.1. Farm type sizes and distribution

It was assumed that arable farm types were distributed evenly among and throughout municipalities. Consequently, the average arable farm size is 55.2 ha throughout the province, while in reality, the average arable farm size ranges from 36.6 ha in the Noordoostpolder to 61.0 ha in Zeewolde (Table A 5) (CBS, 2018b). Furthermore, farms in the Noordoostpolder are known to have a more intensive crop rotation with more root and tuber crops and less cereals than farm in the Flevopolder. The assumption that farm types are distributed evenly is therefore most likely false. While municipality specific dairy farm sizes and densities did capture some of the differences between regions, municipal differences in arable farms and stocking rates could be improved.

5.8.2. Lack of flowers in model

Flevoland has between 3000 and 4000 ha of flowers and flower bulbs out of about 77200 ha arable crops an field horticulture (about 5%) (CBS, 2019b). Flower bulbs are a financially important crop in Flevoland but is lacking in this thesis. Including flower bulbs in the model will likely increase the income of arable farms. Flower bulbs are likely to also partially replace one of the current profitable root or tuber crops, as bulbs are also root or tuber crops. Flower bulbs are regarded as horticulture crops despite often being cultivated on arable land. Because of this, sources with information on arable crops often did not include flower bulbs, making it harder to find information. Therefore, flower bulbs were not included in this study.

5.8.3. Dairy regimes

In this model it was assumed that farms can pick one of three feeding regimes, which determines the milk price, milk production, costs, and feed requirements. While farmers have some control over the milk production per cow by means of rationing feed, milk production is also determined by the (lactation) age of the cow. By adding a constraint limiting the fraction of cows of a certain lactation age, a more realistic herd population can be created with a more realistic milk production per farm. Furthermore, a single price for milk was assumed, while real farmers can get a premium for meadow or organic milk. In 2018, 20 out of 251 dairy farms in Flevoland were organic (CBS, 2019c) and about 40% of dairy farms in Flevoland let their dairy cows and young stock graze (CBS, 2019d). Extra feeding regimes could be added with different milk prices and different costs in terms of money, labour, and feed requirements.

5.9. Disadvantages of methodology

The downsides of mechanistic normative models include that they easily adopt or recommend better alternative technologies or farm configurations where these adoptions are not as easy in reality (Janssen and van Ittersum, 2007). Furthermore, McCown (2001) described a gap between researchers that use models to calculate what farmers should do and the practitioners themselves. This gap can be due to the researchers not using local data or not seeing all farmers’ constraints. To bridge the gap between researchers and farmers, local data from Flevoland was used as much as possible, collecting census data on provincial or municipal level, and relying on data collected from farms by Mandryk et al. (2014, 2012) where possible.

6. Concluding remarks

By extending a previously proposed bio-economic regional model, this study reaffirmed that land exchange can increase regional profits. Through inclusion of dairy farms' objectives it was made clear that distributing additional profits from land exchange equitably, is more difficult than previously thought. In future research this could be accomplished by including direct monetary transactions in the model, or extending the possibilities to access feed or transfer manure within the system.

Land exchange can have a large impact on which crops are cultivated, which in turn affects regional nutrient use and input of effective organic matter. In this thesis, optimisation of regional profit with land exchange decreased the area cultivated by dairy farms, reducing the amount of regionally applied manure and increasing the modelled systems reliance on extenally produced feed. By extending system boundries to include feed and manure processors, paired with a wider range of possibilities to transfer feed and manure between farms, modelling studies can provide better insight in regional circularity.

In this study, land exchange decreased regional N application while increasing P application. This is largely related to shifts in the areas of cultivated crops. It is unclear wether changes in nutrient use is overall environmentally positive or negative.

Land exchange allows arable farms to cultivate more cash crops at the expense of less valuable crops cultivated for due to crop rotation constraints or as soil fertilitiy enhancer. In Flevoland the cash crops seed potato and winter carrot have low effective organic matter (EOM) contributions while the less valuble crop, winter wheat, has high EOM inputs. Consequently, land exchange reduced regional EOM inputs. However, individual arable parcels may be unaffected as these soils will not have a higher frequency of low EOM input cash crops and wheat cultivated on these parcels might be replaced by high EOM input fodder crops such as grass. Dairy parcels might have a reduction in soil organic matter content, as the introduction of cash crops in the rotation on these parcels reduces the rotations EOM input. Calculations on smaller integration levels are required to test this theory.

Moreover, multiple goals for both arable and dairy farms could be taken into account to better reflect actual farm behaviour. Combining farm surveys and improvements to simulating farm-farm interactions can be used to more realistically simulate integration of arable and dairy farms.

Greening payments seemed to have little influence in this study. It is suggested that futures studies similair to this one, disregard greening payments for the sake of simplifying the model.

This study supports the idea that land exchange, as well as other forms of farm-farm integration, should be taken into account when designing circular agricultural systems. In addition, this study identified several factors to pay attention to when modelling land exchange in a circular agriculture context.

7. Acknowledgement

I am thankfull for the feedback and support I enjoyed from my supervisors Argyris and Pytrik. It was a pleasure working with them. I am very gratefull for the practical insights my farmer friends have shared with me throughout my studies and while writing this thesis.

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Appendix

I. Crop parameters

Table A 1. Crop fodder properties based on (Federatie Nederlandse Diervoederketen, 2016).

Crop	Crop name in source	VEM/kg	DVE g/kg	Structure value	DM (kg/kg)	Saturation value
Grass permanent	Graskuil, I) jaargemiddelde	888	65	3.03	0.474	0.89
Grass temporary	Graskuil, I) jaargemiddelde	888	65	3.03	0.474	0.89
Maize silage	Snijmais, kuil	893	45.5	1.85	0.285	0.91

Table A 2. Ecological focus area weighing factor of crops (RVO, 2018f).

Crop	*$WEFA_c$*
Seed potato (SP)	0
Winter carrot (WC)	0
Seed onion (SO)	0
Consumption potato (CP)	0
Sugar beet (SB)	0
Chicory (CH)	0
Green peas (PE)	0
Winter wheat (WW)	0
Fallow (FA)	1
Winter wheat + Oil radish (WO)	0.3
Grass permanent (GP)	0
Grass temporary (GT)	0
Maize silage (MS)	0

Table A 3. Production cost (excluding fertiliser costs), market price, and required labour of crops (van der Voort, 2018).

Crop	*Production cost (€/ha)*	*Market price (€/ton)*	*Required labour (h/y)*
Seed potato (SP)	2043	280	76.6
Winter carrot (WC)	2992	120	44.00
Seed onion (SO)	2727	100	35.2
Consumption potato (CP)	2610	140	30.2
Sugar beet (SB)	1635	46	13.2
Chicory (CH)	2255	0.05[1]	43.0
Green peas (PE)	170	330	5.1
Winter wheat (WW)	786	170	9.6
Fallow (FA)	0	0	0
Winter wheat + Oil radish (WO)	982	170	14.2
Grass permanent (GP)	1883	0	7.2
Grass temporary (GT)	1964	0	11.2
Maize silage (MS)	1095	0	7.7

[1] Market price of chicory is given per harvestable root instead of per ton.

Table A 4. Yield per hectare in tons in this thesis and Nakasaka (2016) for each farm type. "-" indicates missing values. Maize silage yield is given in kg dry matter. The farm types are determined by their orientation (Production, Entrepreneurial, or Nature), size (Medium or Large), and intensity (Medium, or High) (Nakasaka, 2016)

		Seed potato	Winter carrot	Seed onion	Consumption potato	Sugar beet	Chicory	Green peas	Winter wheat	Fallow	Winter wheat+ Oil radish	Grass permanent	Grass temporary	Maize silage
	KWIN-AGV	39.9	85	59.5	52.2	94.5	153[1]	7.5	9.5	0	9.5	-	-	16.5
PMM	**This thesis**	45	85	70	63	100	153[1]	8	11	0	11	0	0	0
	Nakasaka	45	85	70	63	100	35	8	11	0	-	-	-	-
PMH	**This thesis**	44	85	90	63	90	153[1]	8	11	0	11	0	0	0
	Nakasaka	44	85	90	63	90	35	8	11	0	-	-	-	-
PLM	**This thesis**	45	85	70	63	100	153[1]	8	11	0	11	0	0	0
	Nakasaka	45	85	70	63	100	35	8	11	0	-	-	-	-
PLH	**This thesis**	44	85	90	63	90	153	8	11	0	11	0	0	0
	Nakasaka	44	85	90	63	90	35	8	11	0	-	-	-	-
EMM	**This thesis**	45	85	80	55	90	153[1]	7	10	0	10	0	0	0
	Nakasaka	45	85	80	55	90	35	7	10	0	-	-	-	-
ELM	**This thesis**	45	85	80	55	90	153[1]	7	10	0	10	0	0	0
	Nakasaka	45	85	80	55	90	35	7	10	0	-	-	-	-
NLM	**This thesis**	45	85	70	63	100	0	7	11	0	11	0	0	0
	Nakasaka	45	85	70	63	100	35	7	11	0	-	-	-	-
D	**This thesis**	0	0	0	0	0	0	0	0	0	0	10.8	10.8	16.5

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[1] Chicory values for this thesis are given in harvestable roots *1000 but in tons/ha for Nakasaka.

II. Farm distribution

Table A 5 Actual and simulated numbers of farms, dimensions, and surface areas of municipalities in Flevoland. Almere and Urk were not simulated due to their small number of farms. The simulated surface area of Lelystad was altered to exclude urban and nature area in the west of the municipality, so simulated farm density is more representative to the actual situation. The farm types are determined by their orientation (Production, Entrepreneurial, or Nature), size (Medium or Large), and intensity (Medium, or High) (Nakasaka, 2016). The farm assignment method is explained in Table A 6.

	Flevoland	**Almere**	**Dronten**	**Lelystad**	**Noordoost-polder**	**Urk**	**Zeewolde**
Number of arable farms total (2017)	1326	13	353	100	689	8	163
Number of dairy farms (2017)	261	7	55	22	90	2	85
Number of arable farms per dairy farm (2017)	5.08	1.86	6.42	4.55	7.66	4.00	1.92
Fraction arable farms of region	1.00	0.01	0.27	0.08	0.52	0.01	0.12
Fraction dairy farms of region	1.00	0.03	0.21	0.08	0.34	0.01	0.33
Assigned number of farms per farm type (excluding farms in Almere and Urk)							
PMM	426		116	32	225		53
PMH	121		33	9	64		15
PLM	418		114	32	220		52
PLH	198		53	16	104		25
EMM	43		11	4	22		6
ELM	72		19	5	39		9
NLM	27		7	2	15		3
D	252		55	22	90		85
Dimensions							
Estimated width (km)	47		20	10	26		20
Estimated height (km)	65		20	15	25		20
Surface area (km^2)	1417	129.6	333	231	460	11.53	248
Agricultural area (km^2)	772.6	11.4	212.7	85.0	296.6	2.8	145.4
Simulated agricultural area (km^2)	882.5		230.4	69.7	438.1		144.2
Simulated width (km) x-axis	32		17	8.5	20		15
Simulated height (km), y-axis	61.5		19	10	23		16.5
Simulated surface area (km^2)	1115.5		323	85	460		247.5
Average arable farm size (ha)	47.1	58.5	51.0	64.2	36.6	26.0	61.0
Average simulated arable farm size (ha)	55.2		55.2	55.5	55.2		55.2

Table A 6 Number of arable farms by arable farm type used by Nakasaka (2016), and based on Mandryk et al. (2012)*, the fraction of all farms per farm type. These fractions are used to determine simulated numbers of farms per type for the four largest agricultural municipalities (Dronten, Lelystad, Noordoostpolder, and Zeewolde). Due to rounding the sum of farms per farm type was per municipality was lower than the actual number of arable farms per municipality. These leftover farms later assigned by count (Dronten: + PMM, PMH, PLM; Lelystad: + PLH, EMM; Noordoostpolder: + ELM, NLM, PMM, PMH; Zeewolde + PLM, PLH). The definitive number of farms per type per municipality can be found in Table A 5. The farm types are differentiated by their orientation (Production, Entrepreneurial, or Nature), size (Medium or Large), and intensity (Medium, or High).*

	Nr. of farms used by Nakasaka (2016)	**Fraction**	**Total nr. of farms (this thesis)**	**Nr. of farms Dronten**	**Nr. of farms Lelystad**	**Nr. of farms Noordoost-polder**	**Nr of farms Zeewolde**
Total arable farms (CBS)	920	1	1305[1]	353	100	689	163
PMM	300	0.326	432.39	115	32	224	53
PMH	85	0.092	122.51	32	9	63	15
PLM	295	0.321	425.18	113	32	220	52
PLH	140	0.152	201.78	53	15	104	24
EMM	30	0.033	43.24	11	3	22	5
ELM	51	0.055	73.51	19	5	38	9
NLM	19	0.021	27.38	7	2	14	3
Unspecified				3	2	4	2

[1] Excluding farms in Almere and Urk which were not simulated.

III. Livestock units

The average milk production per dairy cow per year over 2013-2017 in the Netherlands is 8140,5 kg (CBS, 2018c). The average number of young stock per dairy cow in Flevoland is 0.7 (Table A 7 Number of dairy farms, animals, and animals per farm in Flevoland and the six municipalities in Flevoland, averaged over the years 2013-2017 *(CBS, 2018b)*.). The daily energy requirement expressed in VEM of a mature dairy cow weighing 650 kg can be described as:

$$VEM = 5323 + 440 * CM + 0.73 * CM^2 \qquad (44)$$

Where CM is daily standard milk production in kg. Standard milk is used for measurements and comparison, it has 3.3% protein and 4% fat (Federatie Nederlandse Diervoederketen, 2016).

Table A 7 Number of dairy farms, animals, and animals per farm in Flevoland and the six municipalities in Flevoland, averaged over the years 2013-2017 (CBS, 2018b).

	Flevoland	**Almere**	**Dronten**	**Lelystad**	**Noordoost-polder**	**Urk**	**Zeewolde**
Young stock	25885.0	684.4	5782.4	2876.4	7123.4	171.2	9247.2
Dairy cows (>= 2years)	35281.4	932.4	7308.2	4525.4	9081.0	168.0	13266.4
Farms with dairy cows (>=2 years)	267.4	7.4	55.0	22.6	94.0	2.2	86.2
Young stock per dairy cow	0.7	0.7	0.8	0.6	0.8	1.0	0.7
Dairy cows per farm	131.9	126.0	132.9	200.2	96.6	76.4	153.9
Average farm size (ha)	64	64	64	64	64	64	64

Daily protein requirement of a 650kg dairy cow and a milk protein content of 3.3% (33g protein/kg milk) can be described as:

$$DVE = 119 + 1.396 * (CM * 33) + 0.000195 * (CM * 33)^2 \qquad (45)$$

IV. Dairy activities

Table A 8. Parameters of dairy activities (R1, R2, R3). Whenever livestock units (LU) are mentioned, young stock values are included. Values for parameters that are the same among dairy activities in this model are given in column ALL. One can easily introduce a new dairy activity where one of these values can be different from other activities.

	R1	R2	R3	ALL
Milk (kg/LU/d) [1] (4%fat, 3.32%protein)	18	24	30	
VEM (cow/d)[1]	13480	16310	19180	
DVE (cow/d)[1]	1020	1360	1700	
Manure production (m^3/LU/y) [2] (50% grass 50% silage maize)	29.25	32.75	37.45	
VEM/l milk[1]	4839.6	4770.4	4730.1	
DVE/l milk[1]				308.51
Labour h/LU/year excluding land work[3]				34.9
Max DM uptake (kg/LU /d)[1]				18.9
Cost per LU (€)[2]				216
Milk price (€/l)[2] expected average price till 2028				0.355
Young stock/cow				0.73
VEM young stock (VEM/YS/d)				5603.85
DVE young stock (DVE/YS/d)				345
Minimum structural value				1

[1] (Federatie Nederlandse Diervoederketen, 2016)

[2] (Blanken et al., 2018)

[3] (Valacon, n.d.)

V. Fodder and concentrate parameters

	Grass permanent	Grass temporary	Maize silage	Sojaschroot bestendig: Rumi S	Soybean heated/roasted	Citrus pulp
VEM/kg	888	888	893	996	1417	974
DVE/kg	65	65	45.5	380	157	80
Structure	3.03	3.03	1.85	0.14	0.18	0.17
Cost €/kg	0.174	0.182	0.066	0.320	0.400	0.180
DS (kg/kg)	1	1	1	0.873	0.897	0.914
Saturation value	0.89	0.89	0.91	0.25	0.26	0.29
VEM cost (€/1000 VEM)	0.196	0.205	0.074	0.321	0.282	0.185

VI. Fertilisation

Table A 9. Maximum nutrient use space per ha for each crop (RVO, 2019e, 2018d).

	Max P (kg/ha)	Max N (kg/ha)
SP	60	120
WC	60	110
SO	60	170
CP	60	250
SB	60	150
CH	60	100
PE	60	30
WW	60	245
FA	60	0
WO	60	305
GP	60	385
GT	60	310
MS	60	160/180[1]

[1] 180 is allowed if the farm has derogation

Table A 10 (next page) Minimum nitrogen, phosphorous and potassium requirements of crops for each farm type (farm types are determined by their orientation (Production, Entrepreneurial, or Nature), size (Medium or Large), and intensity (Medium, or High) or Dairy). The last column lists nutrient supply indicated by van der Voort (2018), deviating values in the table are the sum of supplied nutrient through artificial fertiliser and manure based on Mandryk et al. (2014), N from manure was corrected with a working coefficient of 0.6.

		PMM	PMH	PLM	PLH	EMM	ELM	NLM	D	KWIN 2018
Seed potato	N	72	78	72	78	114	114	72	0	120
	P	60	60	60	60	60	60	60	0	60
	K	180	180	180	180	180	180	180	0	180
Winter carrot	N	54	54	54	54	175	175	175	0	110
	P	60	60	60	60	60	60	60	0	60
	K	180	180	180	180	180	180	180	0	180
Seed onion	N	125	48	125	48	133	133	140	0	170
	P	60	60	60	60	60	60	60	0	60
	K	180	180	180	180	180	180	180	0	180
Consumption potato	N	150	150	150	150	359	359	265	0	250
	P	60	60	60	60	60	60	60	0	60
	K	180	180	180	180	180	180	180	0	180
Sugar beet	N	120	102	120	102	122	128	122	0	150
	P	60	60	60	60	60	60	60	0	60
	K	50	50	50	50	50	50	50	0	50
Chicory	N	48	48	48	48	24	24	24	0	100
	P	0	0	0	0	0	0	0	0	0
	K	80	80	80	80	80	80	80	0	80
Green peas	N	27	27	27	27	87	87	87	0	30
	P	60	60	60	60	60	60	60	0	60
	K	80	80	80	80	80	80	80	0	80
Winter wheat	N	153	153	153	153	213	213	199	0	245
	P	0	0	0	0	0	0	0	0	0
	K	0	0	0	0	0	0	0	0	0
Fallow	N	0	0	0	0	0	0	0	0	0
	P	0	0	0	0	0	0	0	0	0
	K	0	0	0	0	0	0	0	0	0
Winter wheat + Oil radish	N	213	213	213	213	273	273	259	0	305
	P	0	0	0	0	0	0	0	0	0
	K	0	0	0	0	0	0	0	0	0
Grass permanent	N	165	165	165	165	165	165	165	310	165
	P	0	0	0	0	0	0	0	37.8	0
	K	0	0	0	0	0	0	0	0	0
Grass temporary	N	200	200	200	200	200	200	200	354	200
	P	0	0	0	0	0	0	0	37.8	0
	K	0	0	0	0	0	0	0	0	0
Maize silage	N	160	160	160	160	160	160	160	160	160
	P	60	60	60	60	60	60	60	60	60
	K	0	0	0	0	0	0	0	0	0

VII. Detailed results data

Table A 11. Simulated crop area in ha.

	Flevopolder				*Noordoostpolder*			
	NO	**MAX**	**EQUIT**	**MAX2**	**NO**	**MAX**	**EQUIT**	**MAX2**
SP	8507	16921	8599	10588	9513	14645	9883	10665
WC	5784	11807	5889	7866	6469	11292	6827	7621
SO	1495	645	1562	1772	1671	1011	1681	2082
CP	2581	662	2571	2443	2881	2122	2838	2732
SB	0	0	0	0	0	0	0	0
CH	5451	367	5211	3231	6102	1761	5743	4687
PE	5784	8678	5707	7866	6469	9503	6831	7621
WW	596	4	291	0	34	10	321	0
FA	405	137	613	1136	1043	416	1269	1170
WO	3422	371	3545	1206	4300	1071	3308	2628
GP	8325	975	8355	6661	4610	110	4306	3688
GT	0	3061	0	0	0	1644	7	0
MS	2081	807	2089	1665	722	228	799	919

Table A 12. Crop production in 1000 tons per polder. Yield of chicory is given in billion harvestable roots instead of 1000 tons.

	Flevopolder				*Noordoostpolder*			
	NO	**MAX**	**EQUIT**	**MAX2**	**NO**	**MAX**	**EQUIT**	**MAX2**
SP	296	594	299	368	332	511	345	371
WC	383	780	389	520	428	748	452	505
SO	104	43	105	124	116	71	117	146
CP	127	28	126	120	141	104	139	134
SB	0	0	0	0	0	0	0	0
CH	647	48	626	383	725	209	682	557
PE	35	53	35	48	40	59	42	46
WW[1]	34	1	34	10	37	7	31	22
FA	0	0	0	0	0	0	0	0
GP	70	7	70	56	39	1	36	31
GT	0	28	0	0	0	14	0	0
MS	27	10	27	21	9	3	10	12

[1] Includes the production of WO

VIII. Crop effective organic matter input and nutrient requirement comparison

Table A 13. Crop effective organic matter (EOM) input, average N and P requirement parameters, and EOM and N scores. The scores are the crop's value for EOM or N divided by the mean value of either all crops or all arable crops. A number below 1 indicates the crops' value is below mean, a number larger than 1 indicates an above average value.

	EOM input (kg/ha)	EOM score arable crops	EOM score all crops	Mean N requirement for all farm types (kg/ha)	N comparison to average arable crops	N comparison to all crops	Mean P requirement for all farm types (kg/ha)
Mean	1457			140			34
Mean arable crops[1]	1174	1	0.8	129	1.0	0.9	36
SP	875	0.7	0.6	95	0.7	0.7	60
WC	150	0.1	0.1	124	1.0	0.9	60
SO	500	0.4	0.3	117	0.9	0.8	60
CP	875	0.7	0.6	265	2.0	1.9	60
SB	1275	1.1	0.9	126	1.0	0.9	60
CH	650	0.6	0.4	57	0.4	0.4	0
PE	650	0.6	0.4	71	0.5	0.5	60
WW	2630	2.2	1.8	206	1.6	1.5	0
FA	500	0.4	0.3	0	0.0	0.0	0
WO	3630	3.1	2.5	233	1.8	1.7	0
GP	3975	3.4	2.7	165	1.3	1.2	37.8
GT	2575	2.2	1.8	200	1.5	1.4	37.8
MS	660	0.6	0.5	160	1.2	1.1	0

[1] Excluding GP, GT, and MS