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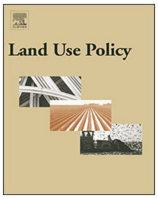

Projected vegetation changes are amplified by the combination of climate change, socio-economic changes and hydrological climate adaptation measures

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ABSTRACT

Climate change is projected to strongly affect the hydrological cycle, altering water availability and causing successive shifts in vegetation composition and distribution. To reduce potential negative effects on vegetation, policymakers may implement hydrological climate adaptation measures, which may -in turn- require land use changes to be successful. Policy driven land use changes should therefore be taken into account when evaluating climate change and adaptation effects on the water-vegetation system, but this is rarely done. To support such policy interventions, we applied a coupled land use – hydrology – vegetation model to simulate effects of (i) climate change, (ii) socio-economic change, (iii) hydrological measures and (iv) policy driven land use change, alone and in interaction, on vegetation communities in the Netherlands. We simulated two climate scenarios for 2050 that differed in predicted temperature (+0.9 °C and +2.8 °C) and precipitation changes (groundwater recharge +4% or −14%). The associated socio-economic scenarios differed in the increase of gross margins per agricultural class. The land use changes concerned agricultural changes and development of new nature areas from agricultural land. Individually, land use changes had the biggest effect on vegetation distribution and composition, followed by the hydrological measures and climate change itself. Our results also indicate that the combination of all four factors triggered the biggest response in the extent of newly created nature areas (+6.5%) and the highest diversity in vegetation types, compared to other combinations (max. +5.4%) and separate factors. This study shows that an interdisciplinary, coupled modelling approach is essential when evaluating climate adaptation measures.

1. Introduction

Climate change predictions indicate significant changes in the hydrological cycle (IPCC, 2013), including changes in precipitation patterns and in potential evaporation (Alexander et al., 2006; Rajczak et al., 2013; van Haren et al., 2013; Vautard et al., 2014). These changes may increase the risk of flooding and/or drought, depending on the region, thereby modifying water availability (Bakker and Bessembinder, 2007; Briffa et al., 2009; Arnell and Gosling, 2013; IPCC, 2013; Rajczak et al., 2013; Zolina et al., 2013). Water availability is an important environmental factor that drives plant species composition worldwide (Weltzin et al., 2003; Ordoñez et al., 2010; Bartholomeus et al., 2011; Douma et al., 2012b; Witte et al., 2012). Changes in water availability therefore also affect vegetation distribution and composition. Moreover, many agricultural practices are located on groundwater dependent lands and will be affected too. To reduce potential negative effects of climate change on these systems, policymakers intend to implement hydrological climate adaptation measures to ensure sufficient water availability for agriculture and plant communities. The goal of these measures is to increase the resilience of the water-vegetation system to climate change (Van der Knaap et al., 2015).

Successful implementation of the aforementioned hydrological

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measures in areas with multiple land uses may require policy-driven land use change. This is especially true for hydrological measures that lead to higher groundwater tables. Farmers with parcels that are susceptible to waterlogging, may find themselves in an unfavourable situation if such measures are implemented. They may be forced to take such parcels out of production or use them less intensively, and if so, they are likely to demand some kind of compensation. This, therefore, requires a sound land use policy to stimulate local support for these measures. Furthermore, land use will also develop in response to socio-economic changes, such as fluctuations in market prices, national and European policy, and internal dynamics such as farmers retiring with or without having a successor. Since land use changes are known to affect local and regional hydrology (Qiu et al., 2011), it is essential to take them into account to successfully simulate the effects of climate change and hydrological measures on hydrology, agricultural productivity, and vegetation.

Until recently most land use, hydrology and vegetation simulation-based studies focused on just one or two of the aforementioned factors. Models that combine multiple factors mostly take land use as a static condition, or use exogenous scenarios specifying land use change, which interact with hydrological processes through simplified or advanced hydrological models (Fohrer et al., 2001; van Roosmalen et al., 2009; Memarian et al., 2014). Moreover, hydrological changes that are projected upon vegetation communities do not take potential changes in land use into account, although land use changes can affect vegetation composition and distribution (Bakker et al., 2015c).

These previous studies show that the individual factors (i.e. land use and hydrology) can have profound effects on vegetation distribution and composition. However, due to interactions among these factors the combined effect may even be larger than expected based on the sum of the individual effects, but so far this is unknown. Since land use changes and the associated changes in hydrology and vegetation are all interdependent, a fully coupled, interdisciplinary land use – hydrology – vegetation simulation is required to better evaluate impacts of climate and socio-economic change, hydrological measures, and land use policy on vegetation distribution and composition. In this study, we developed and present such an approach and use this to test the necessity of using an interdisciplinary approach. This study is therefore a methodological research. We used three models: a hydrological model (MODFLOW-MetaSWAP) which has been calibrated and validated previously and is used by regional water managers in the Netherlands; an agent-based land use model (RULEX) which has been specifically developed for the Netherlands and which has been calibrated for our case-study region; and the trait-based vegetation model PROBE to simulate vegetation responses. These models were coupled and used to simulate the separate and combined effects of climate and socio-economic change, hydrological measures, and land use policy on vegetation distribution. Through this integration, we aimed to answer the following research questions:

- What is the combined effect of climate change, land use change (both socio-economic and policy driven), and hydrological measures on predicted vegetation distribution and composition?
- Which of these factors has the biggest effect?

We expect that the combined effect triggers the biggest changes in predicted vegetation distribution and composition.

2. Methods

2.1. Modelling framework and general approach

To assess the combined effects of socio-economic developments, climate change, hydrological measures and land use policy on land use change, hydrology, and vegetation, we coupled an agent-based land use model to a hydrological model and a vegetation model (Fig. 1). We assessed these different factors in a step-wise nested approach. In this modelling framework, vegetation responds to climate change, both directly and indirectly through hydrological changes (Step 1). The hydrological changes result in the first instance from climate change and the implementation of hydrological measures. The combined hydrological effects on vegetation are simulated in Step 2. The hydrological changes also affect land use. In turn, land use change will affect hydrological conditions, as different agricultural land uses (crops) have different evapotranspiration demands. Land use is also influenced by climate and socio-economic change: the demand for crops is driven by changes in climate (via biofuel demand), demographic developments, and diet changes, while supply is determined by growing conditions, which are also affected by climate change. These effects of the land use changes on vegetation are simulated in Step 3. Finally, land use policy measures allow farmers to take parcels out of production that are negatively affected by the hydrological measures, by selling them to a collective that is raised for this purpose (more information is given below). We combined these policy impacts with climate change, socio-economic change and hydrological measures in Step 4 to simulate the final vegetation response.

Within this conceptual framework, we implemented two climate change and associated socio-economic scenarios, which are based on the A1B, A2 and B1 scenarios developed by the IPCC (IPCC, 2007). They differ in climatological and socio-economic attributes and were downscaled to our case study area. We based our hydrological measures on Dutch policy measures aiming at increasing the water availability for both agriculture and nature areas in stream valley catchments. As these stream valleys are mostly used for farming, land use adaptation in these areas may be needed. Hereto, we implemented policy measures which were used to stimulate the development of agricultural land into nature areas. This resulted in nine scenarios, including a reference scenario. The modelling steps and the climate change scenario have been included in the scenario names (Table 1). The various components and scenarios of our approach are explained in more detail below (Sections 2.3–2.6).

2.2. Case study

We applied our integrated models to the stream valley catchment of the 'Tungelroyse Beek' (approx. 157 km^2), located in the southeastern part of the Netherlands (Fig. 2). Policy makers from the province and water boards expressed the ambition to increase water availability in this stream valley to anticipate on negative effects of climate change. These ambitions were based on the Dutch Administrative Agreement for Water Affairs (Ministry of Infrastructure and the Environment, 2011), which requires the development and implementation of regional targets for groundwater and surface water regimes before 2020. These targets aim at developing and maintaining a stable and resilient water system to support the allocated functions. The implemented land use policy was inspired by the European set-aside policy (European Commission). We formulated, in close collaboration with the policy makers of the area, a measure to accommodate those farmers that would be disadvantaged by the implementation of the hydrological measures. Although the set-aside legislation has been abolished in 2009, it serves as an example of how farmers, through policy, can contribute to nature development.

Agricultural land use is the dominant land use (ca. 67%, including grasslands), followed by urban and nature areas (both ca. 16%) and open water (ca.1%) (Straatman and Luijendijk, 2002). Mean annual temperature for the period 1980–2010 is 10 °C, with the mean highest temperature in July (18 °C) and mean lowest temperature in January (3 °C). The mean annual precipitation ranges from 750 to 775 mm and is evenly distributed over the year. The mean annual evaporation ranges from 570 to 580 mm and the yearly precipitation surplus ranges from 160 to 200 mm (KNMI, 2011). In the past, the catchment has been extensively drained for agricultural purposes, which led to a severe

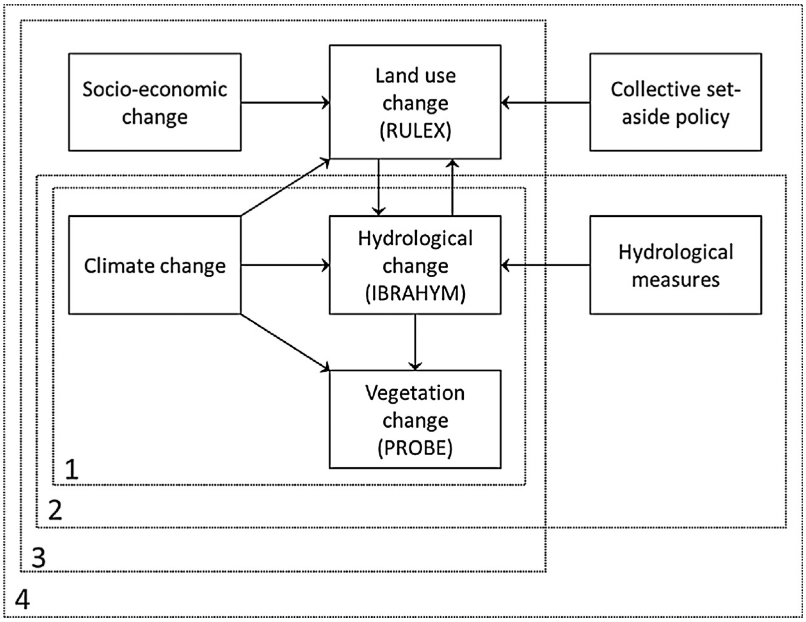

Fig. 1. Overview of our conceptual framework. The models that we used are indicated between brackets. In a step-wise approach, these models are used to simulate vegetation responses to: (step 1) climate change and climate driven hydrological changes; (step 2) as step 1, but with additional hydrological measures; (step 3) as step 1, but with additional climate and socio-economic driven land use changes and its subsequent effects on hydrology; (step 4) a combination of step 2 and 3 with the additional collective set-aside policy driven land use changes and its subsequent effects on hydrology. The interaction between land use and hydrology is simulated once (hydrology → land use → hydrology) instead of as an iterating process, due to computational limitations.

desiccation of the nature areas (Straatman and Luijendijk, 2002).

2.3. Global change scenarios

2.3.1. Climate change

The two climate change scenarios that we implemented were based on the A1B, A2 and B1 storylines as developed by IPCC (2007). These scenarios have been downscaled to the Netherlands by the Royal Netherlands Meteorological Institute (van den Hurk et al., 2006; IPCC, 2007). The scenarios represent changes in 2050 compared to the conditions in 1990. One scenario represents an increase in precipitation in both summer (+3%) and winter (+4%) (Wet scenario, based on B1, referred to as W), and the other represents a decrease in summer precipitation (−19%) and an increase in winter (+14%) (Dry scenario, based on A1B and A2, and referred to as D). The Wet scenario includes a global temperature increase of 1 °C and a regional temperature increase of 0.9 °C. The Dry scenario represents a global increase of 2 °C and a regional increase of +2.8 °C. Potential summer evaporation increases in both scenarios, by 3% in the Wet scenario and by 15% in the Dry scenario. The meteorological conditions correspond to an average groundwater recharge for the entire catchment of 184 mm for the reference scenario. Groundwater recharge was 191 mm year^{-1} (+4%) in the Wet scenario and 159 mm year^{-1} (−14%) for the Dry scenario.

2.3.2. Socio-economic change

Land use change is partly driven by climate change but perhaps even more by changes in markets and national and international policies. Since at the global level, climate change and economic change are intertwined, each climate scenario was linked to a particular socio-economic scenario. The Wet scenario was combined (following Riedijk et al., 2007) with the B2 storyline, which assumes an increase in energy efficiency and income equality, while employment and labour productivity growth both decline. For the Netherlands, this storyline is expected to result in a relatively strong increase in prices for arable products, while prices for dairy and meat products are likely to experience a more moderate growth (Wolf et al., 2011; de Vries et al., 2013; Paas, 2013; Kanellopoulos et al., 2014). The Dry scenario is associated with a combination of the A1B and A2 storyline, showing a strong increase of employment and labour productivity growth; income inequality and consequently the use of fossil-fuels increases, decreasing energy efficiency. In the Netherlands, this is expected to result in a stronger increase of all agricultural prices than in the socio economic scenario that was coupled to the Wet scenario, and in particular for arable and horticulture products (Wolf et al., 2011; de Vries et al., 2013; Paas, 2013; Kanellopoulos et al. 2014). Finally, according to the B2 storyline, ambitions (and thus budgets) for nature development are higher in the scenario associated with wetter conditions than in the scenario associated with drier conditions. Summarizing, according to

Table 1
Overview of the nine scenarios. The modelling step coinciding with Fig. 1 is given in the first column (*Step)*. The scenario characteristics are given in the second column (*Scenario)* and the section where the scenarios are described is shown in the third column (*Section)*. The *Scenario name* which is used throughout this paper is shown in the fourth column, followed by the three characteristic differences between the scenarios. The *Climate change* column indicates the type of scenario implemented (*Wet* or *Dry)*. The *Hydrological measures* refer to the implementation of the hydrological climate adaptation measures to increase water availability. The *LU change* refers to whether or not changes in the land use (LU) patterns were simulated. *Policy* in the *Scenario* column refers to the implementation of the collective set-aside policy.

Step	Scenario	Section	Scenario name	Climate change	Hydrological measures	LU change
	Reference		Reference	No	No	No
1	Wet climate	2.3.1	1W	Wet	No	No
1	Dry climate	2.3.1	1D	Dry	No	No
2	Wet climate + measures	2.4.1	2W	Wet	Yes	No
2	Dry climate + measures	2.4.1	2D	Dry	Yes	No
3	Wet climate + LU	2.3.2	3W	Wet	No	Yes
3	Dry climate + LU	2.3.2	3D	Dry	No	Yes
4	Wet climate + measures + LU + Policy	2.4.2	4W	Wet	Yes	Yes
4	Dry climate + measures + LU + Policy	2.4.2	4D	Dry	Yes	Yes

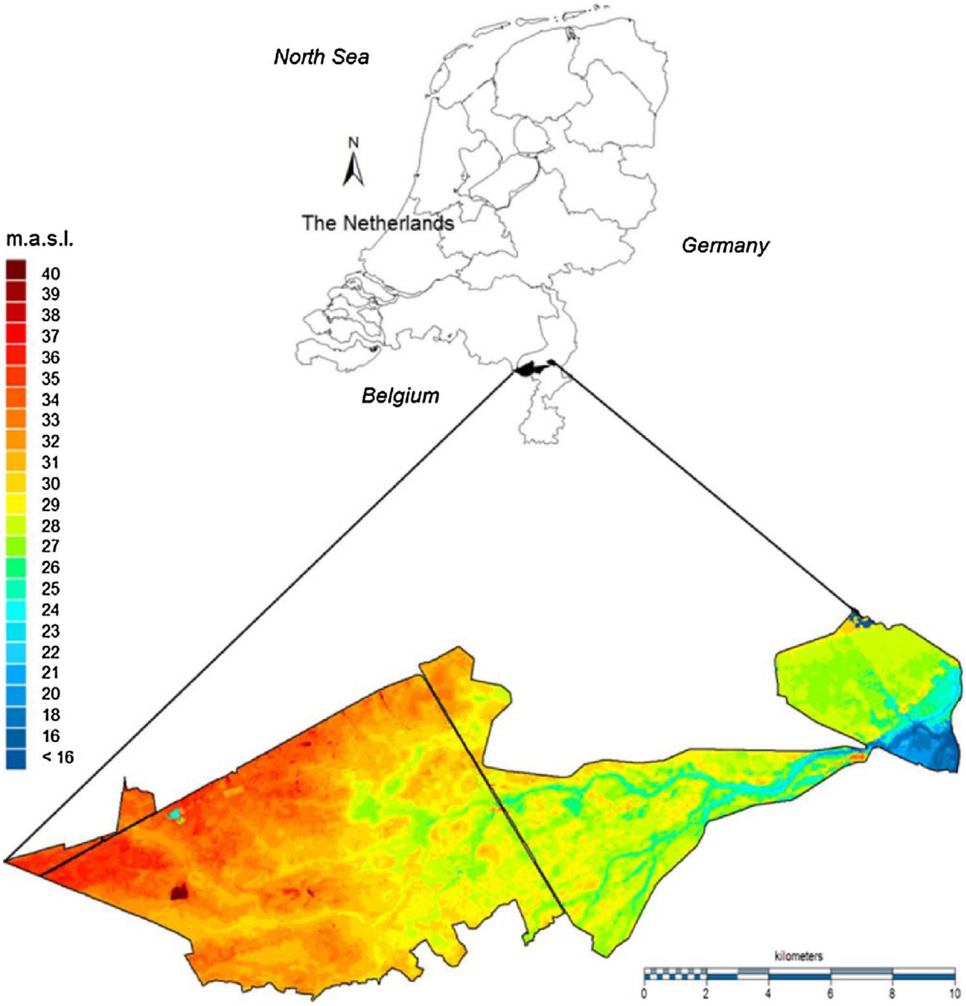

Fig. 2. The case study area of the Tungelroyse Beek. The figure in the lower panel indicates the metres above sea level (legend on the left).

these scenarios, economic conditions for farmers will improve in the Netherlands, although local hydrological changes may disrupt this. For more details about the two socio-economic scenarios, see Bakker et al. (2015a) and Kros et al. (2015). These socio-economic changes are implemented and expressed in model steps 3 and 4 (Table 1).

2.4. Climate adaptation scenarios

2.4.1. Hydrological measures

To develop and maintain a stable and resilient water system, we implemented a multitude of hydrological adaptation measures, proposed by the local water managers, to increase water availability for agriculture and nature areas. Measures included consolidation of groundwater extractions and widening water courses in agricultural areas and removing small ditches and restrict drainage in nature areas. The groundwater tables around the streams were allowed to rise considerably, without taking land use into account so that the groundwater table increase was not constrained by land use restrictions. Model adjustments included turning off irrigation and removing level-regulated pipe drainage. van der Knaap et al. (2015) provide an elaborate description of the hydrological measures and the associated model adjustments. The measures were combined with the Wet and Dry scenario and were included in steps 2 and 4 (Table 1).

2.4.2. Collective set-aside policy

The traditional implementation of the set-aside policy required farmers to set aside a certain percentage of their land. Farmers generally selected their least favourable agricultural parcels, and because they did this individually, the resulting pattern of set-aside was scattered. However, in line with new insights of CAP (Common Agricultural Policy) implementation, collective schemes are probably more efficient in achieving synergies with CAP objectives (in this case reducing production) and other objectives (e.g. improving biodiversity or facilitating rewetting schemes). Therefore, we formulated a policy in which all farmers are required to set aside 7% of their land or to buy off this obligation by joining a collective to which they make a financial contribution that is equivalent to the rent of the land that they would otherwise have set-aside. The farmers' collective uses this money to purchase land from other farmers that are disadvantaged by the implementation of the hydrological measures. The collective set-aside legislation was combined with the hydrological measures, socio-economic land use changes and the Wet (scenario 4W) and Dry scenario (scenario 4D).

2.5. Models

2.5.1. Hydrology model

We used the spatially-explicit hydrology model IBRAHYM to simulate the hydrological processes. This model is also applied by water managers in the case study area, and is updated and calibrated regularly. Outputs from IBRAHYM served as hydrological input for our land use model by simulating the effects of climate change and climate adaptation measures on hydrology (results of which will not be further discussed here). The model combines a fully coupled model for the saturated and unsaturated zone. The saturated zone was modelled with MODFLOW (McDonald and Harbaugh, 1988) and the unsaturated zone and surface water was simulated with SIMGRO (van Walsum and Groenendijk, 2008). The hydrogeological schematisation was based on the Dutch geo-hydrological REGIS model (TNO-NITG, 1998) and physical soil properties were based on 23 soil physical units as derived from the Dutch soil map (Wösten et al., 2001). The soil surface elevation was based on the general elevation database of the Netherlands which has a spatial resolution of 5 m (van der Sande et al., 2010). The location of water courses and drainage levels were based on the Dutch topographic map (scale 1:10,000) and on additional information provided by the regional water managers. The models have a spatial resolution of 25 m and a temporal resolution of one day. The modelled phreatic groundwater heads in IBRAHYM are approximately 15 cm lower than the observed data. This is mostly caused by uncertainties in the input data, such as local outliers in subsurface parameters and inaccurate position and permeability of faults (Vermeulen et al., 2007). The uncertainty of the difference in groundwater levels between scenarios will be considerably lower, since systematic errors are levelled-off when subtracting model results.

2.5.2. Land exchange model

We applied the agent based model RULEX (RUral Land EXchange) which simulates rural land use change as a result of land transactions among farmers, and between farmers and nature conservation organizations. These transactions are the dominant mechanism driving land use change in the Netherlands (Bakker et al., 2015b). RULEX runs on an annual time scale. The model uses the spatial configuration of existing farms, parcels and nature reserves as a starting point for simulations. Land transactions over the subsequent year depend on the different land-market strategies of farmers and nature conservation organizations. Each farmer-agent chooses between a strategy focusing on expanding, intensifying, shrinking, or doing nothing. The selection of these strategies occurs according to an empirically-derived, probabilistic function of a farmer agent's age, farm area, economic farm size, and farming type. The model simulates five farming types, being: Arable, Dairy, Mixed, Pigs and Poultry, and Horticulture. Nature conservation organizations, which actively purchase agricultural land in the area in order to realize ecological objectives, are by definition expanders. In RULEX, parcels are exchanged between sellers (always farmer agents) and buyers (farmer agents and nature organizations agents). Exchange of parcels depends on the willingness to pay (WTP) by the potential buyer and the willingness to accept (WTA) by the seller. WTP and WTA are primarily determined by distance to (potential) owner (be it a nature organization's existing property or a farmer's farmstead). In addition, for farmer agents, the WTA and WTP will drop when agricultural productivity is negatively affected by either too wet or too dry conditions. For nature conservation organizations, parcel hydrological properties also affect the WTP, but in a different way, as nature organizations favour wet conditions while farmers do not.

After each time step (year), all agent attributes and ownership links are updated, and another round of transactions begins. Each year, farmer agents choose only one of the four strategies, but during a model run agents may alternate strategies. Farm succession is considered when a farmer agents reaches retirement age, but only occurs if a farm surpasses a minimum economic size. Economically marginal farmer agents have no successor, and continue farming until they die (a probabilistic function based on life expectancy tables by WHO for the year 2009; the base year used in the model). Changes in economic farm size of all simulated farms are, next to changes arising from land transactions, subject to overall economic developments. These trends, as specified in the scenarios, are imposed on all individual farmer-agents in RULEX. A detailed description of RULEX and its calibration can be found in Bakker et al. (2015b).

The trends of the W-scenario of steps 3 and 4 increase the probability that arable farmer agents choose for expanding or intensifying, and decrease the probability that they choose for selling land. The same is true but to a lesser extent for livestock farmer agents. The socio-economic trends of the D-scenarios of steps 3 and 4 cause the expanding/intensifying behaviour of all farmers to increase even more, resulting in less land becoming available for nature development. The implemented set-aside rules do not differ between the Wet and Dry scenarios, but since the collective is composed of expanding and intensifying farmer agents (i.e. those that want to buy-off their set-aside obligation), the collective will grow as agricultural prices go up. This will increase the collective's financial resources. This could increase the amount of new nature areas, provided that enough shrinking farmer agents are present to sell their land to the collective.

In this study, the probabilistic function that relates strategy selection to farmer agent's attributes such as age, size and farm type was recalibrated for the case study area. Furthermore, RULEX was adapted so that the set-aside policy stimulating land use adaptation could be simulated. Thereto, the farmers' collective was introduced in RULEX as a new agent, whose main purpose is to buy agricultural parcels that lose their production value due to the rewetting measures, and use it for nature development. Since little empirical information on such a collective was available, decision rules were derived from interviews with local experts. The following rules were established:

- the collective is composed of farmer agents who are interested in buying off their set-aside obligation. These were assumed to be farmer agents with a high willingness to expand (probability on expanding > 0.7), and who have no low-productivity parcels (i.e. all parcels produce > 80% of the potential yield);
- the collective places a market-conform bid (€40,000 per hectare) on each parcel that is placed on the market, where the implementation of the hydrological measures results in productivity decline of 5 percentage point or more;
- the collective's purchasing power is equivalent to 7% (the set-aside requirement) of the total land area of all participating farmers.

2.5.3. Vegetation model

The vegetation model PROBE (PRObability-Based Ecological target model) (Douma et al., 2012a; Witte et al., 2015) simulates the occurrence probability of vegetation types based on abiotic properties and vegetation characteristics. It requires data on soil type, groundwater levels, seepage fluxes, and land use and uses transfer functions to simulate environmental drivers of vegetation. These are root respiration stress due to anoxic conditions, drought stress, soil pH, and nutrient availability (as indicated by P mineralization rate). The transfer functions were generated with a pre-processor (Bartholomeus and Witte, 2013) and were specifically derived for this case study area as a function of the local climate (data obtained from the Royal Netherlands Meteorological Institute). The environmental drivers translate into predicted community-mean vegetation characteristics, through process-based relationships. The vegetation typology we used defined vegetation units based on the vegetation characteristics (i) structure (which indirectly accounts for light availability), (ii) moisture, (iii) nutrient availability and (iv) acidity (Witte and Van der Meijden, 2000; Runhaar et al., 2004). Each vegetation type has its own specific position along these axes. An overview of all vegetation types modelled in the case study area is shown in Table 2. The letter in the vegetation code represents the influence of structure ("short vegetation" (K) and "high vegetation" (H)), the first number represents the position along the moisture axis and the second number represents the combined influences of nutrient availability and acidity (Witte et al., 2007). The local occurrence probabilities of a vegetation type is calculated based its position in comparison to the predicted set of community-mean vegetation characteristics (Witte et al., 2007). This procedure accounts for the possibility that vegetation types partly share the same habitat requirements. The vegetation type with the highest probability is assumed to occur.

We validated the vegetation types as modelled in the reference scenario with existing data on vegetation type distributions to evaluate

Table 2
Overview of the vegetation codes as modelled by PROBE in the case study area. The area of each vegetation type in the reference scenario is indicated in the second column (in hectares and with percentage of the total nature area in brackets). The description of the vegetation codes is given in the third column.

Vegetation code	Area in ha (%)	Description
A11	0.1 (< 0.01)	Semi-terrestrial vegetation in stagnant, oligotrophic, acid water
K21	0.5 (0.02)	Herbaceous vegetation on wet, oligotrophic, acid soil
K22	5.3 (0.23)	Herbaceous vegetation on wet, oligotrophic, neutral soil
K27	0.0	Herbaceous vegetation on wet, mesotrophic soil
K41	19.3 (0.85)	Herbaceous vegetation on moist, oligotrophic, acid soil
K42	2.8 (0.12)	Herbaceous vegetation on moist, oligotrophic, neutral soil
K47	9.0 (0.39)	Herbaceous vegetation on moist, mesotrophic soil
K61	176.3 (7.71)	Herbaceous vegetation on dry, oligotrophic, acid soil
K67	6.4 (0.28)	Herbaceous vegetation on dry, mesotrophic soil
H21	11.8 (0.51)	Forests and shrubs on wet, oligotrophic, acid soil
H22	4.4 (0.19)	Forests and shrubs on wet, oligotrophic, neutral soil
H27	59.9 (2.62)	Forests and shrubs on wet, mesotrophic soil
H41	73.5 (3.22)	Forests and shrubs on moist, oligotrophic, acid soil
H42	3.4 (0.15)	Forests and shrubs on moist, oligotrophic, neutral soil
H47	364.8 (15.97)	Forests and shrubs on moist, mesotrophic soil
H61	1,532.9 (67.09)	Forests and shrubs on dry, oligotrophic, acid soil
H62	1.7 (0.07)	Forests and shrubs on dry, oligotrophic, neutral soil
H67	13.1 (0.57)	Forests and shrubs on dry, mesotrophic soil

if the model predicted the observed vegetation type (Appendix A). We found that in 80.4% of the nature areas, the modelled vegetation type matched the one as found in the field. In 12.2% there was no match and 7.4% of the data could not be validated due to data restrictions.

2.6. *The interaction between land use change and hydrology*

To evaluate the effects of climate change, hydrological measures, and land use change on hydrology another round of IBRAHYM simulations was run. To use the land use maps generated by the RULEX model for IBRAHYM we had to disaggregate the land use classes from RULEX into a wider range of land cover types for the hydrological modelling, being: pasture, corn, potatoes, beets, cereals, other agriculture, and orchards. Based on the original land use information, we calculated the probability that a RULEX class corresponds to a particular hydrological land use type. For example, a land parcel in RULEX with a land use type 'Arable' can be either potatoes, beets, cereals or other agriculture. For every cell, we checked in the reference run whether the RULEX land use class corresponded with one of the possible hydrological land use types in that cell. If so, that cell was given its original hydrological land use type. If not, it was assigned one of the four possible land use types, based on chance (25% chance of each of the classes). An overview of the conversion of land use classes is shown in Table 3. The same approach was applied to the scenarios, but only if the RULEX class changed. Arable land that remained Arable, had the same hydrological land use type in the reference run as in the corresponding scenario run. The new nature areas were all classified as short, herbaceous vegetation (i.e. any of the K classes from Table 2). The exact vegetation type depended on the local soil and hydrological conditions.

In the subsequent hydrological simulations, no surface water component was implemented (using MODFLOW-metaSWAP instead of MODFLOW-SIMGRO). As a consequence of this model choice, the surface water levels had to be implemented as non-dynamic data (but with a winter and summer stage). Water availability for the surface water was therefore not taken into account. All other model components of the saturated and unsaturated zone are similar to the previously mentioned IBRAHYM model.

Table 3
Conversion of the RULEX land use classes into the hydrological land use classes.

RULEX land use class	Hydrological land use class
Dairy	50% pasture/corn
Arable	25% potatoes/beets/cereals/other agriculture
Horticulture	50% pasture/orchard
Pigs & Poultry	16.7% pasture/potatoes/beets/cereals/other agriculture/orchard
Mixed	16.7% pasture/potatoes/beets/cereals/other agriculture/orchard

3. Results

3.1. *Step 1: climate change*

Climate change alone had little effect on the hydrology in our case study catchment. The mean lowest and highest groundwater tables hardly changed in the Wet scenario (scenario 1W) (median of 0 and +3 cm, respectively) (Table 4). The changes were slightly bigger in the Dry scenario (scenario 1D), where the mean lowest groundwater table (MLGT) decreased on average with 8 cm (median of −7 cm, 1st and 99th percentiles of −1 and −21 cm, respectively) but the mean highest groundwater table (MHGT) hardly changed (median of 0 cm, Table 4). As shown by the extreme percentiles, the local changes were bigger than the mean change for the entire catchment (Appendix B).

The small hydrological changes triggered minor changes in the dominant vegetation types in the nature areas (Figs. 3 and 4, Appendix C). In the scenario 1W, the biggest increases were for forest and shrublands of wet, oligotrophic, acid and mesotrophic soils (+0.1 and +0.7 percentage point, respectively) and forest and shrublands of moist, oligotrophic, acid soils (+0.1 percentage point), mostly at the expense of forest and shrublands of moist, mesotrophic soils and forest

Table 4
Changes in mean lowest and highest groundwater table (MLGT and MHGT, respectively) compared to the reference situation. The median, 1st and 99th percentiles are shown. Changes are in centimetres, ' + ' indicates an increase of the groundwater table, ' − ' indicates a decrease. For a description of the scenarios, see Table 1.

	MLGT				MHGT			
Scenario	mean	1st	median	99th	mean	1st	median	99th
1W	+1	+4	0	−1	+4	+10	+3	0
1D	−8	−1	−7	−21	−1	+3	0	−13
2W	+20	+123	+11	−11	+28	+139	+19	−10
2D	+10	+114	+3	−23	+23	+133	+16	−16
3W	+1	+13	+1	−3	+3	+16	+3	−3
3D	−8	−1	−7	−21	−1	+4	0	−14
4W	+19	+135	+11	−11	+24	+145	+15	−13
4D	+10	+125	+3	−24	+20	+139	+12	−19

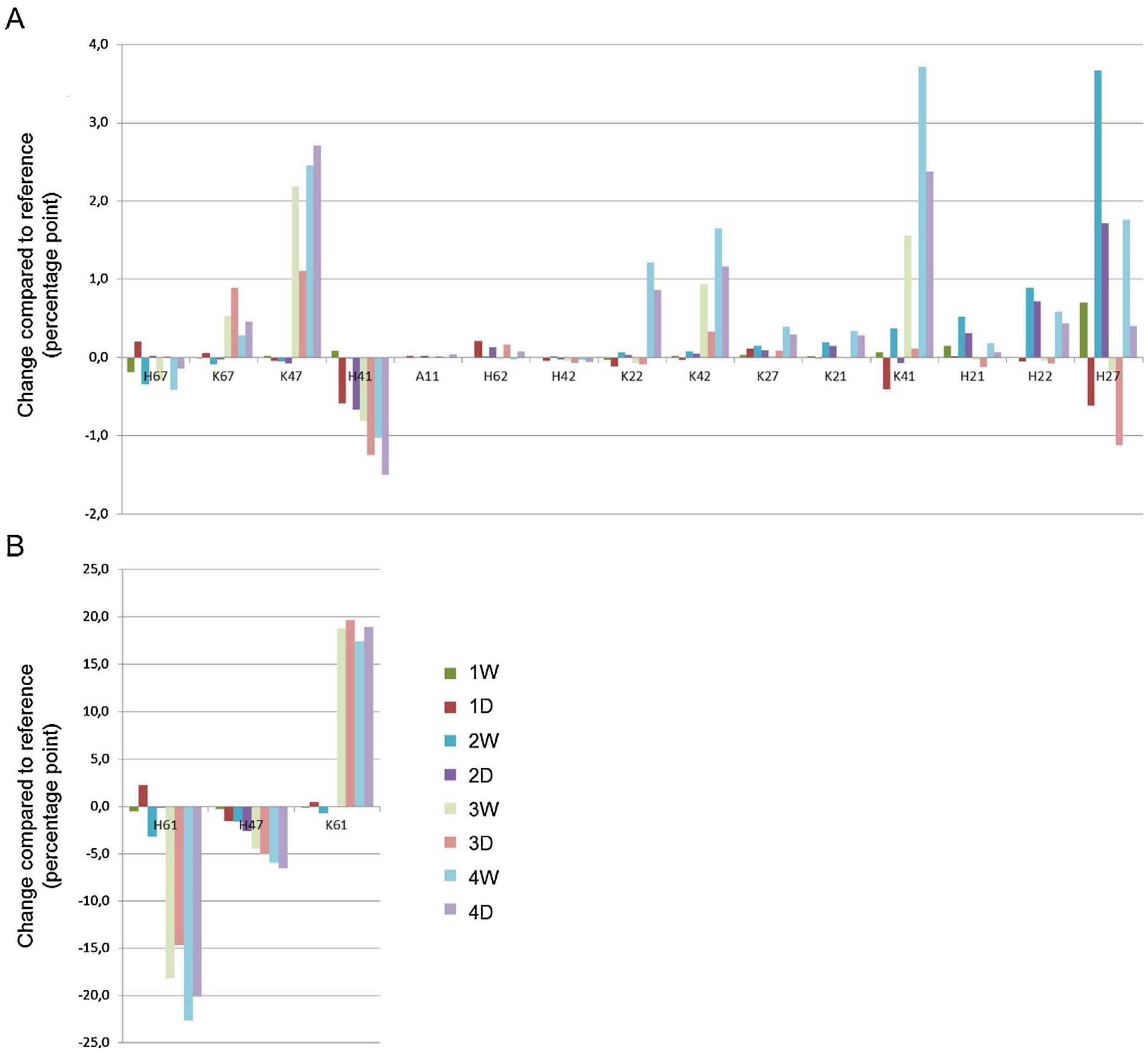

Fig. 3. Vegetation changes in the nature areas per vegetation type compared to the reference scenario, in percentage points. The x-axis shows the vegetation types (see Table 2 for explanation). The vegetation types are divided over two panels to improve clarity of the graph. Panel A shows the changes < 5%, which are mostly vegetation types that are not abundant on a catchment scale. It also includes vegetation types that are rare (K21, K22, K41 and K42) and are protected under the European Habitat Directive (see also Section 4.1). Panel B shows the vegetation types that were dominant in all scenarios and show the biggest changes (> 5%).

and shrublands of dry, oligotrophic, acid and mesotrophic soils (−0.03, −0.04 and −0.2 percentage point respectively). The number of different vegetation types remained the same as in the reference scenario (17 types). The changes in dominant vegetation types were slightly bigger in scenario 1D, where especially herbaceous vegetation and forest and shrublands of dry, oligotrophic, acid soils increased (+0.5 and +2.3 percentage point respectively). The biggest decreases occurred in the forest and shrublands of moist, mesotrophic soils (−1.5 percentage point) and forest and shrublands on wet, mesotrophic soils and moist, oligotrophic, acid soils (both −0.6 percentage point). The number of different vegetation types increased with one to 18.

3.2. *Step 2: climate change and hydrological measures*

In contrast to the impact of climate change alone, the implementation of the hydrological measures led to a considerable increase of the groundwater table. In both climate scenarios, the MHGT increased on average with 24 cm. The MLGT increased with 20 cm in the Wet scenario (scenario 2W) and with 10 cm in the Dry scenario (scenario 2D) (Table 4). The local differences were large, as shown in the percentiles; +123 cm and −11 cm for the 1st and 99th percentiles of the Wet scenario, and +114 cm and −23 cm for the 1st and 99th percentiles in the Dry scenario. Furthermore, the seepage fluxes changed considerably since a large part of the stream switched from a receiving stream to an infiltrating stream (Appendix B).

The subsequent vegetation responses in scenario 2W included an increase of all wet forest types (oligotrophic, acid +0.5; oligotrophic, weakly acid +0.9 and mesotrophic +3.7 percentage point) and a decrease of moist and dry forest types (moist, mesotrophic −1.6; dry, oligotrophic, acid −3.2 percentage point) (Figs. 3 and 4, Appendix C). One extra vegetation type was simulated compared to the reference scenario, making a total of 18. The wet forest types also increased in scenario 2D, but to a lesser extent than in scenario 2W (oligotrophic, acid +0.3; oligotrophic, weakly acid +0.9 and mesotrophic +1.7 percentage point). The biggest decreases occurred here in the moist forest types (oligotrophic, acid −0.7; mesotrophic −2.6 percentage point). Four extra vegetation types were simulated, coming to a total of 21 vegetation types.

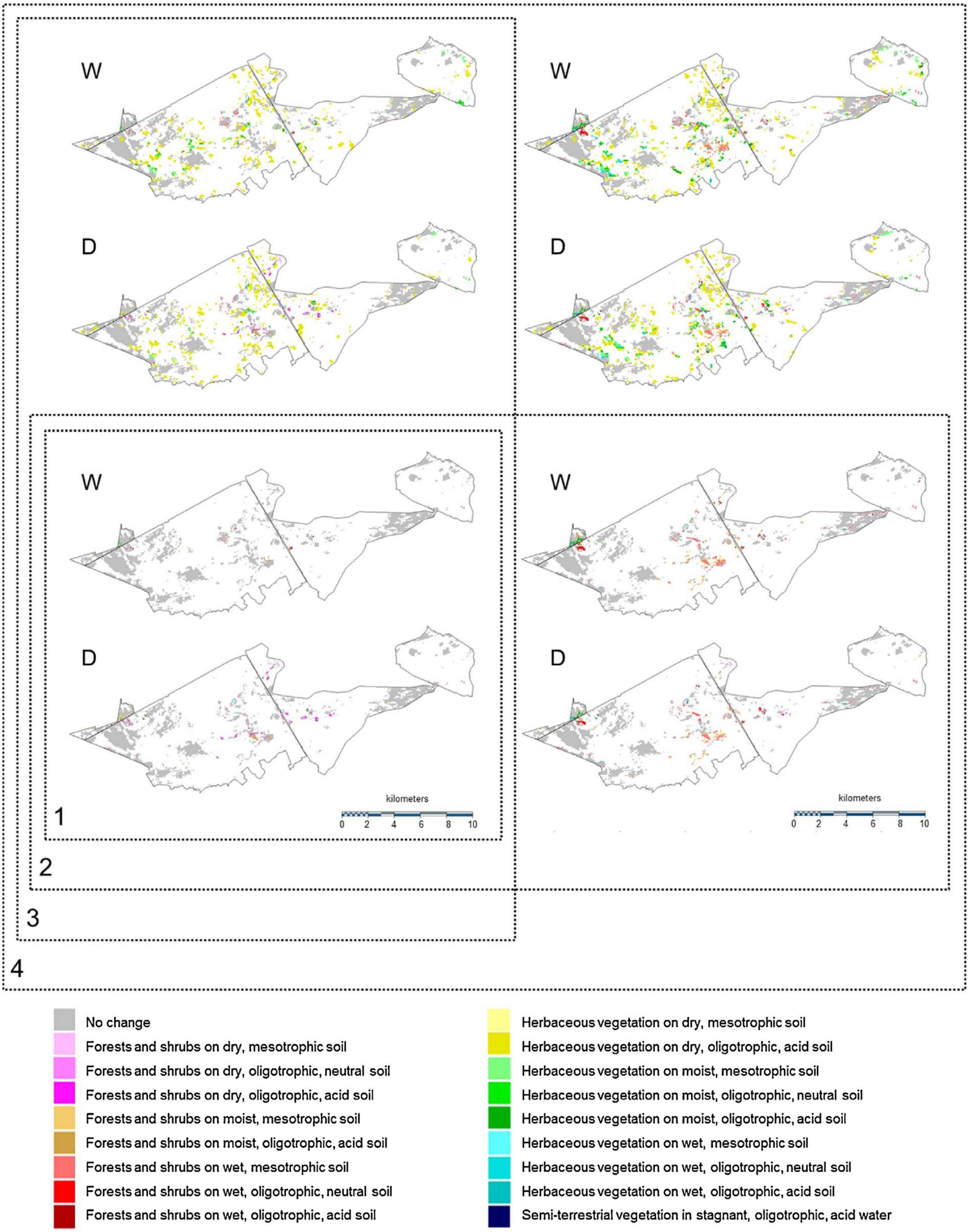

Fig. 4. Overview of the changes in vegetation types, compared to the reference scenario. Only the nature areas are shown (current and the new ones). The grey areas indicate no change, compared to the reference scenario. Changes in vegetation type are given the colour of the new vegetation type (see Legend). The figures are placed in the boxes of the subsequent modelling steps (see also Fig. 1). The "W" and "D" indicate the Wet and Dry scenario, respectively.

3.3. *Step 3: climate and socio-economic change*

The land use change that was projected by RULEX in response to climate and socio-economic changes in scenarios 3W and 3D concerned the development of new nature areas (Fig. 5). The new nature was the only land use type that increased in the Wet scenario (+5.4 percentage point). All other land uses decreased in occurrence, especially the pastures (−3 percentage point). In the Dry scenario, both new nature areas (+4.7 percentage point) and other agriculture (+0.4 percentage point) increased in area. All other land uses decreased, also here especially the pastures (−3 percentage point).

These land use changes hardly affected the average groundwater

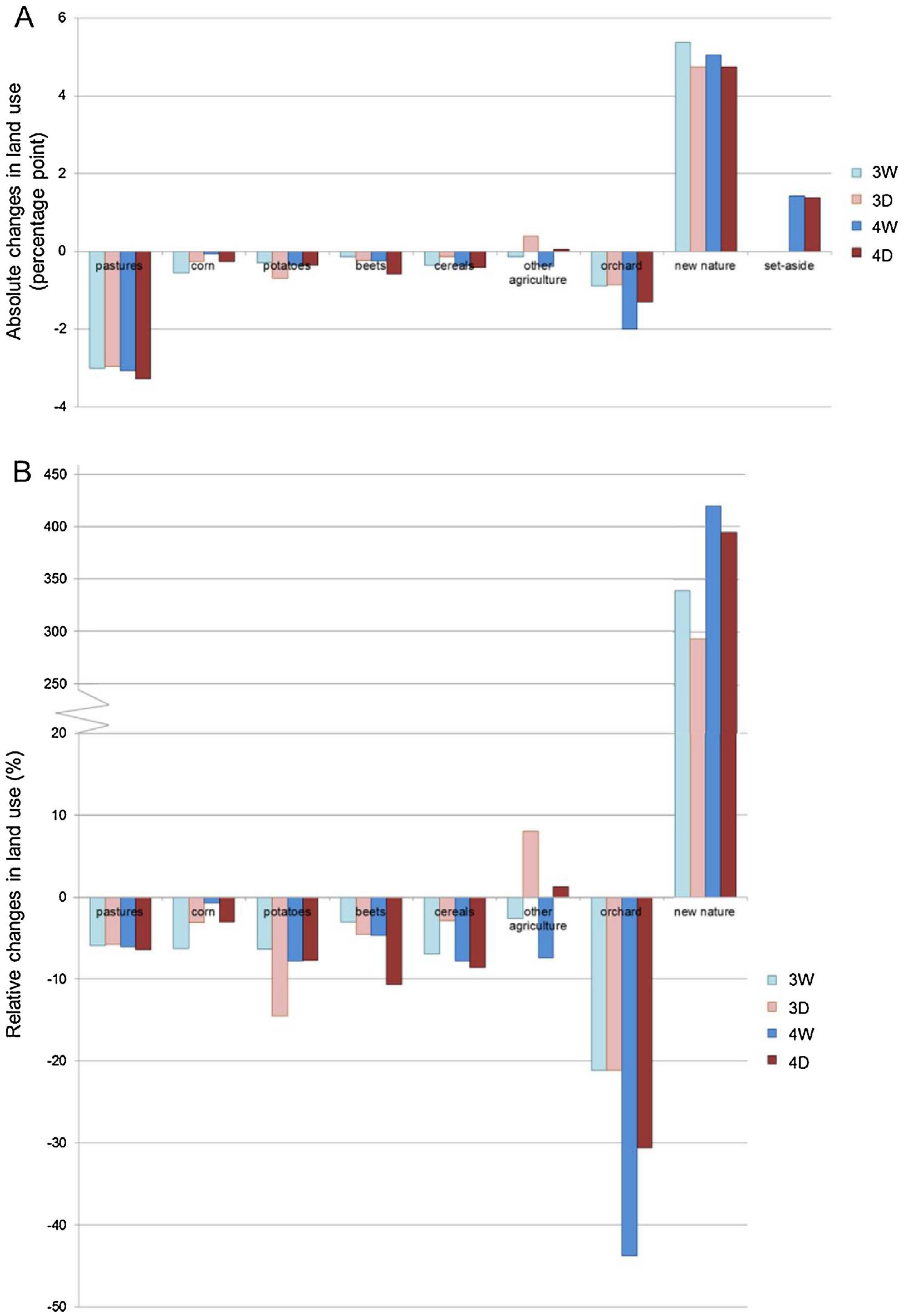

Fig. 5. The changes in land use for the entire catchment, compared to the reference scenario in absolute changes (panel A) and in relative changes (panel B). For specification of the scenario names, see Table 1. In Panel B the*new nature* category refers to the increment of new nature compared to already existing nature. Set-aside increases from 0% in the reference scenario, which makes it therefore not possible to show its relative increase in panel B.

tables (Table 4). The local changes in the Wet scenario (scenario 3W) were however larger, as indicated by the 1st and 99th percentiles. These were −13 cm to +3 cm for the MLGT and −16 cm to +3 cm for the MHGT. In the Dry scenario (scenario 3D), the range of change of the MLGT did not differ from the scenarios without land use changes (Table 4).

The new nature areas that were created because of nature conservation organizations purchasing farm land resulted in the biggest changes in dominant vegetation types (Figs. 3 and 4, Appendix C). In both scenarios, herbaceous vegetation on dry, oligotrophic, acid soils increased the most (+18.8 and +19.7 percentage point for 3W and 3D, respectively). The second-largest vegetation type increase in scenarios 3W and 3D was for herbaceous vegetation on moist, mesotrophic soil (+2.2 and +1.1 percentage point, respectively), followed by moist, oligotrophic, acid vegetation (+1.6 percentage point) in scenario 3W and by dry, mesotrophic vegetation (+0.9 percentage point) in scenario 3D. The number of different vegetation types increased in both scenario, with two in scenario 3W (19 types) and with three in scenario 3D (20 types).

3.4. Step 4: climate and socio-economic change, hydrological measures and collective set-aside policy

Implementation of the hydrological measures in combination with the collective set-aside policy led to the development of set-aside land, which was 1.4% in both climate scenarios (Fig. 5). The new nature areas (i.e. those purchased by the nature conservation organizations) increased with 5.1 percentage point in the Wet scenario (scenario 4W) and with 4.8 percentage point in the Dry scenario (scenario 4D), which is comparable to scenarios 3W and 3D, suggesting that the farmers collective hardly competed with the traditional nature conservation organizations. Pastures decreased even further with an additional −0.1 percentage point in the Wet scenario and −0.3 percentage point in the Dry scenario. The land that was sold to the collective mostly concerned orchards (an additional −1.1 percentage point in the Wet and −0.4 percentage point in the Dry scenario). In scenario 4D other agriculture increased, but less than in scenario 3D without hydrological measures and set-aside policy (now +0.1 percentage point instead of +0.4 percentage point). Furthermore, the decrease of corn in scenario 4W was less (−0.1 percentage point) than in 3W (−0.6 percentage point). In the dry scenarios the same pattern was observed for potatoes which decreased by 0.7 percentage point in 3D and by 0.4 percentage point in 4D.

The resulting changes in the groundwater tables were small, compared to the implementation of the hydrological measures alone (thus without land use change; scenarios 2W and 2D) (Table 4). The MLGT in scenario 4W increased one cm less than with hydrological measures alone (scenario 2W). Also the large spatial differences as shown in the 1st percentile were similar to scenarios 2W and 2D (135 cm increase compared to 123 cm) (Table 4, Appendix B). The MHGT increased on average with 24 cm in scenario 4W, which is 4 cm less than with solely hydrological measures. The spatial differences increased (1st and 99th percentiles of +145 cm and −13 cm, respectively). In scenario 4D, the MLGT only showed local differences (1st and 99th percentiles of +125 cm and −24 cm) (Table 4, Appendix B). The MHGT increased on average less than with the hydrological measures alone (now +20 cm instead of +23 cm, with a similar range of change for the local differences).

The new nature areas mostly developed into herbaceous vegetation on dry, oligotrophic, acid soils in both 4W (+17.5 percentage point) and 4D (+19.0 percentage point) (Figs. 3 and 4, Appendix C). The second-largest increase in vegetation type in scenario 4W was for moist, oligotrophic, acid vegetation (+3.7 percentage point), followed by moist, mesotrophic vegetation (+2.5 percentage point). The number of vegetation types increased up to 21 (+4). In scenario 4D the moist, mesotrophic vegetation was the second-largest increase (+2.7 percentage point), followed by moist, oligotrophic, acid vegetation (+2.4 percentage point). The total number of different vegetation types was highest in scenario 4D: 22 vegetation types.

4. Discussion

4.1. Land use changes in the Tungelroyse Beek

With our research we aimed to (1) test the combined impacts of climate and socio-economic change, hydrological measures, and policy-driven land use change on vegetation distribution and composition, and (2) assess the relative importance of these factors on vegetation distribution and composition. The combination of all four factors triggered the biggest response in vegetation distribution and composition. Especially the Wet scenario, with hydrological measures and land use change (driven both by socio-economic change and local policy) (scenario 4W), led to the highest increment of new nature areas (6.5 percentage point, including set-aside).

Land use change driven by nature organizations buying farmland, led to a strong increase in herbaceous vegetation on dry, oligotrophic, acid soil, even in combination with the hydrological measures. These new nature areas were created somewhat further away from the stream where the groundwater tables are low(er) than close to the stream, which provided opportunities for dry vegetation types. Additionally, the areas that were purchased by the farmers' collective were situated at sites with different hydrological conditions than most of the existing nature areas in the catchment. This led to the simulated development of different vegetation types, which may increase biodiversity on a catchment scale. In addition, the hydrological measures led to the development of wet and moist, oligotrophic, weakly acid to acid vegetation communities. These vegetation types are of special interest to nature managers because, on a European scale, these vegetation types are relatively abundant in the Netherlands and are protected according to the European Habitat Directive (Council Directive of the European Communities, 1992; Ministry of Economic Affairs, 2009). The Netherlands has therefore an international responsibility to ensure the protection of these vegetation types. The fact that most scenarios led to an increment of especially these vegetation types has therefore international significance. These vegetation types also occurred on land that was purchased by the farmers' collective. This means that the implementation of the hydrological measures and the collective set-aside policy increased the area of vegetation types of special interest. The magnitude of climate change, the implementation of hydrological measures, and socio-economic and policy driven land use changes all contribute significantly in shaping the future rural landscape. The future landscape patterns are therefore very different between the eight scenarios.

When considering the individual effects, the land use change that was brought about by the collective set-aside policy had the biggest effect on (1) future vegetation distribution because of the highest increment of new nature areas (+6.5 percentage point in 4W) and (2) future vegetation composition through the development of most diverse vegetation types (22 in 4D). The land use changes driven by climate and socio-economic changes (including the planned acquisition of land by nature conservation organizations) led to an increment of new nature areas of 5.4 percentage point (3W) and to 20 different vegetation types (3D). Most of the new developed vegetation types were H61, H47 and K61, which were also the most abundant vegetation types in the reference scenario. Although it is not surprising that the new nature areas acquired through land use change led to the biggest vegetation changes, because of the increment in new nature areas, it is surprising that it stimulated the development of protected, and thus rare, vegetation types. These vegetation types are represented in our model by K21, K22, K41 and K42. The development of these vegetation types were also stimulated by the hydrological measures (+0.2 percentage point in 2D and +0.7 percentage point in 2W). The abundance of these vegetation types increased even further when combined with land use change (+4.7 percentage point in 4D and +6.9 percentage point in 4W). Nevertheless, some vegetation types (H21, H22 and H27 for 2W) increased the most in the 2D and 2W scenarios. Effects of climate change on vegetation distribution (only two additional vegetation types for 1D, none for 1W) and composition were minor. The hydrological measures triggered a bigger response than the climate change scenarios (an additional four vegetation types for 2D and one additional type for 2W), but the response was still less than the one triggered by the land use change. The stronger effects of hydrological measures compared to climate change raises the question of whether, given the costs involved, hydrological measures are needed to such extents. Particularly increased local flooding, caused by the hydrological measures that were implemented to reduce the potential negative effects of increased droughts, are undesired. These measures and the associated costs of implementing them, should therefore be carefully considered. It suggests that the type and magnitude of these measures should be tested in the context of anticipated land use change before implementing them.

Besides affecting the water-vegetation system, the hydrological measures combined with the collective set-aside policy also led to different agricultural land use patterns. Compared to climate and socio-economic change alone, the implementation of the hydrological measures and the set-aside policy led to a further non-linear decrease of all agricultural practises in both scenarios, with the exception of corn (Wet) and potatoes (Dry). Apparently these types of agriculture are less unattractive when the hydrological measures are implemented than if they were not.

4.2. Importance of the interdisciplinary approach

With our interdisciplinary modelling approach we made a first step in projecting expected climate and socio-economic changes, hydrological climate adaptation measures, and policy regulations on a detailed scale for an entire catchment. These integrated models provide a more holistic perspective and are likely to be more useful to policy makers when selecting the most effective climate adaptation strategy on a catchment scale, than one of these models alone. Our results indicate that the highest impact on vegetation development was triggered by a combination of all four factors: socio-economic and policy driven land use change, climate change and hydrological climate adaptation measures, which stresses the necessity of an interdisciplinary approach.

Furthermore, this research shows the significance of incorporating, by for example agent-based modelling, the behaviour of people as a dominant factor in shaping vegetation communities. Previously, agent-based models have been coupled to other model types, e.g. to improve the effectiveness of conservation policies on water quality (Daloğlu et al., 2014). To our knowledge, such approaches have not yet been combined in relation to hydrological changes and vegetation development, let alone on a catchment scale. Our approach appears suited for implementation in other catchments as well, as long as there is sufficient information available about local agents (e.g. farmers), regional soil, subsurface and hydrological conditions and meteorology.

The necessity of interdisciplinary research is acknowledged widely in the international community, as it would increase the success of understanding system responses to e.g. climate change mitigation and adaptation plans, if potential future pitfalls are known (Fohrer et al., 2002; Smith et al., 2008; Hughes et al., 2012; Capon et al., 2013; Susnik et al., 2015). The lack of fully integrated interdisciplinary studies however, stresses the difficulties in accomplishing this. Despite the increasing interest in interdisciplinary research, as shown by an increasing number of papers published with *interdisciplinary* and *land use* as topic in the last 15 years, there is a long way to go. Despite necessary model improvements to improve the validity of our integrated model, our approach has shown a feasible and promising way forward.

4.3. Model uncertainties and future explorations

Although we emphasize the need for an integrated modelling approach, there are still a number of challenges to be tackled. Further integration can be achieved by improving the consistencies in land cover classifications. The current necessary conversion of land use classes may have increased the uncertainties in the map of actual land use types on top of uncertainties in the RULEX projections. Also, hydrological insights on water-induced crop damage may be used to improve RULEX decision rules. Additionally, all models have a different time step. RULEX runs on an annual basis, while IBRAHYM runs with a daily time step and PROBE uses one time step, based on climatological averages. Although these time steps reflect the necessary accuracy for each model, it may hamper an integrated model approach through discrepancies in model feedback loops. It should also be mentioned that the current PROBE model does not take existing nutrient loadings of soils due to agricultural practices into account. These are probably very high for land that was until recently used for agricultural purposes. Without active management (e.g. scraping off the top soil layer), the actual occurrence of oligo- and mesotrophic vegetation on such soils is not very likely.

A next step would be to incorporate a more structural feedback between the models by means of e.g. an online coupling. We did not apply this approach here because of computational limitations. Furthermore, our aim was to test the combined impact of all four factors on vegetation distribution and composition and to evaluate if an integrated approach is necessary. Our results indicate that this is indeed the case. An online integrated approach would shed light on questions such as: How do the different vegetation distributions and compositions dynamically influence catchment hydrology? And does this affect farmers' willingness to pay and sell and thereby the land use patterns? For future research, it is especially important to ensure model consistencies between the different scientific disciplines, as has been extensively underlined by Laniak et al. (2013). An online integrated modelling approach which allows the models to feed back to one another would therefore be the next big step to further improve realism and thereby applicability of the model results.

Acknowledgements

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Appendix A. Validation of the PROBE model

We analysed whether the output of the coupled interdisciplinary model simulated the right vegetation types at the designated nature areas. We have applied the same method used for validation as in Van der Knaap et al. (2015). The modelled vegetation types were compared to current vegetation management types (Table A1) and checked whether they matched. In case of a match we considered the model to be successful. To this

Table A1
Modelled vegetation types and the associated vegetation management types. The modelled vegetation types are in the left column and the vegetation management types are in the right column. Nine modelled vegetation types were not validated since they could not be linked to a vegetation management type.

Vegetation type	Management type
Herbaceous vegetation on wet, mesotrophic to very eutrophic soil	Swamp
Herbaceous vegetation on wet to moist, oligotrophic, acid soil	Moist heath
Forest and shrubs on wet to moist, oligotrophic to mesotrophic, acid to neutral soil	River and stream forest
Herbaceous vegetation on wet, oligotrophic, neutral soil	Wet nutrient poor grassland
Herbaceous vegetation on moist, oligotrophic, acid to neutral soil	Moist nutrient poor grassland
Herbaceous vegetation on dry, oligotrophic to mesotrophic, neutral soil	Dry nutrient poor grassland
Herbaceous vegetation on moist, mesotrophic soil	Fauna and herb rich grassland
Forest and shrubs on moist, oligotrophic to mesotrophic soil	Hornbeam and ash forest
Forest and shrubs on dry, oligotrophic, acid to neutral soil	Pine, oak and beech forest
Forest and shrubs on dry, oligotrophic to mesotrophic, acid to neutral soil	Dry production forest
Herbaceous vegetation on dry, oligotrophic, acid soil	Dry heath
Herbaceous vegetation on moist, mesotrophic soil	Mesotrophic grassland
Forest and shrubs on moist, mesotrophic soil	Moist (old) coppice forest or moist production forest

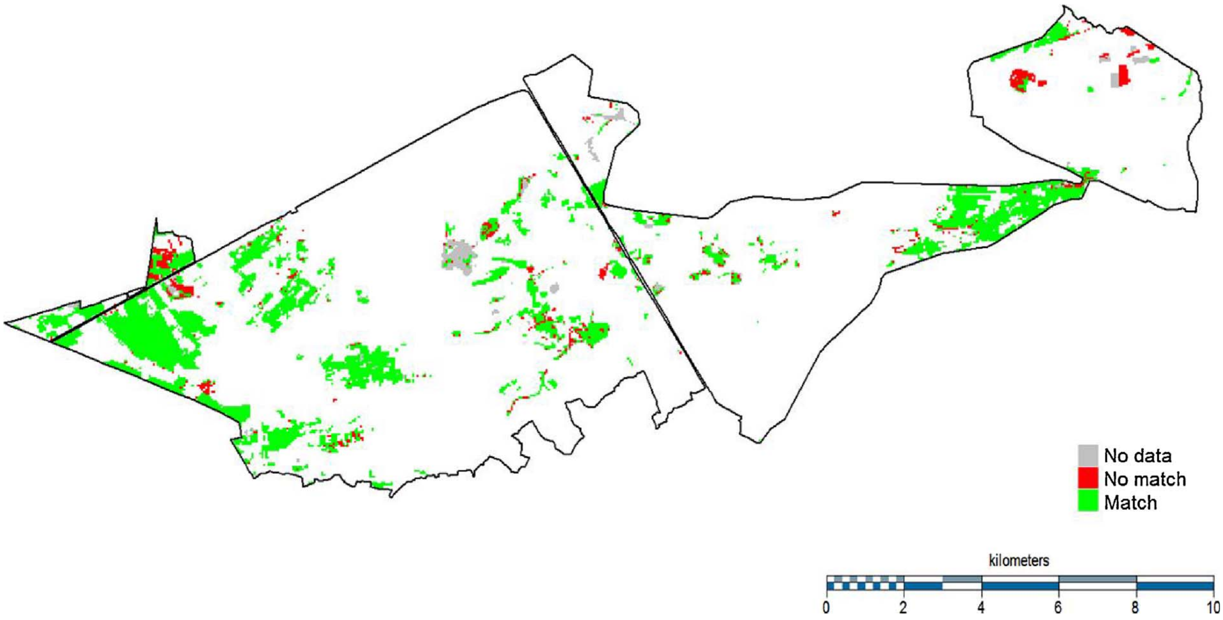

Fig. A1. Overview of the case study area and the locations of where vegetation types were modelled correctly (in green) and where they were not (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

end, each grid cell was classified to the vegetation type with the highest occurrence probability according to PROBE. In 80.4% of the cases there was a positive match between modelled vegetation type and vegetation management type (Fig. A1). 12.2% of the modelled data did not match with the vegetation management types and 7.4% could not be validated since these vegetation types were not represented by vegetation management types.

The dominant vegetation types that were not correctly modelled were forest and shrubs on moist, mesotrophic soil and forest and shrubs on dry, oligotrophic, acid soil. The wetness of the vegetation types was most often incorrect, followed by nutrient status.

Appendix B. Spatial climate change, hydrological measures and land use change effects on hydrology

Although the changes in groundwater tables and seepage fluxes were small on a catchment scale, there were large spatial differences. The spatial changes in the mean lowest groundwater table (MLGT) and average seepage fluxes in the climate scenarios are shown in Fig. B1. It is clear that the decrease of MLGT is biggest in the Dry climate, due to the drier summers. The reduced groundwater recharge in this scenario led to a decrease of the average seepage flux. However, the seepage area increased which may be due to the precipitation increase in winter and decrease in summer. The wet winters increase the groundwater supply in winter. Combined with less precipitation in summer, this stimulates a decrease of groundwater levels in areas with high groundwater tables (i.e. where evapotranspiration affects groundwater levels). This leads to larger areas with big differences between groundwater heads at high and low areas and thus results in an increase of the seepage area. However, because the groundwater tables decrease, the increase in seepage flux does not mean that it will enter the root zone and be available to plants.

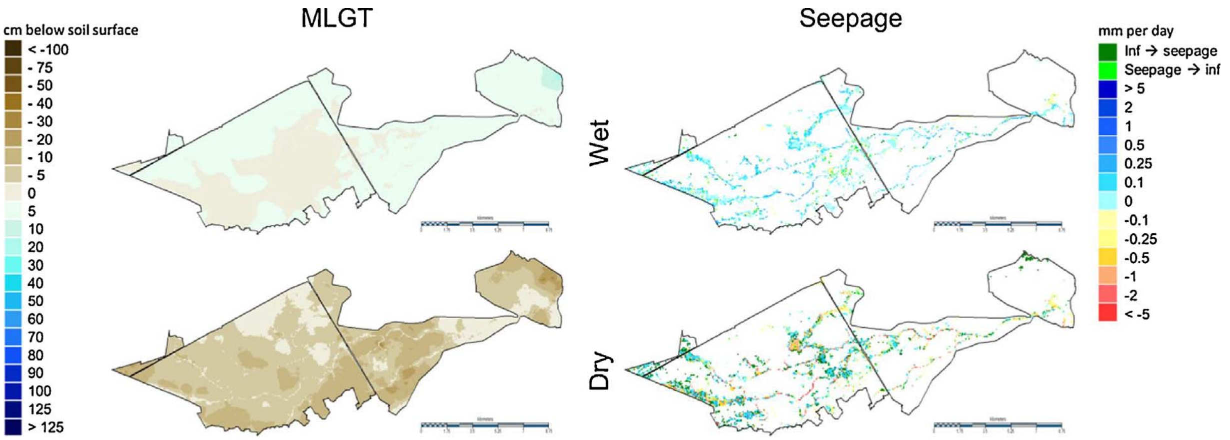

Fig. B1. Climate change effects on mean lowest groundwater table and seepage flux. The left two figures are the mean lowest groundwater table (MLGT) for the Wet (1W, top) and Dry (1D, bottom) climate scenario. The changes in groundwater table are compared to the reference scenario, the legend is shown on the left (in centimetres). The two figures on the right are the changes in average seepage flux, in mm per day, compared to the reference scenario. The legend is on the right. The dark green colour indicates a switch from infiltration to seepage, while the light green colour indicates the opposite switch. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

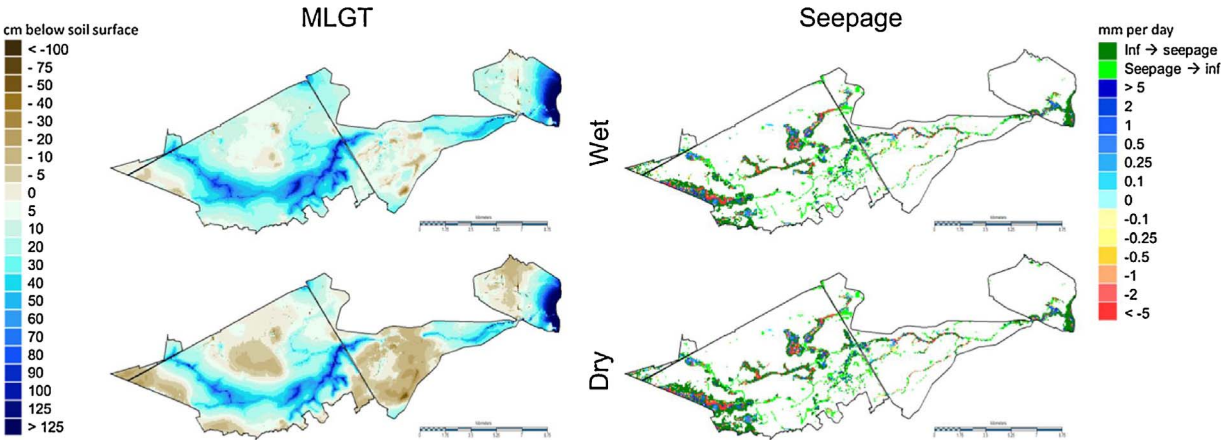

Fig. B2. Combined climate change and hydrological measures effects on mean lowest groundwater table and seepage flux. The left two figures are the mean lowest groundwater table (MLGT) for the Wet (top) and Dry (bottom) climate scenario. The changes in groundwater table are compared to the reference scenario, the legend is shown on the left (in centimetres). The two figures on the right are the changes in average seepage flux, in mm per day, compared to the reference scenario. The legend is on the right. The dark green colour indicates a switch from infiltration to seepage, while the light green colour indicates the opposite switch. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

When the hydrological measures were implemented, the groundwater table rose considerably around the stream, increasing the spatial differences in groundwater table changes (Fig. B2).The spatial differences in groundwater table changes are biggest in the Dry scenario. Especially in the downstream area, the groundwater table rose considerably. The seepage fluxes in a large part of the stream switched from seepage to infiltrating fluxes. However, many infiltration fluxes switched to seepage fluxes in the areas were the groundwater table decreased due to the reduction of groundwater recharge. At some locations, the rise of the groundwater table led to an increase of seepage areas.

The land use changes driven by the socio-economic changes and the collective set-aside policy triggered minor changes in the mean groundwater tables on a catchment scale. The changes were bigger at local sites, although less than the climate change or hydrological measures effects (Fig. B3). The spatial changes differed between the four scenarios, although the magnitude of the local changes is more or less the same.

The land use changes also triggered minor effects in the seepage fluxes (Fig. B4). The local changes are small and differ between the climate change and hydrological measures scenarios. The magnitude of the changes is the same between the scenarios. Our results indicate that even small land use changes, i.e. on a parcel scale, lead to changes in groundwater tables and seepage fluxes.

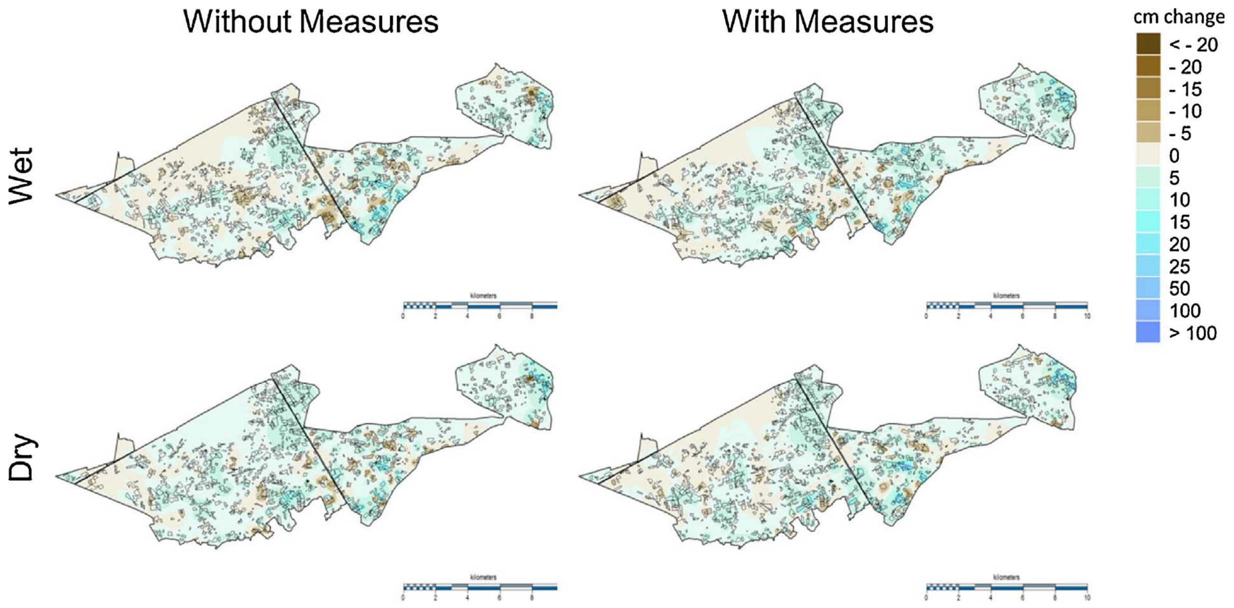

Fig. B3. Effect of land use changes on the mean lowest groundwater table. The data shown here resemble the change in groundwater table due to the land use changes. The left two figures are the climate scenarios without hydrological measures (Without Measures) for the Wet (top) and Dry (bottom) scenario. The two figures on the right are the climate scenarios with the hydrological measures (With Measures). The changes in groundwater table are compared to the corresponding four scenarios without land use changes, thus showing the differences triggered by land use change. The legend on the right is in centimetres.

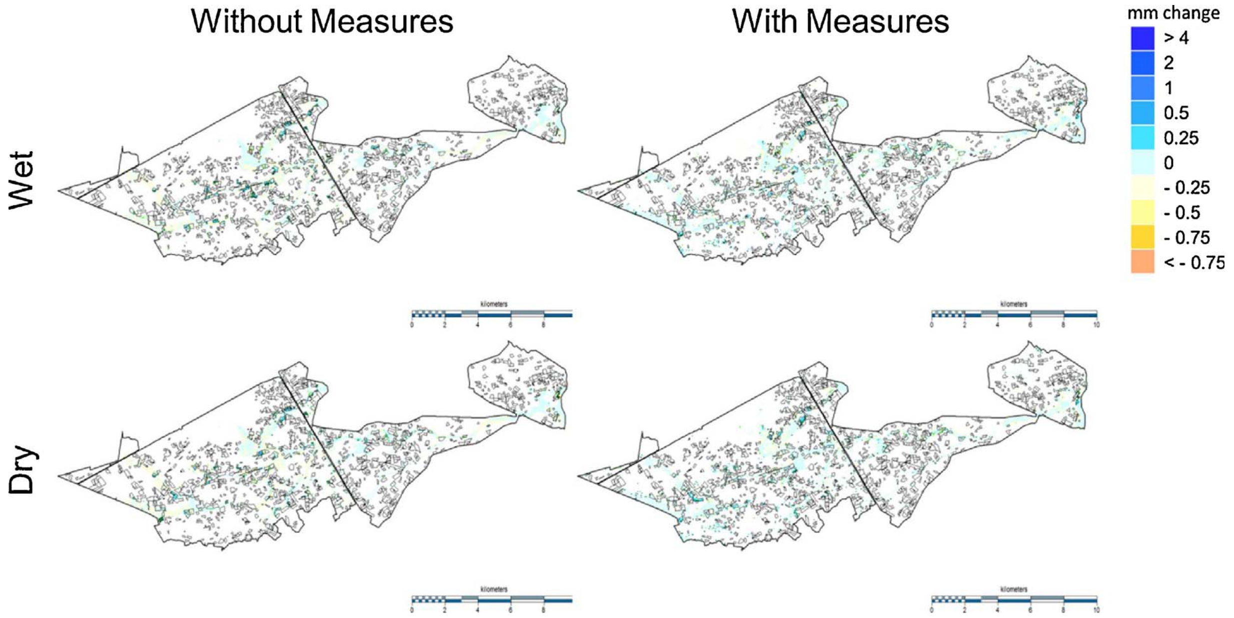

Fig. B4. Effect of land use changes on the average seepage flux. The data shown here resemble the change in seepage flux due to the land use changes. The left two figures are the two climate scenarios Wet (top) and Dry (bottom) without the hydrological measures. The two figures on the right include the implementation of the hydrological measures. The figures depict the change in seepage flux compared to the same four scenarios without land use changes, thereby showing the change as triggered by land use changes. The legend on the right is in mm per day. The land use changes did not trigger a switch in flux type as the climate and climate adaptation scenarios did.

Appendix C. Changes in vegetation types in hectare

This appendix shows total surface area (in ha.) of the vegetation types in the Reference scenario and the vegetation changes in hectare for all other scenarios (Table C1).

Table C1
Total vegetation type abundance in hectare in the Reference scenario and the changes (in ha.) for the other scenarios. *Ref* stands for Reference scenario. All numbers smaller than -1 and bigger than 1 are rounded to improve the readability of the table.

Vegetation code	Ref	1W	1D	2W	2D	3W	3D	4W	4D
A11	0.1	−0.1	+0.4	−0.1	+0.6	0	+0.4	−0.1	+1
A12	0	0	+0.1	0	+0.3	0	+0.1	+0.3	+2
A15	0	0	0	0	+2	0	0	+0.7	+3
K21	0.5	+0.1	−0.3	+4	+3	0	−0.3	+11	+9
K22	5	−1	−3	+2	+0.5	−0.1	−1.0	+42	+29
K27	0	+1	+3	+3	+2	+0.8	+3	+13	+9
K41	19	+2	−9	+8	−2	+56	+9	+130	+82
K42	3	+0.6	−0.8	+2	+1	+30	+11	+55	+38
K47	9	+0.4	−1	−1	−2	+72	+36	+85	+89
K61	176	−2	+10	−16	−5	+652	+642	+649	+666
K62	0	0	0	0	0	+0.1	+0.9	+0.7	+0.4
K67	6	−0.3	+1	−2	−0.8	+19	+29	+12	+17
H21	12	+3	+0.1	+12	+7	+3	0	+11	+7
H22	4	−0.1	−1	+20	+16	+0.2	−0.9	+21	+16
H27	60	+16	−15	+83	+36	+16	−15	+84	+35
H41	74	+2	−14	−0.5	−17	+2	−15	−2	−19
H42	3	−0.1	−0.9	+0.3	−0.6	−0.1	−0.9	+0.4	−0.6
H43	0	0	0	+0.5	+0.6	0	0	+0.4	+0.6
H47	365	−5	−39	−37	−68	−5	−39	−36	−67
H61	1533	−6	+33	−77	−50	−6	+33	−77	−49
H62	2	−0.1	+5	+0.1	+3	−0.1	+5	−0.1	+3
H67	13	−4	+5	−8	+0.1	−4	+4	−8	+0.6

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