

Modeling crop suitability for rewetting landscapes in the Netherlands across present and future climate scenarios

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ABSTRACT

Draining peatlands and other wetlands for agricultural use triggers several environmental problems, including greenhouse gas emissions, land subsidence, and biodiversity loss. Paludiculture, farming on rewetted land, is a strategy that can help restore some of the natural functions of wetlands while maintaining agricultural use. However, little is known about where paludiculture is feasible or with which crops. In this study, we address this knowledge gap by assessing the biophysical suitability of 12 potential paludicultural crops for the Netherlands. Selected crops include both native wetland crops as well as East Asian paddy crops. We first identified areas with potential for paludiculture based on groundwater levels, seepage and available water capacity. Around a quarter of the Netherlands has the hydrological potential for paludiculture. We then successfully expanded the crop suitability model EcoCrop (Hijmans et al., 2001) with a water balance function. Our study shows that current (drained) conditions limit suitability for many paludicultural crops. However, under raised water conditions most investigated crops—including cattail (*Typha latifolia* and *angustifolia*), reed (*Phragmites australis*), reed canary grass (*Phalaris arundinacea*), barnyard grass (*Echinochloa crus-galli*), rice (*Oryza sativa*), water cress (*Nasturtium officinale*), European blueberry (*Vaccinium myrtillus*), water spinach (*Ipomoea aquatica*), and cranberry (*Vaccinium macrocarpon*)—were predicted to have at least moderate suitability in some parts of the Netherlands. The impact of climate change on the suitability of the selected crops was minimal, with 8 out of 12 crops experiencing no relevant change in mean suitability; however some East Asian crops will benefit from temperature increase. Our findings complement existing field trials with paludicultural crops by providing the first spatial paludicultural suitability analysis on a national scale. These results support evidence-based discussions on the potential of paludiculture in temperate lowland areas, not only in the Netherlands but also surrounding regions.

1. Introduction

Peatlands and other wetlands are crucial ecosystems providing multiple ecosystem services such as water regulation, water filtration, carbon storage, and habitat for biodiversity (e.g. Zedler and Kercher, 2005). However, many wetlands are degraded, especially in regions with high population pressure and/or intensive agriculture (Ballut-Dajud et al., 2022). The main driver of peat degradation is drainage, which is intended mostly to transform wetlands into agricultural land (Boonman et al., 2022; Brouns et al., 2015; Tanneberger et al., 2021). Drainage results in lowering of groundwater levels, which promotes oxidation of soil organic matter. This process results in land

subsidence and greenhouse gas emissions (Ma et al., 2022).

Land subsidence rates vary in magnitude depending on the groundwater level, the type of soil and climatic variables (Huning et al., 2024), and are a threat to long-term land suitability particularly in low-lying, coastal areas. Greatest rates are reported for strongly lowered groundwater levels (> 1 m), high soil organic matter content (Brouns et al., 2015), and under warm and dry conditions (Berglund et al., 2010; Erkens et al., 2016). In the western part of the Netherlands, drainage of peatland to enable agricultural use already started around the 11th-12th century and resulted in subsidence of several meters over time (Brouns et al., 2015; Erkens et al., 2016). For a peat-meadow farm in Zegveld, average subsidence rates of 4.8 mm/yr to 5.8 mm/yr were observed for

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over a ~50 year period; the majority of this subsidence is caused by aeration due to lowered groundwater levels, causing shrinkage and oxidation of peat in the upper meter (Massop et al., 2024). Other studies even report subsidence rates up to 1–3 cm/year in temperate Europe (Leifeld et al., 2011; Oleszczuk et al., 2020), with most subsidence occurring during spring and summer due to increased decomposition rates (van Asselen et al., 2020, van Asselen et al., 2025). Dry and warm future scenarios pose a threat to peatlands as these conditions imply even lower groundwater tables during summertime while accelerating decomposition (Ma et al., 2022).

Drainage of wetlands turns these areas from carbon sink into a carbon source (van Giersbergen et al., 2025). While organic matter accumulation in wetlands captures CO₂, drained wetlands emit CO₂ emissions as a result of peat oxidation (Ma et al., 2022). For the Netherlands, it is estimated that emissions from peat and mire soils (4.362 km²) are 6.2 Mt CO₂ eq/yr (Verstand et al., 2020). Hu et al., (2017) found that under drained conditions the average daily CO₂ and N₂O emissions of peat are around 8 and 3 times higher respectively than under flooded conditions. There is an urgent need to reduce these emissions to meet the Paris Climate Agreement of 2015.

There is abundant evidence that increasing groundwater levels, especially in summer, is needed to reduce both land subsidence and greenhouse gas emission (e.g. Erkens et al., 2016). Recent research in the Netherlands has focused on the effect of elevating ditch water levels (e.g. Massop et al., 2024) and subsoil irrigation via underwater drainage systems (e.g. Boonman et al., 2022). These efforts focus on water management practices that support the current land use on drained wetlands, which is primarily dairy farming. However, due to limiting rewetting possibilities the reductions possible under current land-use are insufficient to restore the carbon sink potential of these areas (Mander et al., 2025). Another limitation is that raising the water level increases methane emissions (Buzacott et al., 2024), negating at least part of the climate mitigation effect (Wüst-Galley et al., 2023).

It is clear that drained (former) wetlands should be rewetted to safeguard or restore the many ecosystem functions and services they provide. In this study we focus on drained former wetlands in the Netherlands that are now in agricultural use. While rewetting and rewilding these former wetlands may be desirable from biophysical perspectives, this may not be feasible given their role in food production and livelihood for farmers and local communities. In such cases paludiculture could provide an economically interesting alternative.

Paludiculture is a form of agriculture where biomass is produced on rewetted lands. Although paludiculture has been primarily proposed for peatland restoration (Wichmann and Joosten, 2007), it can also be applied for other wetland types. According to Abel et al. (2012), rewetting in conjunction with paludiculture has the potential to reduce greenhouse gas emissions, restore the peatlands carbon sink function and water storage capacity, and re-establish vital habitats for vulnerable species.

Given these benefits, paludiculture now receives a lot of attention in a wide range of research projects and feasibility studies in NW Europe. Examples include the PALUS DEMOS project (European Commission, 2024), the CANAPE project (Interreg North Sea Region, 2020), and the Peatland Programme (IUCN UK Peatland Programme, 2023). Notably sphagnum mosses, reed and cattail have been extensively studied (Geurts and Fritz, 2018; Liu et al., 2023; Ren et al., 2019; Wichmann and Nordt, 2024). Also in the Netherlands multiple pilots have investigated the viability of reed and cattail cultivation and its effect on the environment (de Jong et al., 2021; Geurts and Fritz, 2018; Vroom et al., 2022). Many of these projects also address concerns with regards to enhanced methane emissions upon rewetting (Yang et al., 2022).

However, little is known about where in the landscape paludiculture would be most feasible from a biophysical perspective, and what crops would be suitable depending on the location-specific soil and climate conditions. Furthermore, the above mentioned paludicultural research in NW Europe focused mostly on non-food crops, while in other parts of

the world there is a long-tradition of wetland (paddy) agriculture. More insight into possibilities of growing these crops in northwest European paludiculture settings would broaden potential applications. The aim of this research is to determine which paludicultural crops are suitable for cultivation in the Netherlands under current and future climatic conditions, and where in the Netherlands these crops could be cultivated.

Towards this aim, we first identify areas with high potential for paludiculture from a hydrological and soil perspective. Then we perform a crop suitability analysis with the EcoCrop model (Ramirez-Villegas et al., 2013), which we expand with a water balance function, soil texture and pH information. We perform spatially explicit crop suitability analysis for present and future climatic conditions, to identify opportunities and risks. Although our focus is on the Netherlands, the developed approach is universally applicable given availability of input data, and the results are relevant also for other temperate regions.

2. Methodology

2.1. Study area

The Netherlands is a country with a land surface area of 33,671 km² (CBS, 2020) located in Northwestern Europe. Around 26 % of this country lies below sea level and in absence of water defense structures, 59 % would be prone to flooding (Planbureau voor de Leefomgeving n.d.) from the rivers and sea. Due to the low altitude, there are also very shallow groundwater tables, which are on average less than 2 m below surface level (Wong et al., 2007). During the Iron Age, roughly 50 % of The Netherlands used to be covered by peatlands (Jongmans et al., 2018), which has been significantly reduced to ~7 % of the land surface in current day by peat cutting and drainage (Aben et al., 2024). Fig. 1 presents the distribution of peatlands alongside the most important soil textures. Due to the readily available climatic, hydrologic and soil data and the growing interest in paludiculture in this country (Bestman et al., 2019; de Jong et al., 2021; Fritz et al., 2014; Geurts and Fritz, 2018), the Netherlands is an ideal case study area.

2.2. Identification of area with high hydrological potential for paludiculture

Paludiculture is only feasible in areas where ample water is available, or through intense water management. For selecting areas in the Netherlands with potential for paludiculture, we focus on those areas with ample water availability. This prerequisite is met for areas with shallow groundwater tables in summer, and for areas with natural occurring seepage, i.e. upward groundwater flow towards the surface. Moreover, it should be possible to retain the water in the area, which requires soils with relatively low permeability and sufficient capacity to hold water for crop uptake. The latter is expressed as available water capacity (AWC), also known as water holding capacity, which is the soil moisture between field capacity and permanent wilting point.

Spatially explicit data for each of these criteria is obtained from literature or estimated based on available information for 250 × 250 m raster cells for the whole of the Netherlands. In absence of spatially explicit data on AWC, we calculated this parameter from available information on soil texture (Helfenstein et al., 2024b), in combination with pedo-transfer functions describing the relationship between soil texture and AWC (Clark n.d.; Easton n.d.; Evans, 2014; Noble Research Institute, 2022; Rai et al., 2017; Salter and Williams, 1965). This resulted in an AWC map of the Netherlands at the required resolution. We assigned three categories of suitability for paludiculture with regard to AWC (Table 1). Spatially explicit information on the mean lowest groundwater level (MLG) and seepage fluxes are available for grid cells of 250 × 250 m from De Louw et al. (2022) based on groundwater model calculations on a national scale. The MLG represents the average for the three months with lowest groundwater levels in a hydrological year, while seepage refers to the upward flow from the first aquifer

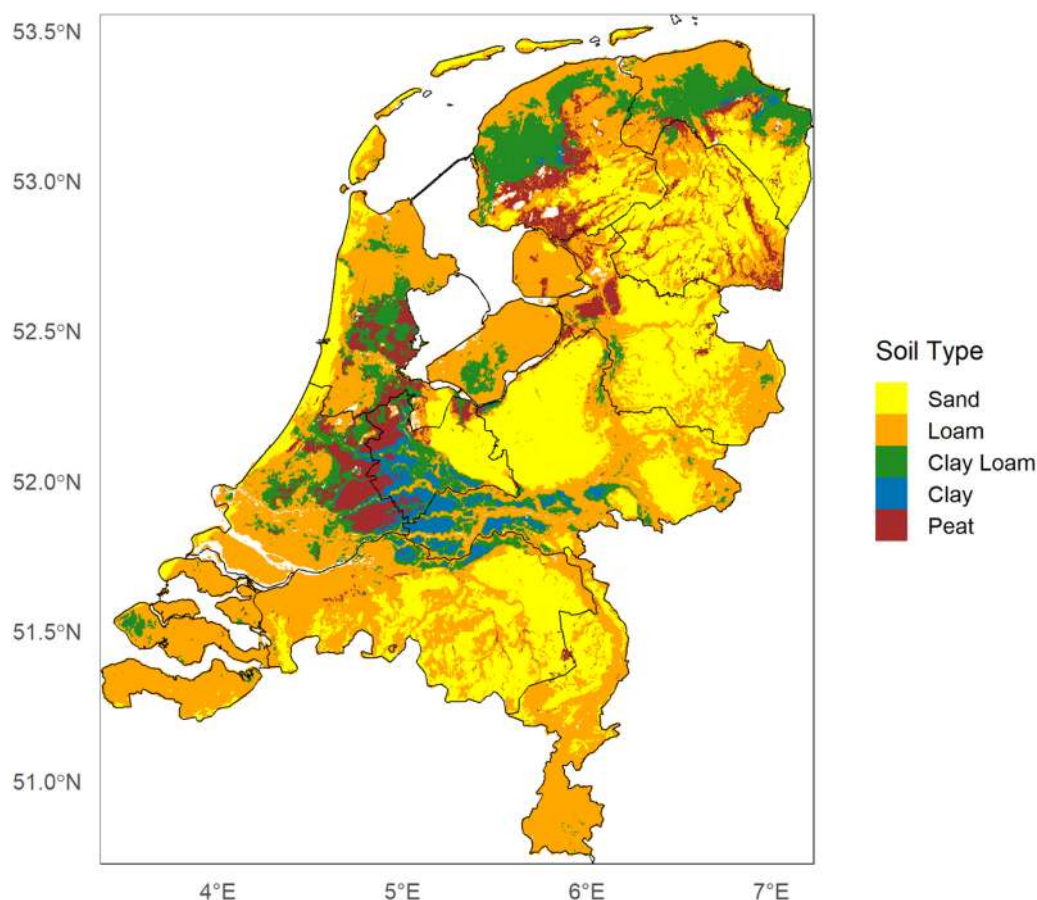


Fig. 1. Soil map of the Netherlands based on soil texture data from [Helfenstein et al. \(2024a\)](#) and peatland locations from [Wageningen Environmental Research \(n.d.\)](#). The main world reference base soil types on each soil unit are: podzols and cambisols on sand; fluvisols, cambisols, luvisols and gleysols on loam, clay loam, and clay soils; and histosols on peat. All maps are oriented with north at the top.

Table 1

Paludiculture potential based on AWC, MLG and seepage.

Suitability score	AWC	MLG	Seepage
High Potential (3)	> 30 %	0–30 cm	< -0.1 mm/d (upward)
Moderate Potential (2)	15–30 %	30–80 cm	-0.1–0.1 mm/d (neutral)
Marginal Potential (1)	10–15 %	80–160 cm	0.1–0.5 mm/d (downward)

towards the phreatic water table. Also for these criteria we assigned three categories of suitability (Table 1).

For each of the variables, areas with high, moderate and marginal values were defined, and awarded suitability scores of 3, 2 and 1 respectively. Overall potential of an area was calculated by multiplying the suitability scores for the three variables, resulting in overall suitability scores between 1 (marginal potential in all three variables) to 27 (high potential in all three variables). Areas with overall suitability score of 8 or higher were included for further analysis. The resolution of the output was set to the resolution of the precipitation and temperature maps (see Sections 2.5.1), 1×1 km.

2.3. Crop selection process

For this study, a selection of potential paludicultural crops was made (Table 2), with a broad range of uses and from multiple continents. A set of widely researched and other relevant crops, selected with a focus on ecological suitability and practical viability, were chosen from the extensive paludiculture inventory by the Greifswald Mire Centre ([Abel and Kallweit, 2022](#)). Furthermore, a selection of widely cultivated wet agriculture crops and relevant species from East Asia, selected based on

their prevalence in regional agriculture and paludicultural potential, but not included in the aforementioned inventory, were added to the selection. These crops were afterwards checked in the FAO GAEZ EcoCrop database ([FAO, 2022](#)) to make sure that they are either annually cultivatable or perennial and able to survive the winters in the Netherlands. This led to a selection of 14 crops, which were then checked for missing data in the EcoCrop database. Any missing data was augmented with information from literature. For one crop, the *Phragmites australis* (common reed), the optimum temperature range from [Tang et al. \(2022\)](#) was shifted downward by 3° to reflect the climate adaptation in the Dutch population based on acclimatization to cooler climates of this species as documented by [Lessmann et al. \(2001\)](#). For three crops missing information on growing periods was added based on literature: for *Echinochloa crus-galli* (barnyard grass), 50–90 days ([Cornell University n.d.; Donayre et al., 2018](#)); for *Vaccinium myrtillus* (European blueberry), 120–180 days ([Tirmenstein, 1990](#)); and for *Trapa natans* (water chestnut), 150–210 days ([Palm et al., 2024](#)). For *Phalaris arundinacea* (reed canary grass) peat was also added as an optimal soil texture, for *Phragmites australis* (common reed), *Vaccinium macrocarpon* (cranberry) and *Salix babylonica* var. *sacramenta* (Sacramento weeping willow) peat was added as an absolute soil texture based on the information in [Abel and Kallweit \(2022\)](#).

2.4. EcoCrop model and modifications

The EcoCrop model ([Hijmans et al., 2001](#)) is a simple mechanistic model in which the suitability of crops (minimum 0, maximum 1) is calculated based on a linear function between absolute and ideal temperature and precipitation thresholds, with the final suitability based on

Table 2
Overview of selected crops, their regions of occurrence and utilized parts.

Latin name	English name	Region of occurrence	Agriculturally used parts
<i>Echinochloa crus-galli</i>	Barnyard grass	Europe	Aboveground biomass
<i>Nasturtium officinale</i>	Watercress	Europe	Aboveground biomass
<i>Phalaris arundinacea</i>	Reed canary grass	Europe	Aboveground biomass
<i>Phragmites australis</i>	Common reed	Europe	Aboveground biomass
<i>Typha angustifolia</i>	Narrowleaf cattail	Europe	Above- and belowground biomass
<i>Typha latifolia</i>	Broadleaf cattail	Europe	Above- and belowground biomass
<i>Vaccinium myrtillus</i>	European blueberry	Europe	Berries
<i>Colocasia esculenta</i>	Taro	East Asia	Belowground biomass
<i>Ipomoea aquatica</i>	Water spinach	East Asia	Aboveground biomass
<i>Oryza sativa</i>	Rice	East Asia	Aboveground biomass
<i>Trapa natans</i>	Water chestnut	East Asia	Belowground biomass
<i>Salix babylonica</i> var. <i>sacramenta</i>	Sacramento weeping willow	East Asia	Aboveground biomass
<i>Zizania latifolia</i>	Manchurian wild rice	East Asia	Aboveground biomass
<i>Vaccinium macrocarpon</i>	Cranberry	North America	Berries

the most limiting factor (Ramirez-Villegas et al., 2013). Due to its simplicity, applicability for a wide range of plants, and extendibility it was the model of choice for this research. In addition, the EcoCrop model has been used to model suitability of various crops at national to continental spatial scale (Hunter and Crespo, 2019; Ramirez-Villegas et al., 2013; Salgado-Velázquez et al., 2025), including to identify overlooked alternative crops in Switzerland (Heinz et al., 2024) and for dryland agriculture in the Netherlands (van Etten et al., 2025).

For this study we developed and used two extended versions of the model; both were scripted in programming language R using the recocrop package version 0.4–1 (Hijmans, 2022). The first model is the base EcoCrop model, extended with suitability calculations based on soil pH and soil texture. While the EcoCrop model is often applied using climatic data alone (Heinz et al., 2024; Ramirez-Villegas et al., 2013; Redhead et al., 2025), we included pH and soil texture because they are fundamental soil properties that control many other soil characteristics and vary widely across the Netherlands. Suitability scores for the soil characteristics are based on the relevant crop requirements in the FAO GAEZ EcoCrop data sheets (FAO, 2022), which also include absolute and ideal ranges. The pH suitability is calculated following the same approach as precipitation and temperature, based on absolute and optimal ranges. For soil texture, the USDA soil texture classes were reclassified as “heavy”, “medium”, “light” and “organic” texture types (Supplementary Table 2). Per raster cell a final suitability score was based on the lowest suitability score of all input variables (i.e. temperature, precipitation, soil pH, soil texture).

Previous applications of EcoCrop have indicated widespread water limitation of crops across Europe (Manners et al., 2020), even though many of these crops typically grow successfully under non-irrigated conditions. We hypothesize that this discrepancy arises because EcoCrop does not account for soil water storage, instead assuming that all crop water requirements must be met solely by precipitation during the growing season (Hijmans, 2022). In temperate regions, however, crops often use water reserves accumulated over the wetter winter season. Therefore, we developed a second model on the basis of the first model,

but in this version the precipitation input is replaced with a simplified water balance, accounting for water storage in the soil. We calculated the total available water (AW) in the rooting zone for each month, ensuring that water stored in the soil outside of the growing season is used. The total available water is calculated with Eq. 1, which is based on Kim (1995).

$$AW_1 = AW_0 + P - ET_p \times (AW_0 + AW_1) \div (2 \times AW_{\max}) \quad (1)$$

$$AW_{\max} = AWC \times RD \quad (2)$$

Here AW is available water (mm), P is precipitation (mm), ET_p is Makkink potential evapotranspiration for a reference grassland (mm), AWC is the (plant) available water capacity of the soil (mm/mm) and RD is the rooting zone depth (mm). The AWC is the field capacity minus the wilting point per mm.

In this water balance AW_0 is set as a soil at field capacity ($AW_{\max}$) in January, i.e., set as the AW of January, as it is assumed that most soils are at or near saturation during winter due to higher precipitation and shallow groundwater tables. For the rooting depth, two categories were used based on the average optimal rooting depth per crop, indicated in EcoCrop as ‘shallow (20–50 cm)’ and ‘medium (50–150 cm)’. The depths used in the model were taken as the mean within these categories, and thus 350 and 1000 mm for shallow and medium, respectively. Furthermore, in areas where the MLG was within the rooting zone, the saturated part is set as $AW_{\max}$.

To reflect long-term changes, both versions of the model were applied under current and future climatic and hydrological conditions, as outlined in Section 2.5.

2.5. Model inputs and supporting data

Most data used in this study is open source, or can easily be replaced by open source data. The full list of data with its sources can be found in Supplementary Table 1. The majority of this data needed to be pre-processed or transformed before it could be used. Unless specified otherwise, all data preprocessing, calculations and transformations were performed in R.

2.5.1. Climate data

All climate data used in this study was gathered from the Koninklijk Nederlands Meteorologisch Instituut (KNMI) data platform (KNMI, 2012a, 2012b, 2021). This data had the preference over using WorldClim data due to the availability of more recent data and the use of more measurement stations increasing the spatial accuracy. The precipitation and temperature data from KNMI has a 1×1 km resolution.

Three types of climate data were used: precipitation, temperature and Makkink evaporation. These data consisted of monthly climatological normals for the period of 1981–2010. The Makkink evaporation is the potential evapotranspiration of a hypothetical reference grassland, as also defined for the Penman-Monteith method (Allen and FAO, 1998). To calculate the Makkink evaporation a thin plate spline was performed in ArcGIS Pro to create a potential evapotranspiration map. Data from 16 weather stations in the Netherlands were interpolated with this method to replicate the Makkink evaporation data used by the KNMI in their models (Hiemstra and Sluiter, 2011). Afterwards all data was transformed into 1991–2020 monthly climatological normals by comparing the seasonal average values of 1991–2020 with the 1981–2010 seasonal averages indicated by the KNMI (Klein Tank et al., 2014; van Dorland et al., 2024) to emulate the current climate.

To reflect possible future scenarios, the four climate scenarios of the KNMI 23 (van Dorland et al., 2024) report, were used. These scenarios are the Ld, Ln, Hd and Hn scenarios for 2050. They respectively reflect a low emission increase (L; SSP1–2.6) and a high emission increase (H; SSP5–8.5) scenario, in combination with a dry (d) or wet (n) climate (van Dorland et al., 2024). The 1991–2020 data was transformed into these future scenarios the same way the original 1981–2010 data was

transformed into the 1991–2020 data, by adding or subtracting relative or absolute differences depending on the variable, as outlined in the KNMI'23 report (van Dorland et al., 2024).

2.5.2. Soil data

The soil data used in this study consists of a Dutch soil map from Bodemdata.nl (Wageningen Environmental Research n.d.), which includes soil classifications; soil pH maps with a resolution of 25×25 m from Helfenstein et al. (2022) and clay, silt and sand fraction maps with the same resolution (Helfenstein et al., 2024a). Each of these datasets consisted of maps for different soil depths. For pH the maps for 0–5 cm, 5–15 cm and 15–30 cm were transformed into a 0–30 cm pH map by calculating the weighted average. This depth reflects one of the average depths that is used to determine the suitability of a crop (Koopmans and Brands, 2002; McCauley et al., 2017). For the clay, silt and sand fraction next to the abovementioned ranges the maps for the 30–60 cm and 60–100 cm depths were also used in the weighted average calculation to obtain information on the main texture in the top meter. The depth range of 0–100 cm was chosen as for most crops the effective rooting depth is a maximum of 1 m (Lesschen et al., 2004).

These 0–100 cm clay, silt and sand fraction maps were then used to create a soil texture map with 12 classes, following the USDA Soil Texture Triangle. This map was then overlain with all peat areas that were obtainable from the Dutch soil map to create the final soil texture map of the Netherlands.

2.5.3. Hydrological data

For the current climate scenario, three groundwater table raster datasets with a resolution of 250×250 m in The Netherlands (*excl. the Wadden Islands) were supplied by Deltares. These data are representative for the period of 2013–2019 (De Louw et al., 2022). These datasets are based on groundwater model calculations with the Dutch National Hydrological Instrument (De Lange et al., 2014) and contains: Mean low groundwater table (MLG), mean high groundwater table (MHG) and mean spring groundwater table (MSG). The MLG and MHG are the averages of the three lowest and highest groundwater levels in a hydrological year, respectively. The MSG is obtained by averaging calculated groundwater levels on 14 March, 28 March, and 14 April each year (Nationaal Georegister n.d.). Based on the MHG, MLG and MSG and the seasonal dynamics, we derived the groundwater levels for every month. Furthermore, a yearly average calculated seepage flux representative for the same period, supplied by Deltares, was used.

For the future climatic scenarios in 2050 the so-called 2050 Rust and Stoom Deltascenarios from Deltares' 2017 analysis (Wolters et al., 2018) were gathered from the Informatiepunt Leefomgeving website (Rijkswaterstaat, 2018). Deltares' Deltascenarios provide future projections assessing climate change, socioeconomic changes and water management in the Netherlands to guide adaptation strategies. The Rust and Stoom Deltascenarios reflect a neutral SSP1–2.6 and a dry SSP5–8.5 emission scenario respectively, related to the scenarios used by KNMI'23 and are in essence a re-run of the abovementioned MLG, MHG and MSG datasets, with the effect of the emissions and socioeconomic changes taken into account to generate a prediction for 2050. The same interpolation method as above was applied to create the monthly groundwater table raster datasets for the Rust and Stoom Deltascenarios. Additionally, in the peatlands the groundwater table had been set to a minimum depth of 40 cm below surface for the Stoom scenario and 20 cm below surface for the Rust scenario following the Deltares management advise in the Deltascenarios 2024 (Brugge and Winter, 2024).

2.6. Suitability of the selected crops

Crop suitability was calculated for all areas in the Netherlands with moderate to high potential for paludiculture, using both the EcoCrop model and the water balance extended EcoCrop model. Each raster cell's final suitability score was calculated by using a limiting-factor approach,

where the lowest suitability score among the environmental variables determines the final score. This was repeated for both the current and future climate scenarios. Furthermore, for the current and future scenarios additional model runs were performed in which the precipitation/water balance suitability was skipped, mimicking an 'ideal water management' scenario. This was done since many crops are water limited under current conditions and would be more suitable under flooded conditions. Each output was masked with the selected suitable paludicultural area and saved as a GeoTIFF file and later visualized in a different R script. The minimum, median, mean, maximum, 1st quartile and 3rd quartile suitability scores for each crop were also recorded in an Excel spreadsheet for further analysis.

2.7. Sensitivity analysis of the model

A Monte Carlo simulation was performed to assess the sensitivity of the water balance extended EcoCrop model. This was done exemplary for one crop, *Phalaris arundinacea* (reed canary grass). This crop was selected due to its high spatial variability in predicted suitability under current conditions, making it an ideal crop for illustrating uncertainty with the Monte Carlo simulation. Since the sensitivity analysis was based on propagating uncertainty in spatial input data, and this is the same for all crops, the results of the sensitivity analysis for *Phalaris arundinacea* are also informative for interpreting uncertainty for other crops.

In order to perform Monte Carlo simulation, the standard deviation of the input data at every raster cell location was needed. Since the water balance part of this model is a model itself, a standard deviation of the output, the available water, had to be estimated from evapotranspiration and precipitation data. For the evapotranspiration, a graph of yearly evapotranspiration in the De Bilt by the KNMI was analyzed with an online tool for extracting numerical data from images (Rohatgi n.d.) to determine the yearly standard deviation over the period of 1990–2019. For the precipitation, average yearly precipitation values from the period 1991–2020 were used from weather stations De Bilt, Eelde, Maastricht and Rotterdam to calculate the yearly standard deviation. These were both transformed into monthly standard deviations (SD) and added together to be representative for the AW.

Besides the available water, temperature and pH were also used in the Monte Carlo simulation. For temperature, average yearly temperature in De Bilt from 1991 to 2020 was used to calculate the yearly SD representative for the whole of the Netherlands. The yearly SD was converted into the monthly SD by dividing it by $\sqrt{12}$, an approximation that may underestimate true monthly variability. The De Bilt weather station is deemed representative for the Netherlands for temperature data by the KNMI (KNMI n.d.). For the pH data the SD for 0–30 cm was calculated based on the 0–5 cm, 5–15 cm and 15–30 cm 90 % Prediction Interval (PI90) raster datasets gathered from the data supplied with the paper from Helfenstein et al. (2024). These PI90 width datasets were first divided by 2×1.64 (Sterne and Kirkwood, 2003) and then converted into the variance of the whole 30 cm depth range with an equation adapted from the standard pooled variance equation:

$$\sigma_{0-30}^2 = \frac{\sum w_i \cdot \sigma_i^2 + \sum w_i \cdot (\mu_i - \mu_{0-30})^2}{\sum w_i} \quad (3)$$

In this equation σ_{0-30}^2 is the variance of the whole depth range, σ_i^2 is the variance of each layer, μ_i is the mean pH of each layer, μ_{0-30} is the mean of the whole depth range and w_i is the thickness of each layer.

After this conversion the square root of the output was used as the SD of the pH map. The suitability calculation for the soil texture was run before the Monte Carlo simulation and used as a fixed input map. The Monte Carlo simulation that followed contained 10,000 runs. This data was used to create a map of the average suitability of the 10,000 runs and a variance based on these 10,000 runs to determine the sensitivity. In this Monte Carlo simulation soil texture was not plotted from a

normal distribution but kept as a singular input, as was done for the normal model runs. This method was chosen because soil texture classes are not numeric variables.

3. Results

3.1. Paludicultural area selection

Roughly 25 % of the total land area of the Netherlands (8435 km²) was identified as having a moderate (~25 %) or high (~0.1 %) paludiculture potential from a hydrological perspective given current groundwater levels. This potential paludicultural area in Fig. 2 consists of all peatlands in the Netherlands, as well as clayey and silty areas with a shallow groundwater table, such as river clay areas, river valleys and wetlands. Areas with groundwater levels deeper than 1.6 m are by definition not suitable; these areas amount to about 50 % of the Netherlands and are mostly situated in the sandy soil area (east and south, the Veluwe and coastal dunes, Fig. 1) and the province of Limburg (south-east).

3.2. Current climate crop suitability

Note: *Salix babylonica* var. *sacramenta* (Sacramento weeping willow) and *Zizania latifolia* (Manchurian wild rice) are not shown because predicted suitability was zero for all models, for any climate scenario.

The crop suitability was calculated under current climatic conditions with both models. For every crop that has a non-zero suitability score under the 'EcoCrop' model, the 'EcoCrop + Water balance' model produced higher maximum suitability scores compared to the EcoCrop

model. The reed(grass) species also received higher 3rd quartile values compared to the EcoCrop model. Moreover, multiple crops with a suitability score of zero under the EcoCrop model have higher predicted suitability scores using the 'EcoCrop + Water balance' model. When looking at the distribution of *Phalaris arundinacea* (reed canary grass) and *Typha* spp. (cattail) in the Netherlands (Flora van Nederland n.d.-a, Flora van Nederland, n.d.-b), they are often found on the banks of rivers and streams or at the edges of water bodies (Abel and Kallweit, 2022). The 'EcoCrop + Water balance' model reflects this distribution more accurately than the base model, as these wet areas are included in the area selection. Therefore the rest of the analysis will be performed with the 'EcoCrop + Water balance' model. Moreover, the *Typha* spp. (cattail) and *Vaccinium myrtillus* (European blueberry) have lower mean, median and 3rd quartile suitability values with the 'EcoCrop + Water balance' model because the model accounts for lower available water in coarser grained soils, i.e. soils with poor water storage capacity.

In general the European plants perform better in the Netherlands, due to the climate adaptation, as most Asian crops have warmer ideal growing temperature ranges. Additionally, most Asian potential paludicultural crops seemed to be severely water limited in the Netherlands, resulting in suitability scores of zero. Some of these crops are usually cultivated in standing water or extreme wet conditions.

To investigate the potential suitability in case of ideal water management, e.g. raising of the groundwater level as would be the case under paludiculture conditions, the water balance calculation was neglected for this model run, resulting in a suitability calculation only based on temperature and soil variables. Fig. 4 shows that the suitability of nearly every potential crop is significantly higher when water management is ideal, compared to the current state of available water in the

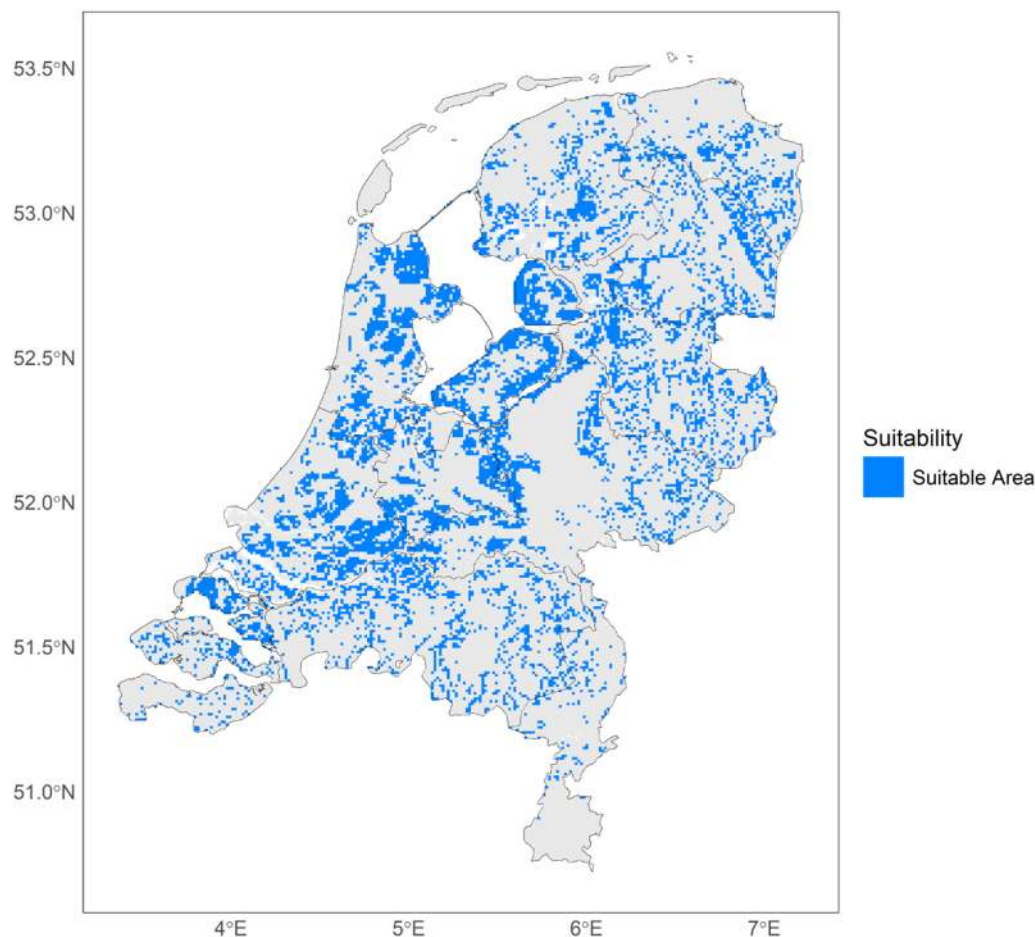


Fig. 2. Area suitable for paludiculture, based on hydrology.

soil (Fig. 3). Fig. 4 also shows that *Ipomoea aquatica* (water spinach), *Nasturtium officinale* (watercress), *Echinochloa crus-galli* (barnyard grass) and *Oryza sativa* (rice) under right circumstances can be grown in the selected area if the water tables are raised to mitigate water limitation. *Colocasia esculenta* (taro) and *Trapa natans* (water chestnut) are mostly temperature limited, as the maximum suitability barely increases in case of ideal water management.

In the 'EcoCrop + Water balance' model *Vaccinium myrtillus* (European blueberry) had the highest mean suitability, with a mean of 0.39, while *Typha angustifolia* (narrowleaf cattail) and *Typha latifolia* (broadleaf cattail) had the highest maximum suitability. For the 'EcoCrop + Ideal water management' model *Typha angustifolia* and *Typha latifolia* had the highest mean suitability, 0.63 and 0.64 respectively, with notably the *Ipomoea aquatica* (water spinach) having the 4th highest mean, with a suitability of 0.57. All suitability scores can be found in tables 3 up to 13 in the [Supplementary Tables](#).

In general, the western part of the Netherlands seemed to be favorable for most paludicultural crops because of shallower groundwater tables and loamy and peaty soils, which have higher available water capacities. For around half of the crops, peatlands were suitable under current conditions, but were not in all cases the most suitable areas when increasing the water table, e.g., *Vaccinium macrocarpon* (cranberry) and *Vaccinium myrtillus* (European blueberry) prefer the sandy soils in the east and south of the Netherlands. Additionally, heavy-textured soils, such as those found in the polders (e.g., in Flevoland) and around the rivers are amongst the most suitable soils for paludiculture owing to high AWC. To illustrate this point, two crops will be presented here, while maps of all the other crops can be found in the [Supplementary Figures 1–12](#).

Fig. 5 shows that the areas suitable for *Oryza sativa* (rice) cultivation under current conditions are peatlands (see Fig. 1). These are especially suitable due to the amount of soil moisture peat can retain. In case of ideal water management, more areas were suitable, owing to increased water availability. This includes other peatlands, clayey soils and even sandy soils with high groundwater tables and/or considerable upward water seepage.

For *Typha angustifolia* (narrowleaf cattail) a similar spatial pattern as for *Oryza sativa* (rice) is observed, though with higher suitability values,

especially under ideal water management. Fig. 6 shows that for some crops, certain peat areas in the Netherlands only experience reduced suitability due to water limitation, resulting in suitability scores of 1 in panel B where ideal hydrological conditions are assumed. In contrast, these same areas in panel B of Fig. 5, which represents the suitability of *Oryza sativa* under ideal hydrological conditions, shows only a slight increase in suitability, suggesting more limitations than only water availability.

3.3. Future climate crop suitability

The effects of climate change on the suitability of crops varies. Panel A in Fig. 7 shows that under current conditions the maximum suitability increased for most crops under future climate scenarios. For around half of the crops the dry scenarios resulted in a higher maximum suitability. Some notable results are that *Vaccinium macrocarpon* (cranberry) and *Vaccinium myrtillus* (European blueberry) have lower suitability scores for all future scenarios while *Phragmites australis* (common reed) has higher suitability scores for future scenarios. In general these boxplots suggest that the drier conditions negatively impact the suitability of some European crops, while temperature increase positively affect some of the East Asian crops.

When considering ideal water management (Fig. 7B), which means a raised groundwater table for most crops, either for uptake or optimal growth conditions, the results are significantly different from the scenario including water requirements (Fig. 7A). Panel B shows a minimal effect of climate change on the suitability of most European crops, but three out of seven do show a distinct response. Specifically *Phalaris arundinacea* (canary reed grass) and *Phragmites australis* (common reed) show a positive effect due to increasing temperatures, while *Vaccinium myrtillus* (European blueberry) experiences a decrease in suitability, as it prefers lower temperatures. Another observation that can be made is that the suitability values for *Ipomoea aquatica* (water spinach) and *Typha spp.* (cattail) are all the same across the climate scenarios in panel B. This is because suitability of those plants is limited by soil conditions rather than climate. In contrast to European crops, East Asian crops tend to perform better under future climatic conditions, with increases in 3rd quartile, mean and maximum suitability scores due to higher

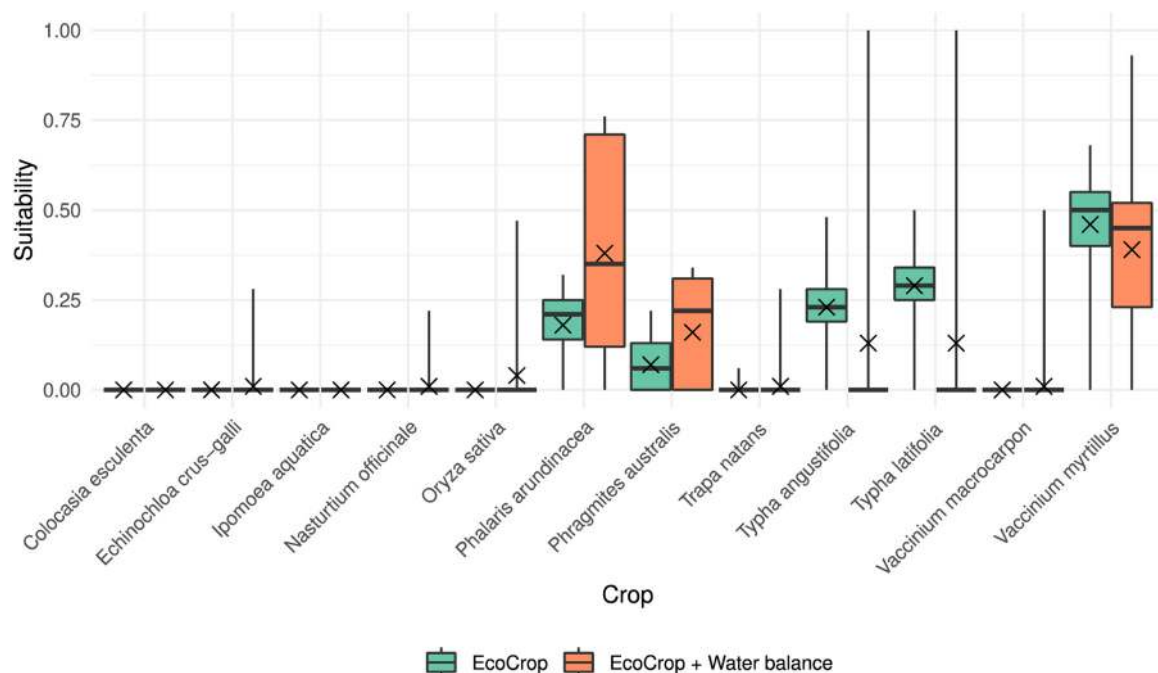


Fig. 3. Boxplot of suitability values per crop for the EcoCrop and 'EcoCrop + Water balance' models under current climatic conditions; crosses represent the mean suitability values.

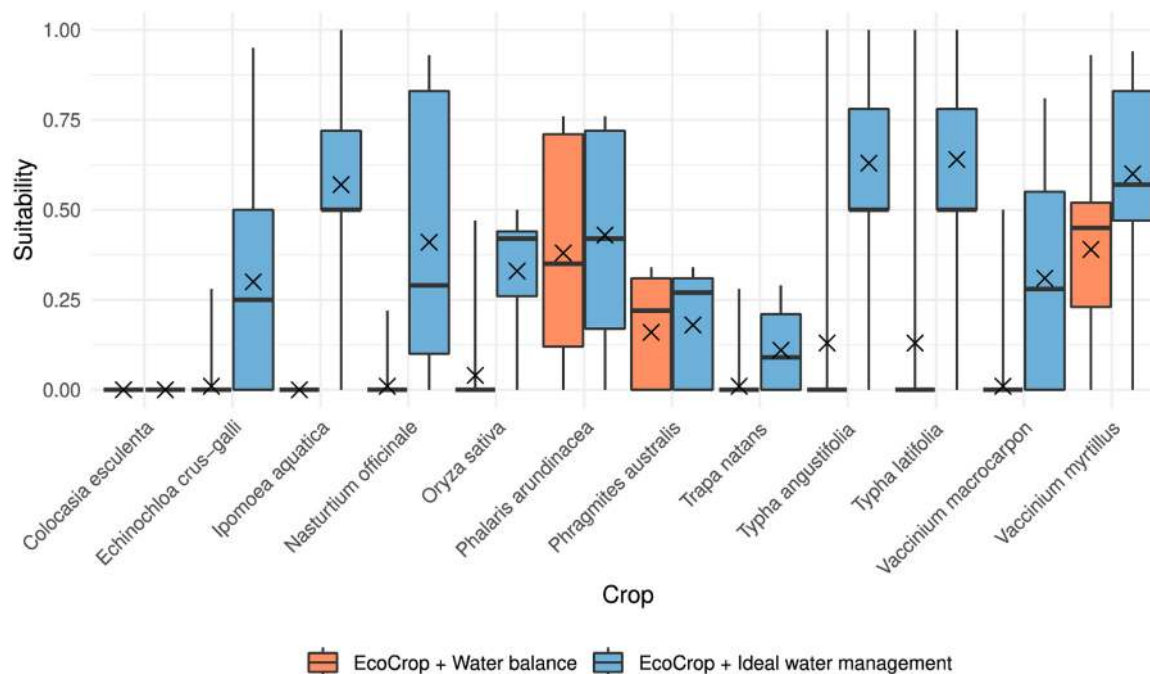


Fig. 4. Boxplot of suitability values per crop for the 'EcoCrop + Water balance' and 'EcoCrop + Ideal water management' models under current climatic conditions; crosses represent the mean suitability values. Increase in suitability for all crops except for *Colocasia esculenta* (taro).

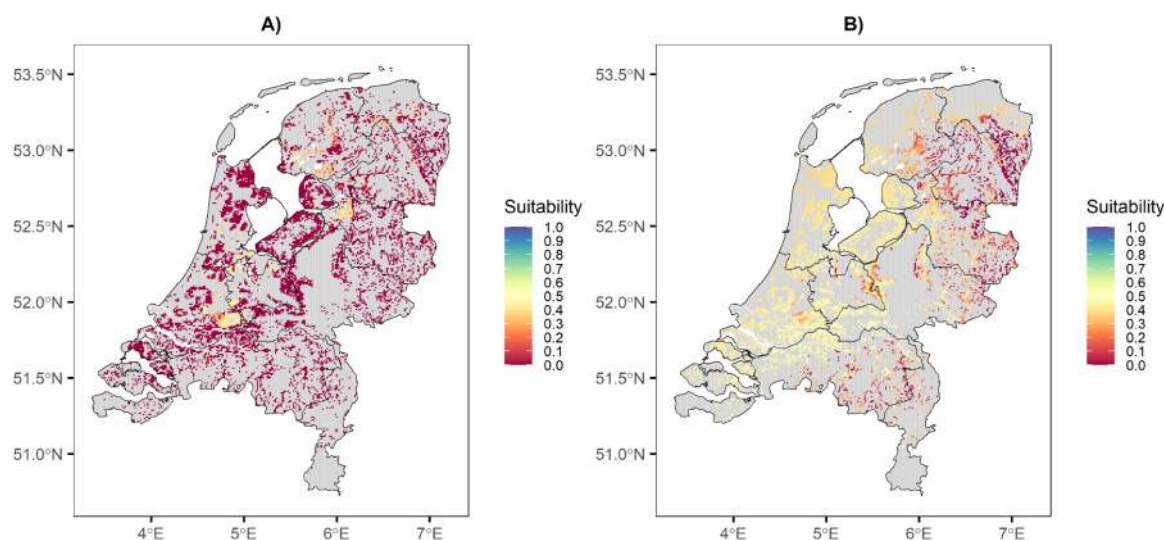


Fig. 5. Suitability maps under current climate for *Oryza sativa* (rice). A) 'EcoCrop + Water balance' model, B) 'EcoCrop + Ideal water management' model.

temperatures in the growing season. For spatial changes between the future climate scenarios, please consult [Supplementary Figures 13–36](#).

3.4. Sensitivity analysis

In general, the sensitivity analysis showed that the areas with a high suitability score ([Fig. 8A](#)) also had a high variance ([Fig. 8B](#)). This occurs because in areas with higher suitability, and thus near or within ideal input variable ranges, small changes in input parameters can produce larger swings in suitability. However, several areas had particularly high variance in predictions. These include parts of Zeeland; around the provincial border where North-Holland, South-Holland and Utrecht come together; and a C-shaped area in the east of South-Holland. Especially South-Holland, which has many areas with moderate suitability (0.3–0.4), exhibits higher variance than some of the more

suitable areas in Flevoland. This suggests that suitability and variance are often related, but other factors like uncertainty in precipitation, temperature, or pH data contribute to uncertainty. However, overall, variance remains relatively low (< 0.1) across most of the Netherlands, signifying stable model predictions.

4. Discussion

The spatial suitability modelling of 12 paludicultural crops across the Netherlands under current and future climate entails several novelties. This study complements existing field trials with paludicultural crops ([de Jong et al., 2021](#); [Geurts and Fritz, 2018](#); [Liu et al., 2023](#); [Ren et al., 2019](#)) by providing the first spatial paludicultural suitability analysis on a national scale. Furthermore, this research includes East Asian crops, which have often been overlooked in European paludicultural research

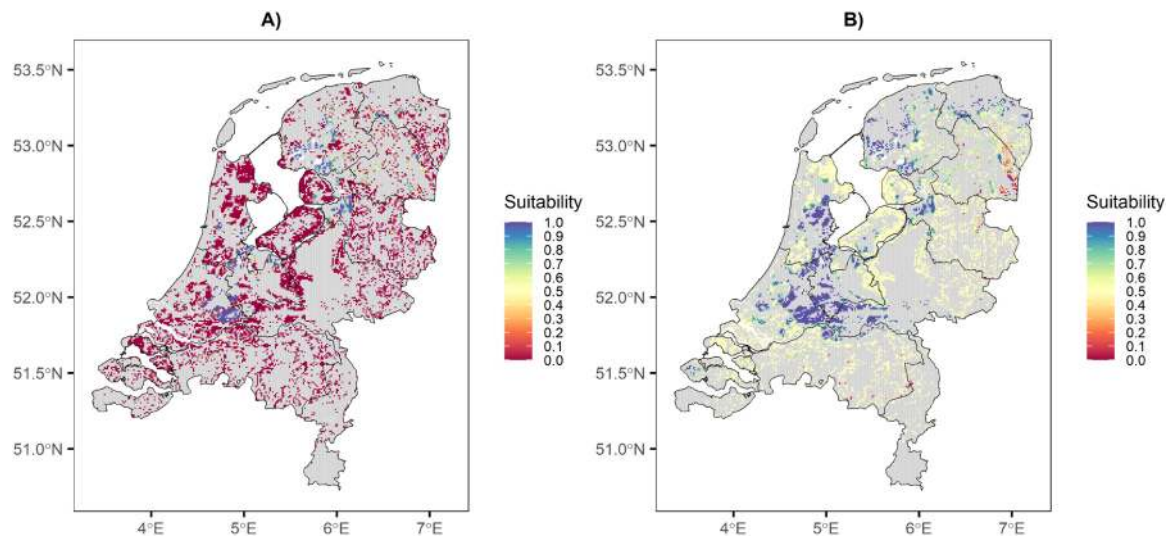


Fig. 6. Suitability maps under current climate for *Typha angustifolia* (narrowleaf cattail). A) 'EcoCrop + Water balance' model, B) 'EcoCrop + Ideal water management' model.

(Geurts and Fritz, 2018; Liu et al., 2023; Ren et al., 2019; Temmink et al., 2026; Vroom et al., 2022), but could contribute to food security and be more attractive economically due to existing value chains and markets. Finally, the developments of the EcoCrop model undertaken in this study, including a water balance function and soil suitability, has potential to improve crop suitability predictions in future studies, also for non-paludicultural applications.

4.1. Implications for paludiculture in NW Europe

While field experiments have been setup in various places across NW Europe to test paludicultural crops (de Jong et al., 2021; Geurts and Fritz, 2018; Liu et al., 2023; Old crops in new places, 2025; Ren et al., 2019), our study adds large scale spatial information of where which crops are suitable. Comparison of the 'EcoCrop + Water balance' with 'EcoCrop + Ideal water management' under current climatic conditions (Fig. 4 and Supplementary Figures), shows that the suitability scores of many crops improve under ideal water management. In most cases this is because in present conditions there is less water available in the soil than would be ideal for the crops. The five crops with the highest maximum suitability score under current climate are incidentally also five out of six crops that have peat as an optimal soil texture. For *Typha* spp. (cattail) and *Oryza sativa* (rice), most peat areas are indeed the most suitable areas, but for *Phalaris arundinacea* (reed canary grass) and *Vaccinium myrtillus* (European blueberry) this is not the case due to problems with the pH and wetness respectively. However, in peatlands where the pH is too low for cultivation of these crops, liming could be considered (Nursyamsi et al., 2016).

For many potential crops the east and south of the Netherlands seems unsuitable for cultivation, even when looking at the 'EcoCrop + Ideal water management' model results in Supplementary Figures. For most crops this is caused by a combination of low soil pH (Helfenstein et al., 2022), and an unsuitable or marginally suitable soil texture (Helfenstein et al., 2024a). In specific cases, e.g. *Nasturtium officinale* (watercress), the low suitability score is only caused by the soil pH. According to EcoCrop only the *Vaccinium* spp. prefer light textured soils (FAO, 2022), which is also reflected in the relatively high suitability scores for this crop in the south and east of the Netherlands (Supplementary Fig. 19).

While the suitability of European potential paludicultural crops is often water limited and/or pH limited, for East Asian crops it is often also temperature limited. Regarding the water limitation of European crops, Fig. 4 shows a significant increase in 1st to 3rd quartile suitability scores of the *Typha* spp. (cattail) which corresponds with the findings of

Geurts and Fritz (2018). They state that the biomass production of *Typha latifolia* (broadleaf cattail) increases with an increase in groundwater level from 20 cm below surface to 20 cm above surface. They also mention that there is no such increase for the *Phragmites australis* (common reed) (Geurts and Fritz, 2018), which can also be seen in the negligible effect on the suitability score in Fig. 4. While their research was performed on peatland, this water table effect can be translated to other suitable soil types as well. Concerning the East Asian crops, panel B of Fig. 7 shows that the maximum suitability scores of *Colocasia esculenta* (taro), *Oryza sativa* (rice) and *Trapa natans* (water chestnut) are higher, maximally 0.07, 0.17 and 0.25 respectively, in the future scenarios than under current climatic conditions for the 'EcoCrop + Ideal water management' model. There the SSP5–8.5 dry and wet scenarios (Hd and Hn) receive higher values than the SSP1–2.6 dry and wet scenarios (Ld and Ln), indicating that the temperature increase positively influences the suitability of the crops. Considering this positive effect, cultivation of East Asian crops in the Netherlands could be a worthwhile investment for the future in case global temperatures keep rising. As Redhead et al. (2025) has shown for the UK, current cultivated crops might become less favourable in the future, increasing the need for exploring alternative crops. Better water management, to maintain raised groundwater tables, will be needed to make use of this increased suitability as dry and warm future climate scenarios will have a negative effect on the groundwater tables (Ma et al., 2022). Maintaining raised groundwater levels will require significant water resources in summer, and might conflict with other demands for water use. These water demands must be carefully weighed when using paludiculture as a strategy to mitigate land subsidence and reduce CO₂ emissions (Temmink et al., 2026). Furthermore, to effectively evaluate future-proof strategies, it is essential to extend the analysis beyond immediate planning horizons. For 2050 most of the selected European potential paludicultural crops retain the same suitability score if managed well, showing short term climate resilience. Climate scenarios for 2100 would need to be used to further investigate the effect of increasing temperatures on European crops and whether East Asian crops could be more suitable for paludicultural cultivation in the future than European crops.

Using *Phalaris arundinacea* (reed canary grass) for the sensitivity analysis provided insight in the main causes for variance in the model. When investigating the Helfenstein et al. (2024a) dataset to check the uncertainty in the pH data, it was visible that the areas directly adjacent to the rivers in the western part of the Netherlands had significantly higher uncertainty values than the areas in between the rivers. This is visible in panel B of Fig. 8 as the dark orange c-shape. In addition, areas

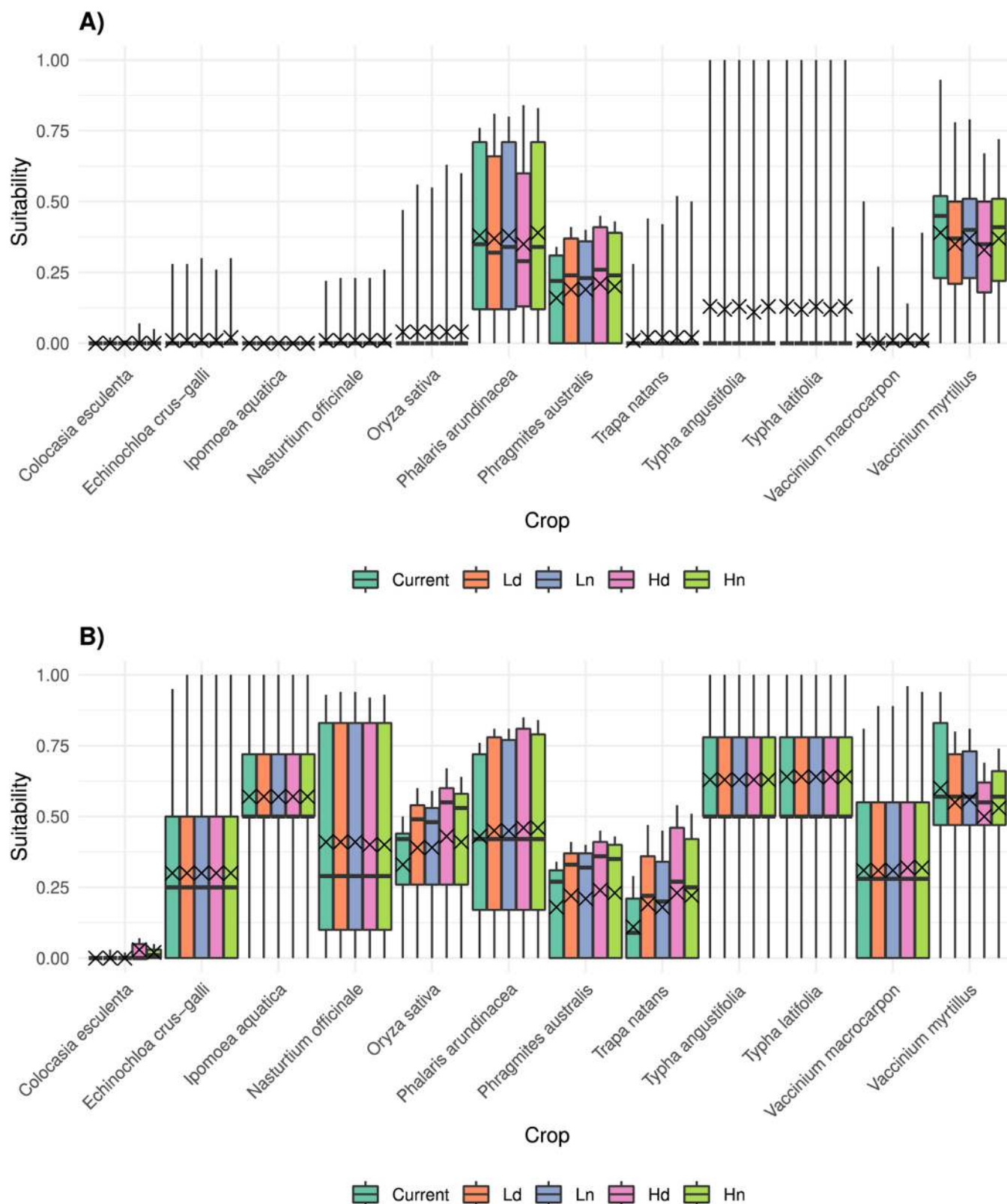


Fig. 7. Boxplots of suitability values per crop under current and future climatic conditions. A) 'EcoCrop + Water balance' model, B) 'EcoCrop + Ideal water management' model; crosses represent the mean suitability values. 'L' and 'H' are SSP1–2.6 and SSP5–8.5 respectively, 'd' is dry and 'n' is the wet scenario.

influenced by paleochannels and reclaimed lakes have a higher uncertainty. Especially the area influenced by the Oude Rijn between Leiden and Bodegraven seems to have an unusually large pH uncertainty, which is also reflected in the variance in panel B. With more exact pH

measurements this variance could be significantly reduced as the pH in these areas seems mostly based on the pH of other areas with the same geomorphology, which is an important covariate in the data of [Helfenstein et al., \(2024a\)](#), showing that the measurement density is low.

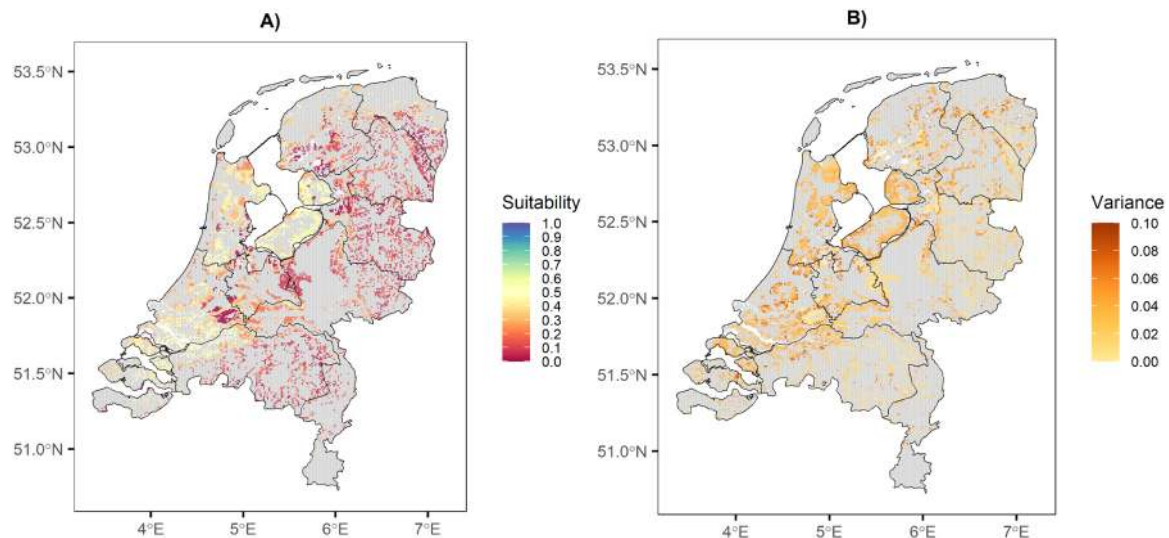


Fig. 8. Outputs from a Monte Carlo simulation with 10,000 runs for *Phalaris arundinacea* (reed canary grass). A) Average suitability map under current climate with the 'EcoCrop + Water balance' model, B) Spatial variance map.

As the Netherlands is characterized by its intensive agriculture and dairy farming, follow-up research should consider economic viability of paludicultural crops, also including East Asian crops. For *Typha* spp. (cattail), *Phragmites australis* (common reed) and Sphagnum moss, some economical assessments have been performed (de Jong et al., 2021; Wichmann, 2021), but other crops have not yet been extensively researched (Temmink et al., 2026). As site data, biomass yield, machinery and labor costs all play a role in the variability of the cost-benefit calculations, various scenarios should be used (Tanneberger et al., 2022). It is especially important to consider differences between the cultivation of crops that are used for fiber and biofuel production and the cultivation of crops that contribute to food security. As crops like *Oryza sativa* (rice) and *Colocasia esculenta* (taro) already have an existing value chain, researching these crops for paludiculture can be more beneficial due to their higher economic viability. Rice in particular can be an interesting future crop in the Netherlands, as witnessed by the northward movement of the crop both in Europe (Old crops in new places, 2025) and NE United States (Liao et al., 2025). Another point of interest could be researching the potential of economic and environmentally sustainable crop rotations. In peatlands the practical challenge of cultivating crops at industrial scale remains, e.g. agronomical practices that maximize synergistic environmental effects of growing crops and machinery that is compatible with low carrying capacity of the soils and does not harm soil structure.

4.2. Improvements, limitations and recommendations for using the EcoCrop model

By adding a suitability calculation based on soil variables and replacing the precipitation suitability calculation with a water balance function, the EcoCrop model now incorporates natural processes in a more realistic way. This enhancement is expected to more accurately reflect real-world crop suitability compared to the base EcoCrop model used in earlier studies (e.g. Heinz et al., 2024; Manners et al., 2020; Ramirez-Villegas et al., 2013; Redhead et al., 2025). Neglecting any soil-based crop requirements in calculating suitability scores can cause significant overestimations of the suitability, resulting in overly optimistic and potentially misleading implications (Navidi et al., 2022). Implementing the water balance function in EcoCrop further enhanced the model, as the higher suitability scores of *Phalaris arundinacea* (reed canary grass) and *Typha* spp. (cattail) as well as the slightly increased suitability of *Phragmites australis* (common reed) better reflected the actual suitability of these crops based on their abundance and spatial

distribution (Flora van Nederland n.d.-a, Flora van Nederland n.d.-a, Flora van Nederland, n.d.-b).

Future studies researching the suitability with the EcoCrop model should implement a water balance function to give a more realistic depiction of suitability. Previous studies that did not include a water balance in their EcoCrop suitability calculations likely underestimated or overestimated the suitability (Heinz et al., 2024; Manners et al., 2020; Salgado-Velázquez et al., 2025). To be able to implement a water balance, year-round data on precipitation, evapotranspiration and groundwater levels are needed. Furthermore, the available water capacity of the soil, based on soil texture is needed to finalize this water balance.

This paludiculture research did however contain several limitations. The selection of the potential paludicultural crops was restricted by the available information about growing parameters of the crops. Even when all data was available in the EcoCrop database (FAO, 2022), since many of these plants are not well-researched, some data had incomplete references, untraceable sources or possibly outdated information, which gives reason to question the correctness of the crop requirements. Moreover, some of these parameters or crop information for the in Europe occurring crops is based on measurements or literature from outside of Europe. The existence of different varieties potentially adapted to a different climate, may result in worse suitability scores when using them in the EcoCrop model. An example of this is the *Salix babylonica* var. *sacramenta*, this weeping willow variant was completely unsuitable for paludiculture in the Netherlands according to the model. In reality, although not native to the country, the weeping willow does grow in the Netherlands, but is most likely the *Salix alba* 'Tristis' (North Carolina State University n.d.) or *Salix sepulcralis* (International Dendrology Society n.d.).

A further limitation is that salinity, and particularly salinity of the upward seepage, is not used as an input for the suitability assessment, but could improve the model to give a more accurate indication whether crops can actually grow in the locations that are now deemed suitable enough. This is particularly relevant in coastal areas and in future scenarios, where more salt water intrusion is expected (Pauw et al., 2014).

Lastly, the water balance could be further improved with more accurate data, especially in applications with crops for which more data is available. By using the Makkink ET, the evapotranspiration is only an approximation, as this is a reference evapotranspiration based on a well-watered grass surface and not the crop itself (de Bruin and Lablans, 1998). This does already improve the model compared to the model which did not include the water balance, but does not reflect reality

accurately. By deriving crop factors for paludicultural crops, as they are currently unavailable, the model could be enhanced further. Using these crop factors combined with a daily timescale for all spatiotemporal variables would improve the model to reflect reality more accurately. Another way to improve the model is by validating the water balance with another model. Process-based agro-hydrological models like the SWAP model (Kroes et al., 2017) or AquaCrop (Vanuytrecht et al., 2014) could be used for this purpose. These models can also be coupled to the EcoCrop model to simulate the stresses exerting on the crops by replacing the water balance function. The output of these models can then be combined with the suitability based on soil variables in EcoCrop to create a suitability map. A possible way to implement this would be to create multiple classes for each hydrological variable within the potential paludicultural area that was selected beforehand. Then the most occurring combinations of classes could be used as inputs for the SWAP or AquaCrop model whereafter it can be combined with the soil variable based suitability of those areas.

While EcoCrop is useful for screening many crops, especially those with limited information on crop growth parameters (Heinz et al., 2024; Manners et al., 2020), more targeted research on individual crops should consider crop specific models, where available. An example is ORYZA, an ecophysiological model for predicting the growth and yield of rice in an irrigated lowland ecosystem (Li et al., 2017), which could be calibrated for the Netherlands.

This study serves as an essential first step towards extensive paludiculture research, providing a baseline assessment of crop suitability. Besides the interest in paludiculture, this study could be taken as an example for exploring possibilities for cultivating new crops, as an adaptation strategy to climate change (Old crops in new places, 2025). While suitability maps offer valuable initial insights, they are based on broad general relationships and should be enhanced with more detailed investigations to refine the integration of specific crop-environment interactions (Akpoti et al., 2019). Future studies should incorporate more localized environmental variables, crop-specific environmental preferences, and extended modeling approaches to ensure the most accurate suitability assessments for paludiculture implementation.

5. Conclusion

Overall, a quarter of the Netherlands' surface area has been identified as having the potential for paludiculture based on hydrological variables. Within this area, peatlands were identified as ideal locations due to shallow water tables and high available water capacity. Additionally, areas characterized by lateral water inflow, such as river valleys, as well as low lying fine grained soils such as silty and clayey soils—due to their water holding capacity—were also identified to have high potential for paludiculture.

Appendix A: Data sources and soil type classification

Table 1

Overview of data used in this study and its sources

Data type	Data description	Source
Precipitation maps	Gridded average monthly precipitation 1981–2010 at 1 km resolution	(KNMI, 2012a)
Temperature maps	Gridded average monthly precipitation 1981–2010 at 1 km resolution	(KNMI, 2012b)
Makkink ET data from climate normals	1991–2020 climate normals per 10 days per automatic weather station	(KNMI, 2021)
Soil type map	Soil type map 1:50,000	(Wageningen Environmental Research, n.d.)
pH map	pH map for depths 0–5 cm, 5–15 cm, 15–30 cm at 25 m resolution in the Netherlands	(Helfenstein et al., 2024b)
Soil texture maps	Clay, sand and silt maps for depths 0–5 cm, 5–15 cm, 15–30 cm, 30–60 cm, 60–100 cm at 25 m resolution in the Netherlands	(Helfenstein et al., 2024b)

(continued on next page)

By integrating a water balance function in the EcoCrop model, which was an unexplored concept in EcoCrop modelling, the suitability assessment could more realistically represent the real-world crop suitability. Within the abovementioned area, *Typha angustifolia* (narrowleaf cattail) and *Typha latifolia* (broadleaf cattail) were found to be most suitable under current conditions. Also *Vaccinium myrtillus* (European blueberry) and *Phalaris arundinacea* (reed canary grass) were suitable, with a well spread suitability over the whole potential paludicultural area. Another notable crop was *Oryza sativa* (rice), which suitability in the high-emission dry and wet climate scenarios for 2050 came close to that of *Vaccinium myrtillus*.

Under ideal water management, which in most cases means raising the water tables, the largest improvers compared to the current conditions situation are *Ipomoea aquatica* (water spinach) and *Nasturtium officinale* (watercress). *Ipomoea aquatica* especially received suitability scores comparable to those of *Typha* spp. (cattail) while *Nasturtium officinale* (watercress) and *Echinochloa crus-galli* (barnyard grass) reached suitability scores higher than *Vaccinium myrtillus* (European blueberry) for the future scenarios, due to increased temperatures. In case of more severe temperature increase, for instance using 2100 climate scenarios, *Oryza sativa* (rice), *Colocasia esculenta* (taro) *Trapa natans* (water chestnut) and *Phragmites australis* (common reed) would receive significantly higher suitability scores as they are still temperature limited under the 2050 SSP5–8.5 climate conditions.

CRedit authorship contribution statement

Ruben T. Brouwer : Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis. **Kim C.I. van Etten**: Software. **Perry G.B. de Louw**: Writing – review & editing, Supervision. **Jakob Wallinga**: Writing – review & editing. **Julian Helfenstein**: Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Table 1 (continued)

Data type	Data description	Source
Groundwater table maps current climate	2013–2019 MLG, MHG and MSG maps of the Netherlands at 250 m resolution	(De Louw et al., 2022)
Seepage maps	2013–2019 Seepage map of the Netherlands at 250 m resolution	(De Louw et al., 2022)
Groundwater table maps future climate	MLG, MHG and MSG maps of the Netherlands at 250 m resolution for Rust and Stoom 2050 Deltascenario	(Rijkswaterstaat, 2018)

Table 2

EcoCrop soil texture classification based on USDA classification

Soil texture EcoCrop	Soil texture USDA + peat
Light	Sand & Loamy Sand
Medium	Sandy Loam, Loam, Silt, Silt Loam & Sandy Clay Loam
Heavy	Clay Loam, Silty Clay Loam, Sandy Clay, Silty Clay & Clay
Organic	Peat

Appendix B: Summary statistics per crop per model

Current Climate Suitability

Table 3

Summary statistics of the suitability scores per crop under current climate using the base EcoCrop model

	Min	1st Qu.	Median	Mean	3rd Qu.	Max
<i>Colocasia esculenta</i>	0	0	0	0	0	0
<i>Echinochloa crus-galli</i>	0	0	0	0	0	0
<i>Ipomoea aquatica</i>	0	0	0	0	0	0
<i>Nasturtium officinale</i>	0	0	0	0	0	0
<i>Oryza sativa</i>	0	0	0	0	0	0
<i>Phalaris arundinacea</i>	0	0.14	0.21	0.18	0.25	0.32
<i>Phragmites australis</i>	0	0	0.06	0.07	0.13	0.22
<i>Trapa natans</i>	0	0	0	0	0	0.06
<i>Typha angustifolia</i>	0	0.19	0.23	0.23	0.28	0.48
<i>Typha latifolia</i>	0	0.25	0.29	0.29	0.34	0.5
<i>Vaccinium macrocarpon</i>	0	0	0	0	0	0
<i>Vaccinium myrtillus</i>	0	0.4	0.5	0.46	0.55	0.68

Table 4

Summary statistics of the suitability scores per crop under current climate using the 'EcoCrop + Water balance' model

	Min	1st Qu.	Median	Mean	3rd Qu.	Max
<i>Colocasia esculenta</i>	0	0	0	0	0	0
<i>Echinochloa crus-galli</i>	0	0	0	0.01	0	0.28
<i>Ipomoea aquatica</i>	0	0	0	0	0	0
<i>Nasturtium officinale</i>	0	0	0	0.01	0	0.22
<i>Oryza sativa</i>	0	0	0	0.04	0	0.47
<i>Phalaris arundinacea</i>	0	0.12	0.35	0.38	0.71	0.76
<i>Phragmites australis</i>	0	0	0.22	0.16	0.31	0.34
<i>Trapa natans</i>	0	0	0	0.01	0	0.28
<i>Typha angustifolia</i>	0	0	0	0.13	0	1
<i>Typha latifolia</i>	0	0	0	0.13	0	1
<i>Vaccinium macrocarpon</i>	0	0	0	0.01	0	0.5
<i>Vaccinium myrtillus</i>	0	0.23	0.45	0.39	0.52	0.93

Table 5

Summary statistics of the suitability scores per crop under current climate using the 'EcoCrop + Ideal water management' model

	Min	1st Qu.	Median	Mean	3rd Qu.	Max
<i>Colocasia esculenta</i>	0	0	0	0	0	0
<i>Echinochloa crus-galli</i>	0	0	0.25	0.3	0.5	0.95
<i>Ipomoea aquatica</i>	0	0.5	0.5	0.57	0.72	1
<i>Nasturtium officinale</i>	0	0.1	0.29	0.41	0.83	0.93
<i>Oryza sativa</i>	0	0.26	0.42	0.33	0.44	0.5
<i>Phalaris arundinacea</i>	0	0.17	0.42	0.43	0.72	0.76
<i>Phragmites australis</i>	0	0	0.27	0.18	0.31	0.34
<i>Trapa natans</i>	0	0	0.09	0.11	0.21	0.29
<i>Typha angustifolia</i>	0	0.5	0.5	0.63	0.78	1
<i>Typha latifolia</i>	0	0.5	0.5	0.64	0.78	1
<i>Vaccinium macrocarpon</i>	0	0	0.28	0.31	0.55	0.81
<i>Vaccinium myrtillus</i>	0	0.47	0.57	0.6	0.83	0.94

*Future Climate suitability***Table 6**

Summary statistics of the suitability scores per crop under the SSP1–2.6 and dry climate scenario (Ld), using the 'EcoCrop + Water balance' model

	Min	1st Qu.	Median	Mean	3rd Qu.	Max
<i>Colocasia esculenta</i>	0	0	0	0	0	0.02
<i>Echinochloa crus-galli</i>	0	0	0	0.01	0	0.28
<i>Ipomoea aquatica</i>	0	0	0	0	0	0
<i>Nasturtium officinale</i>	0	0	0	0.01	0	0.23
<i>Oryza sativa</i>	0	0	0	0.04	0	0.56
<i>Phalaris arundinacea</i>	0	0.12	0.32	0.37	0.66	0.81
<i>Phragmites australis</i>	0	0	0.24	0.19	0.37	0.41
<i>Trapa natans</i>	0	0	0	0.02	0	0.44
<i>Typha angustifolia</i>	0	0	0	0.12	0	1
<i>Typha latifolia</i>	0	0	0	0.12	0	1
<i>Vaccinium macrocarpon</i>	0	0	0	0	0	0.27
<i>Vaccinium myrtillus</i>	0	0.21	0.37	0.35	0.5	0.78

Table 7

Summary statistics of the suitability scores per crop under the SSP1–2.6 and dry climate scenario (Ld), using the 'EcoCrop + Ideal water management' model

	Min	1st Qu.	Median	Mean	3rd Qu.	Max
<i>Colocasia esculenta</i>	0	0	0	0	0	0.03
<i>Echinochloa crus-galli</i>	0	0	0.25	0.3	0.5	1
<i>Ipomoea aquatica</i>	0	0.5	0.5	0.57	0.72	1
<i>Nasturtium officinale</i>	0	0.1	0.29	0.41	0.83	0.94
<i>Oryza sativa</i>	0	0.26	0.49	0.39	0.54	0.6
<i>Phalaris arundinacea</i>	0	0.17	0.42	0.45	0.78	0.81
<i>Phragmites australis</i>	0	0	0.33	0.22	0.37	0.41
<i>Trapa natans</i>	0	0	0.22	0.19	0.36	0.47
<i>Typha angustifolia</i>	0	0.5	0.5	0.63	0.78	1
<i>Typha latifolia</i>	0	0.5	0.5	0.64	0.78	1
<i>Vaccinium macrocarpon</i>	0	0	0.28	0.31	0.55	0.89
<i>Vaccinium myrtillus</i>	0	0.47	0.57	0.55	0.72	0.8

Table 8

Summary statistics of the suitability scores per crop under the SSP1–2.6 and wet climate scenario (Ln), using the 'EcoCrop + Water balance' model

	Min	1st Qu.	Median	Mean	3rd Qu.	Max
<i>Colocasia esculenta</i>	0	0	0	0	0	0.01
<i>Echinochloa crus-galli</i>	0	0	0	0.01	0	0.3
<i>Ipomoea aquatica</i>	0	0	0	0	0	0
<i>Nasturtium officinale</i>	0	0	0	0.01	0	0.23
<i>Oryza sativa</i>	0	0	0	0.04	0	0.55
<i>Phalaris arundinacea</i>	0	0.12	0.34	0.38	0.71	0.8
<i>Phragmites australis</i>	0	0	0.23	0.19	0.36	0.4
<i>Trapa natans</i>	0	0	0	0.02	0	0.42
<i>Typha angustifolia</i>	0	0	0	0.13	0	1

(continued on next page)

Table 8 (continued)

	Min	1st Qu.	Median	Mean	3rd Qu.	Max
<i>Typha latifolia</i>	0	0	0	0.13	0	1
<i>Vaccinium macrocarpon</i>	0	0	0	0.01	0	0.41
<i>Vaccinium myrtillus</i>	0	0.23	0.4	0.37	0.51	0.79

Table 9

Summary statistics of the suitability scores per crop under the SSP1–2.6 and wet climate scenario (Ln), using the ‘EcoCrop + Ideal water management’ model

	Min	1st Qu.	Median	Mean	3rd Qu.	Max
<i>Colocasia esculenta</i>	0	0	0	0	0	0.02
<i>Echinochloa crus-galli</i>	0	0	0.25	0.3	0.5	1
<i>Ipomoea aquatica</i>	0	0.5	0.5	0.57	0.72	1
<i>Nasturtium officinale</i>	0	0.1	0.29	0.41	0.83	0.94
<i>Oryza sativa</i>	0	0.26	0.48	0.39	0.53	0.59
<i>Phalaris arundinacea</i>	0	0.17	0.42	0.45	0.77	0.81
<i>Phragmites australis</i>	0	0	0.32	0.21	0.37	0.4
<i>Trapa natans</i>	0	0	0.2	0.18	0.34	0.45
<i>Typha angustifolia</i>	0	0.5	0.5	0.63	0.78	1
<i>Typha latifolia</i>	0	0.5	0.5	0.64	0.78	1
<i>Vaccinium macrocarpon</i>	0	0	0.28	0.31	0.55	0.89
<i>Vaccinium myrtillus</i>	0	0.47	0.57	0.56	0.73	0.81

Table 10

Summary statistics of the suitability scores per crop under the SSP5–8.5 and dry climate scenario (Hd), using the ‘EcoCrop + Water balance’ model

	Min	1st Qu.	Median	Mean	3rd Qu.	Max
<i>Colocasia esculenta</i>	0	0	0	0	0	0.07
<i>Echinochloa crus-galli</i>	0	0	0	0.01	0	0.26
<i>Ipomoea aquatica</i>	0	0	0	0	0	0
<i>Nasturtium officinale</i>	0	0	0	0.01	0	0.23
<i>Oryza sativa</i>	0	0	0	0.04	0	0.63
<i>Phalaris arundinacea</i>	0	0.13	0.29	0.35	0.6	0.84
<i>Phragmites australis</i>	0	0	0.26	0.21	0.41	0.45
<i>Trapa natans</i>	0	0	0	0.02	0	0.52
<i>Typha angustifolia</i>	0	0	0	0.11	0	1
<i>Typha latifolia</i>	0	0	0	0.12	0	1
<i>Vaccinium macrocarpon</i>	0	0	0	0.01	0	0.14
<i>Vaccinium myrtillus</i>	0	0.18	0.35	0.33	0.5	0.67

Table 11

Summary statistics of the suitability scores per crop under the SSP5–8.5 and dry climate scenario (Hd), using the ‘EcoCrop + Ideal water management’ model

	Min	1st Qu.	Median	Mean	3rd Qu.	Max
<i>Colocasia esculenta</i>	0	0	0	0.03	0.05	0.07
<i>Echinochloa crus-galli</i>	0	0	0.25	0.3	0.5	1
<i>Ipomoea aquatica</i>	0	0.5	0.5	0.57	0.72	1
<i>Nasturtium officinale</i>	0	0.1	0.29	0.4	0.83	0.92
<i>Oryza sativa</i>	0	0.26	0.55	0.43	0.6	0.67
<i>Phalaris arundinacea</i>	0	0.17	0.42	0.46	0.81	0.85
<i>Phragmites australis</i>	0	0	0.36	0.24	0.41	0.45
<i>Trapa natans</i>	0	0	0.27	0.23	0.46	0.54
<i>Typha angustifolia</i>	0	0.5	0.5	0.63	0.78	1
<i>Typha latifolia</i>	0	0.5	0.5	0.64	0.78	1
<i>Vaccinium macrocarpon</i>	0	0	0.28	0.32	0.55	0.96
<i>Vaccinium myrtillus</i>	0	0.47	0.55	0.5	0.62	0.69

Table 12

Summary statistics of the suitability scores per crop under the SSP5–8.5 and wet climate scenario (Hn), using the ‘EcoCrop + Water balance’ model

	Min	1st Qu.	Median	Mean	3rd Qu.	Max
<i>Colocasia esculenta</i>	0	0	0	0	0	0.05
<i>Echinochloa crus-galli</i>	0	0	0	0.02	0	0.3
<i>Ipomoea aquatica</i>	0	0	0	0	0	0
<i>Nasturtium officinale</i>	0	0	0	0.01	0	0.26
<i>Oryza sativa</i>	0	0	0	0.04	0	0.6
<i>Phalaris arundinacea</i>	0	0.12	0.34	0.39	0.71	0.83
<i>Phragmites australis</i>	0	0	0.24	0.2	0.39	0.43
<i>Trapa natans</i>	0	0	0	0.02	0	0.5
<i>Typha angustifolia</i>	0	0	0	0.13	0	1
<i>Typha latifolia</i>	0	0	0	0.13	0	1
<i>Vaccinium macrocarpon</i>	0	0	0	0.01	0	0.39
<i>Vaccinium myrtillus</i>	0	0.22	0.41	0.37	0.51	0.72

Table 13

Summary statistics of the suitability scores per crop under the SSP5–8.5 and wet climate scenario (Hn), using the ‘EcoCrop + Ideal water management’ model

	Min	1st Qu.	Median	Mean	3rd Qu.	Max
<i>Colocasia esculenta</i>	0	0	0.01	0.02	0.03	0.05
<i>Echinochloa crus-galli</i>	0	0	0.25	0.3	0.5	1
<i>Ipomoea aquatica</i>	0	0.5	0.5	0.57	0.72	1
<i>Nasturtium officinale</i>	0	0.1	0.29	0.4	0.83	0.93
<i>Oryza sativa</i>	0	0.26	0.53	0.41	0.58	0.64
<i>Phalaris arundinacea</i>	0	0.17	0.42	0.46	0.79	0.84
<i>Phragmites australis</i>	0	0	0.35	0.23	0.4	0.43
<i>Trapa natans</i>	0	0	0.25	0.22	0.42	0.51
<i>Typha angustifolia</i>	0	0.5	0.5	0.63	0.78	1
<i>Typha latifolia</i>	0	0.5	0.5	0.64	0.78	1
<i>Vaccinium macrocarpon</i>	0	0	0.28	0.32	0.55	0.94
<i>Vaccinium myrtillus</i>	0	0.47	0.57	0.53	0.66	0.74

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.agwat.2026.110190](https://doi.org/10.1016/j.agwat.2026.110190).

Data availability

Shared in Attach File section and referenced in text.

Data & code belonging with research manuscript "Paludiculture in the Netherlands: A Suitable Option in a Changing Climate?" (Yoda)

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