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# PEILIMPACT final report [EN]

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# PEILIMPACT final report [EN]

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## Acknowledgements

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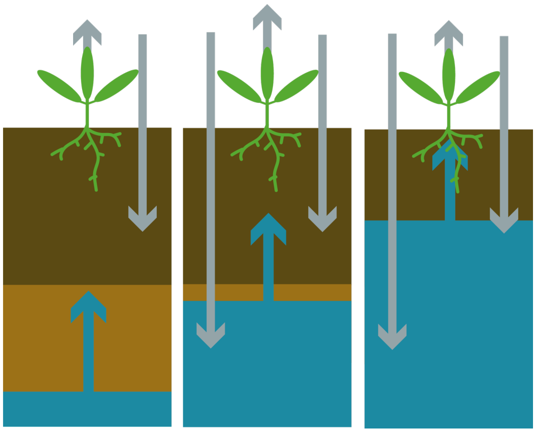
# Project Information



## Context and research question

Suppose that we raise the groundwater levels in certain places, thus increasing the soil moisture content. What impact would that presumably have on the yield of common agricultural crops in Flanders? This research question is addressed in the PEILIMPACT project. In order to mitigate the effects of climate change, the Flemish coalition agreement 2019-2024 strongly emphasizes increased resilience to drought, including through the active deployment of a resilient space with (additional) nature. Agricultural activities can experience positive effects through the water being buffered in the landscape. Yet, there are also possible negative effects: if the water level is too high, this could compromise the ability to work the land, could negatively affect crop growth and increase disease pressure on crops, as well as the availability and leaching of nutrients to surface and groundwater.

## Research methodology

Through targeted dialogue moments with individual farmers from different agricultural regions in Flanders, we obtain experiential knowledge about the effect of too high or too low groundwater levels on certain crops. We detect possible obstacles to their agricultural activity and important effects on yield, both positive and negative, and their causes. The model must help to determine "sufficiently favorable" groundwater levels for agriculture given a number of parameters. Simple guide values are too generalistic, because suitable groundwater levels for agriculture depend on the type of soil, the crop and the depth of the roots, the time of year, and so on. To determine feasible water level increases for a specific situation, model calculations for a range of different weather scenarios and for the crops grown in a specific location, is needed. In this study we determine the effect of groundwater levels in crop yield based on open data layers in Flanders.

## Relevance

An evaluation framework for the impact of groundwater level increases can be used to calculate the effect of water management decisions and to link these to compensation for affected landowners as well as to discuss sustainable solutions with farmers and nature managers. The framework can also assist farmers in crop selection etc. on a particular field with its specific soil and meteorological context.

This project was carried out by the Flemish Institute for Agricultural, Fisheries and Food Research (ILVO) [Diana Estrella, Sarah Garré, Tom De Swaef] i.s.m. KWR Water Research Institute [Ruud Bartholomeus] and Wageningen University & Research (WUR) [Martin Mulder, Mirjam Hack-ten Broeke].

# Contents

**I. Introduction** **11**

**1. Context** **12**
  1.1. Objectives . . . . . 13

**Bibliography** **14**

**2. Impact of groundwater levels and waterlogging on cultivation factors** **15**
  2.1. Introduction . . . . . 16
  2.2. Direct effects . . . . . 18
  2.3. Indirect effects . . . . . 26

**Bibliography** **32**

**II. Modeling framework** **38**

**3. GIS analysis to identify focus crops** **39**
  3.1. Introduction . . . . . 39
  3.2. Materials and Methods . . . . . 39
  3.3. Results and Discussion . . . . . 42
  3.4. Conclusions . . . . . 45

**Bibliography** **46**

**4. Model framework to evaluate the suitability of groundwater regime for crop growth** **47**
  4.1. Introduction . . . . . 47
  4.2. The SWAP-WOFOST model . . . . . 47
  4.3. Model Input . . . . . 56
  4.4. Model setup and running . . . . . 66

**Bibliography** **68**

**5. Use of the model framework** **71**

**III. Results** **73**

**6. Regional analysis and plausibility check** **74**
  6.1. Approach . . . . . 74
  6.2. Results Regional Analysis . . . . . 74

6.3. Plausibility Check . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 81
6.4. Conclusions . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 86

**Bibliography 87**

**7. Case-study: agricultural land around De Zegge-Mosselgoren 88**
7.1. Background and objectives . . . . . . . . . . . . . . . . . . . . . . . . . . . 88
7.2. Methodology . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 89
7.3. Results and Discussion . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 96
7.4. Conclusions . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 100

**Bibliography 101**

**IV. Additional considerations regarding rewetting in agricultural areas 102**

**8. Impact of changing groundwater level on nutrient mobility 103**
8.1. Introduction . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 103
8.2. Chemistry of submerged soils under anaerobic conditions . . . . . . . . . 104
8.3. Phosphorous transformation . . . . . . . . . . . . . . . . . . . . . . . . . . 107
8.4. Nitrogen transformation . . . . . . . . . . . . . . . . . . . . . . . . . . . . 108
8.5. Other transformations . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 110
8.6. Effects on water quality and biodiversity . . . . . . . . . . . . . . . . . . . 110

**Bibliography 112**

**9. Potential of paludiculture crops in Flanders 115**
9.1. Introduction . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 116
9.2. Overview of paludiculture crops . . . . . . . . . . . . . . . . . . . . . . . . 117
9.3. Paludiculture exploration in Flanders . . . . . . . . . . . . . . . . . . . . . 124
9.4. Paludicrops with potential for cultivation in Flanders . . . . . . . . . . . 127
9.5. Business models . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 138
9.6. Further research . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 140

**Bibliography 142**

**10. Conclusions 147**

**11. Recommendations 149**

# Executive Summary

Diana Estrella, Tom De Swaef, Sarah Garré

## Problem Statement

Climate change is causing longer periods of drought, alternating with heavy rainfall. This has a significant impact on agriculture and its negative effects have already been observed in the agriculture sector in W-Europe during the dry summers of 2017, 2018, 2019, 2020, and 2022, and this will most probably continue in the future. The Flemish coalition agreement 2019-2024 focuses on proactive measures to cope with the effects of climate change. It places a strong emphasis on increasing our resilience to drought through the creation of additional wet nature or restoration/remediation of drained wetlands to promote infiltration and water storage. **This means that farmers and policy-makers do not only need to adapt to an increased occurrence of droughts, but probably also to the impacts of excessive soil water (too wet conditions) in agricultural areas close to restored wetlands.** However, little information is available to estimate the impact of high groundwater tables on agriculture due to the implementation of these adaptation measures.

In this study, we developed a **modeling framework to estimate the impact of groundwater levels on the yield of conventional crops in Flanders**. The joint model SWAP-WOFOST, behind the Dutch initiative WaterVision Agriculture, was used to simulate the crop yield and yield reduction due to drought (too dry) and oxygen stress (too wet), for **five main crops in Flanders: grass, silage maize, potato, winter wheat, and sugar beet** using historical data. This model also allows us to include the effect of restrictions in normal agricultural practices due to too-wet or too-cold conditions, called indirect effects. Too-wet conditions in the root zone begin when crops start experiencing oxygen stress, that is when oxygen availability is lower than the oxygen demand of plant roots.

Freely available (online or on-demand) datasets and maps for the entire Flanders region were used, obtained from Flemish institutions or previous projects. We compiled and used a database with experimental yield observations in Flanders to evaluate the performance of the model under Flemish conditions. We also wrote three literature review chapters on the effects of groundwater on agricultural practices, the effect of shallow water tables and rewetting on nutrient mobility, and the potential of paludiculture in Flanders. Finally, the model was applied to the agricultural area around De Zegge-Mosselgoren, near Geel.

**Important**

The model itself can be downloaded at: `https://github.com/ILVO-PEILIMPACT`.

Please note: as indicated in this report, there are still a number of points for improvement. Users of the current version should be aware of the uncertainties of the underlying data layers and yield simulations.

# Results Model Simulations with the PEILIMPACT modeling framework

## Regional

At the regional level, **the yield variability is highly influenced by the regional weather variability, soil heterogeneity, and water tables.** Droughts affect silage maize, potato, and sugar beet yields more than wet conditions. Areas with sandy loam and loamy soils typically have higher yields than clayey soils, since they are more favorable for root growth than other soils. **Shallow groundwater levels negatively affect yield in wet years, but crops can benefit from them in dry years.** Just as the yield decreases with deeper water tables, it also decreases when water tables become too shallow. Deeper water tables result in higher yields in wet years, since more precipitation compensates for the low groundwater contribution to crop root water uptake. The extent of this effect depends on the soil texture and the crop rooting pattern.

## Plausibility check

The results of the plausibility check of the model demonstrated that **the current model is able to describe the general multi-annual trends in average crop yield**, despite many limitations in the input data and model simplifications. **Absolute values are sometimes underestimated**, especially in sugar beet, where an improved yield database and/or targeted field experiments to calibrate and validate the model are needed to get more accurate results.

## Case- study

In the case study De Zegge-Mosselgoren, shallow groundwater levels benefit crop production in dry years, but cause oxygen stress in wet years. The total yield reduction caused by too-dry or too-wet conditions, and by indirect effects is typically lower than 30 % for grass and silage maize. Under the current situation, field management and specifically groundwater level control in the area are close to optimal for agricultural activities in dry years, but already cause restrictions in wet years. In general, oxygen stress is the main cause of yield reduction in this area. **Detailed conclusions of the impact of rising groundwater levels due to rewetting strategies on agriculture cannot yet be given, since groundwater scenarios were not available during the project duration.**

# Main points literature review

## Cultivation factors

During droughts, shallow groundwater levels benefit crops by replenishing soil moisture through capillary rise. However, negative effects on crop production may arise because most of the arable crops are sensitive to oxygen stress, and wet conditions may lead to weed, disease and pest proliferation. Too shallow groundwater levels also affect the agricultural practices involving machinery, because wet soils have less carrying capacity. Soil texture plays a role because soil water retention characteristics regulate water flow through the root zone.

## Nutrient mobilisation

Higher groundwater levels lead to insufficient oxygen in the soil, which drastically changes its physical and electrochemical characteristics. In these new conditions, adsorbed phosphorus and organic carbon substances are more mobile, and can be diffused to surface waters. This will depend on the phosphorous availability in the soil. Leaching of soluble nitrogen is typically lower and mostly lost as gas, with less of it available in the soil.

## Wet farming and Paludiculture

Paludiculture can be used as an alternative to conventional agriculture in areas where rewetting projects are required. These crops can guarantee the production of biomass for various industrial purposes and can also form a transition between cultivated land and wet nature, and also provide water purification and water buffering.

Knowledge of cultivation practices and adapted machinery, along with market opportunities are crucial to encourage farmers to make a transition towards these crops. In Flanders, paludiculture is not well known and more research/pilot projects are needed to determine which paludicrops are more suitable for the Flemish conditions.

The small-scale agricultural areas in Flanders can be a limiting factor for paludiculture to become profitable at industrial levels, processing and use at local scale can be more suitable.

## Conclusions and Recommendations

Groundwater levels have an important indirect effect on crop yield, causing oxygen stress when they are too shallow. However, the ”optimal” water levels change drastically with variability introduced by crops, soils, groundwater dynamics, and weather. These thresholds can be assessed in a context-specific way using the model framework developed in this study. However, there is room for improvement. Further work by the research community on this framework would enable the model to give more realistic and robust results. Improvements include updating crop and soil parameters and using groundwater level dynamics when relevant information becomes available and gathering additional yield data from farmer fields or targeted field experiments, for model calibration and validation. In the study case De Zegge, the impact of specific future rewetting scenarios in the nature reserves on the agricultural activities should be assessed once these scenarios are available. The required model framework is available on Github: `https://github.com/ILVO-PEILIMPACT/model_users_growing_season`.

# Part I.

# Introduction

# 1. Context

Diana Estrella, Tom De Swaef, Sarah Garré

Precipitation and temperature are the most important variables to determine the agricultural production. Combined effects of less precipitation amounts and more extreme events, higher temperatures and atmospheric $CO_2$ concentrations, highly influences crop yield [European Environment Agency., 2019]. Climate scenarios show that agricultural conditions will improve in some regions of northern Europe, but crop productivity will half in southern Europe by 2050, especially in non-irrigated crops like wheat, corn and sugar beet [De Ridder et al., 2020]. Unique climatic anomalies in 2018 caused severe crop yield reductions up to 50% due to dry conditions in northern Europe while excess rainfall in southern Europe produced up to 34 % yield increase, compared with the previous 5-year average [Toreti et al., 2019]. According to Statbels' Land- En Tuinbouwbedrijven in Belgium, the drought in spring/summer 2018 led to high yield reductions in important crops compared to the previous year: -31 % in potatoes, -34 % in grain maize, and -13 % in sugar beet. In contrast, yield decreases in 2021 in winter wheat (-12.5 %), spelt (-10.8 %) and triticale (-20.7 %) were caused by wet conditions. Since climate change scenarios point towards an increase of precipitation and temperature extremes, there is a call for urgent adaptation strategies in agricultural practices and water resources management at landscape scale [Toreti et al., 2019].

The European Agricultural Policy 2021-2027 [European Environment Agency., 2019] proposes different adaptation measures at national, regional and farm levels to cope with the effects of Climate Change. Flood and drought management measures are not isolated and thus need to be integrated (Bressers et al., 2016). Several of these result in temporary or permanent increases of the water table, in and near land which is currently used by agriculture. Strategies include the restoration of floodplains near agricultural fields or land use change of those fields to natural retention areas against flooding. Other strategies involve restoration and sustainable management of former peatlands by stopping agricultural activities, peat extraction and drainage [De La Haye et al., 2021]. Drainage of wetlands for cities and intensive agriculture have led to an important increase in agricultural land, but also to new environmental problems. For example, oxidation and subsidence of peat soil converting drained peatlands in big carbon dioxide emitters and flood-prone areas [Verhoeven and Setter, 2010]. Since the decade of 1970, conservation policies for the wise use of wetlands were included in the 1971 Ramsar Convention [European Commission, 2007], and currently large wetland recovery programs exists in The Netherlands, The U.K., Denmark, Germany, Belgium and other European countries [Verhoeven, 2014]. The Care-Peat, Carbon Connects, and the Life Peat Restore programs are some European examples [De La Haye et al., 2021].

Rewetting and restoring wetlands provide many services such as drinking water supply, groundwater recycle, CO2 fixation and storage, and biodiversity and aquatic life [Verhoeven, 2014, Commission, 2007]. Benefits to agriculture include water supply for irrigation, water table stability and nutrient retention (floodplains), increasing the buffer capacity against flooding and drought, crucial problems nowadays due to climate change. Some disadvantages for agriculture could also arise and reduce crop yield due to excess soil moisture or waterlogging (direct effects), cause cultivation problems and increase disease pressure (indirect effects).

The Flemish coalition agreement 2019-2024 focuses on preventive and adaptative measures, and places a strong emphasis on increasing our resilience to drought, including the active use of a resilient space with (extra) nature to mitigate the effects of climate change. The Blue Deal plan aims to create additional wet nature or restore/remediate drained wetlands to promote infiltration and water storage, in about 38 locations in Flanders. This means that farmers and policy-makers do not only need to adapt to an increased occurrence of droughts, but probably also to the impacts of excessive soil water. However, little information is available to estimate the impact of shallow groundwater levels on agriculture due to the implementation of these adaptation measures.

## 1.1. Objectives

The main objective of this research is to determine the impact of groundwater levels on the yield of common crops in Flanders. Specific objectives include:

1. Perform a systematic literature review on impact estimation of rewetting in agriculture and soil electrochemical processes as well as new crops adapted to wet conditions.
2. Develop a modelling framework using the model SWAP-WOFOST, adapted to Flemish conditions, to evaluate quantitatively the impact of groundwater levels on most common crops in Flanders.
3. Apply the model framework in the case study “De Zegge”.
4. Perfom a plausibility check of the model to evaluate whether it can give acceptable results in the Flemish context.
5. Make the model freely available and documented for interested parties.

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# 2. Impact of groundwater levels and waterlogging on cultivation factors

Diana Estrella, Ruud Bartholomeus, Thijs Vanden Nest, Sarah Garré

## Abstract

Many areas worldwide are looking into rewetting natural areas, with consequences for the surrounding agricultural land. Rising groundwater levels are linked to excess moisture in the root zone. Direct negative effects of excess soil moisture include respiration reduction and damage of roots due to oxygen stress, with subsequent yield decline. Some perennial grasses have high tolerance to saturated conditions compared with arable crops thanks aerenchyma formation (root porosity that allows oxygen transport), or by rooting shallowly. Winter wheat is able to develop physiological adaptations during transient waterlogging, while potatoes and maize are the most sensitive crops, to both too dry and too wet conditions. It is estimated that about 30 % of yield is lost worldwide due to waterlogging in arable crops. Even if yield decrease is not significant, the quality can be highly compromised.

Excess soil moisture also has indirect unfavorable effects on agricultural practices. Decrease of workability and trafficability of the soil are the main concerns for Flemish farmers, since both are essential for optimal planting, plowing and harvesting activities, and are largely limited by soil moisture conditions. Waterlogged soils collapse easily and the soil structure is more vulnerable to damage in the presence of machinery or livestock. Another major concern is sowing and harvesting delays. Lower temperature in wet soils cause delay of the germination process, and harvesting is not possible in soils with low bearing capacity. Harvesting delay in grass compromises its quality as fodder since protein content lowers and fiber content increases. Other indirect effects appear inside the root zone, where anaerobic conditions alter the chemical equilibrium of soil elements, and soil micro-organisms compete with plant roots for the available oxygen and limit the uptake of certain nutrients. Weeds, and bacterial and fungal diseases can be problematic under excess rainfall.

**Key points**

During droughts, shallow groundwater levels benefit crops by replenishing soil moisture through capillary rise. However, negative effects on crop production may arise because most of the arable crops are sensitive to oxygen stress, and wet conditions may lead to weed, disease and pest proliferation. Too shallow groundwater levels also affect the agricultural practices involving machinery, because wet soils have less carrying capacity. Soil texture plays a role because soil water retention characteristics regulate water flow through the root zone.

## 2.1. Introduction

Rewetting natural areas has consequences for the surrounding agricultural land. During droughts, crops benefit from a shallow water table [Zipper et al., 2015], which prevent agricultural drought. Groundwater functions as a buffer replenishing soil moisture through capillary rise, which can contribute up to 50 % of the total evapotranspiration [Liu et al., 2016, Wu et al., 2015]. Deep-rooted crops can access water deep in the soil helping to alleviate drought stress; although, it does not compensate completely for the reduced topsoil water uptake [Rasmussen et al., 2020]. Shallow groundwater can therefore alleviate drought stress, but probably not compensate it. On the other hand, too wet conditions reduces crop yield due to a lack of oxygen in the root zone, which causes a decrease in crop transpiration [Bartholomeus et al., 2008]. In addition, excess soil moisture hampers the accessibility of the field for operations such as ploughing, spraying, harvesting, and may increase disease pressure [Bakel and Hoving, 2017]. The lack of oxygen in (near) saturated soil also affects nutrient cycles and soil biology, which in turn may impact nutrient availability and leaching [Irmak and Rathje, 2008]. Oxygen stress causes more severe damage in crop physiology than drought stress, and the actual yield is drastically reduced with prolonged waterlogging, and the recovery is less successful [Sojka et al., 2005].

**Important**

"Too wet" conditions in the root zone due to rising groundwater levels begin when crops start experiencing oxygen stress, that is when oxygen availability is lower than the oxygen demand of plant roots [Bartholomeus et al., 2008, Hack-ten Broeke et al., 2016]. Critical thresholds for oxygen (and water) stress are difficult to estimate because several factors are involved. The threshold for gas-filled porosity of the soil at which oxygen stress occurs depends on soil type, soil temperature, crop characteristics and development stage, and depth below the soil surface [Bartholomeus et al., 2008]. A critical value of 10 %, firstly introduced as preliminary estimate by Wesseling et al. [1957], has been frequently used. Wesseling [1957] presents some ranges for minimum gas-filled porosity at the bottom of the root zone for some crops (Table 2.1) as well as approximate gas-filled porosity at field capacity in some soils (Table 2.2). It can be seen that for most of the crops, oxygen stress can be experienced at gas-filled porosities higher than 10%. It should be noted that these values do not take e.g. temperature effects into account. Bartholomeus et al. [2008] stated that, for grassland, 10 % is too high for clayey soils and low soil temperatures, and in general overestimates the minimum gas-filled porosity since Wesseling et al. [1957] applied it at the bottom end of the root zone, where this critical value is higher than in the upper part. For other crop characteristics, the critical limits will differ.

With continuously increase of soil moisture in the root zone, soils become saturated. In saturated soils, all the pores are filled with water and the dissolved oxygen in the water is typically around 5 % [Moore et al., 1998]. In the presence of microbiological activity and persistent excess water, the remaining oxygen is quickly depleted leading to waterlogged conditions. "Too wet" conditions refer therefore to the state from where oxygen stress starts taking place, up to more extreme conditions like waterlogging or

Table 2.1.: Minimum gas-filled porosity in the root zone for some crops [Wesseling, 1957]

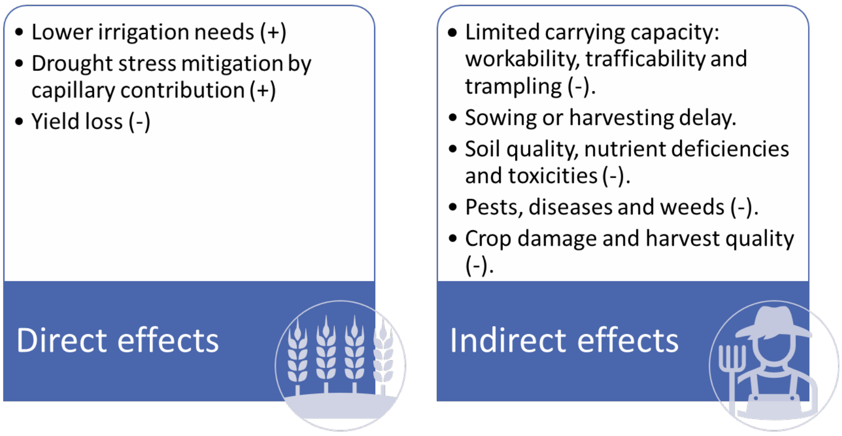
| Crop | Gas-filled porosity |
|---|---|
| Grass | 0.06-0.10 |
| Wheat/Oats | 0.10-0.15 |
| Barley | 0.15-0.20 |
| Sugar beet | 0.15-0.20 |

Table 2.2.: Gas-filled porosity at field capacity (pF 2.7) of various soil types [Wesseling, 1957]

| Soil texture | Gas-filled porosity |
|---|---|
| Silt loam | 0.13-0.15 / 0.10 |
| Clay | 0.12 - 0.15 / 0.18 / 0.115 |
| Loam | 0.11 |
| Sandy clay loam | 0.09-0.13 |

flooding.

Effects of too wet conditions in crops, can be classified as direct and indirect according to the methodology incorporated in WaterVision Agriculture [Bakel and Hoving, 2017, Hack-ten Broeke et al., 2019, 2016]. Direct effects are related to reduced crop growth due to insufficient oxygen for plant respiration and occur within the growing season. Indirect effects, also reducing yields, occur in- and outside the growing season and are related to other aspects like workability, sowing delay, crop quality reduction, and vulnerability to pests. Figure 2.1 gives and overview of these effects. This chapter will therefore describe the direct and indirect effects of too wet conditions due to shallow groundwater levels on crop yield and agricultural practices.



- Lower irrigation needs (+)
- Drought stress mitigation by capillary contribution (+)
- Yield loss (-)

- Limited carrying capacity: workability, trafficability and trampling (-).
- Sowing or harvesting delay.
- Soil quality, nutrient deficiencies and toxicities (-).
- Pests, diseases and weeds (-).
- Crop damage and harvest quality (-).

Figure 2.1.: Direct and indirect effects of increasing groundwater levels on agricultural production and field management [Hack-ten Broeke et al., 2019, 2016].

## 2.2. Direct effects

Oxygen availability in the root zone depends on the physical properties of the soil and microbial activity, which in turn depends on temperature, water and nutrients. Oxygen demand varies according plant physiology, namely crop type, development stage, and root distribution [Gliński and Stępniewski, 1985]. In suitable conditions, plant roots obtain sufficient oxygen for their respiration directly from the air-filled pores in the soil. However, when soil becomes wetter, air in the soil pores is increasingly replaced by water and energy supply for plant metabolism is reduced. Oxygen deficiency in soil affects plant growth by limiting root respiration [Bartholomeus et al., 2008]. Root development can be constrained or stop earlier under such conditions, causing a reduction in water and nutrient transport to the upper plant organs, leading to a decrease of biomass and thus, less yield [Kahlown et al., 2005, Irmak and Rathje, 2008]. Shoot response include reduction in leaf chlorophyll content and stomatal closure, which limits transpiration and $CO_2$ transport [Manik et al., 2019, Bartholomeus et al., 2008, Sojka et al., 2005].

### Relationship between groundwater and yield

Yield reduction at shallow water tables are due to lack of oxygen in the root zone while at lower water tables, yield decrease is caused by water deficiency. The interactions between groundwater and crop yield are mainly controlled by soil texture and weather conditions [Feddes, 1971]. Soil water retention characteristics regulate infiltration through the root zone and capillary rise [Zipper et al., 2015], while yearly variations in weather conditions alter the relationship between groundwater and yield [Feddes, 1971]. Different experiments performed in The Netherlands from the mid-twentieth century on, attempted to investigate the influence of groundwater levels on crop yield, for different soil textures and crops.

Visser [1959] developed yield-decrease curves as function of the mean water table depth for main soil types in The Netherlands (Figure 2.2). Yield decrease at a certain water table is strongly correlated with the water retention capacity of the soil. At shallow groundwater levels, soils with good water retention capacity ( e.g. clay soils) show a higher yield reduction because more oxygen stress occur, while at deep water tables, drought stress is smaller due to capillary contribution. The opposite occurs in coarser soil textures like sandy soils. Peat soils are exceptional for their high organic matter content, their physical and hydraulic properties are significantly altered with soil decomposition upon drainage [Liu and Lennartz, 2018]. In Figure 2.2, they exhibit a drastic yield decrease with small changes in water table depth. The shape of the curves can however vary considerable with the type of crop and discontinuities in the soil profile.

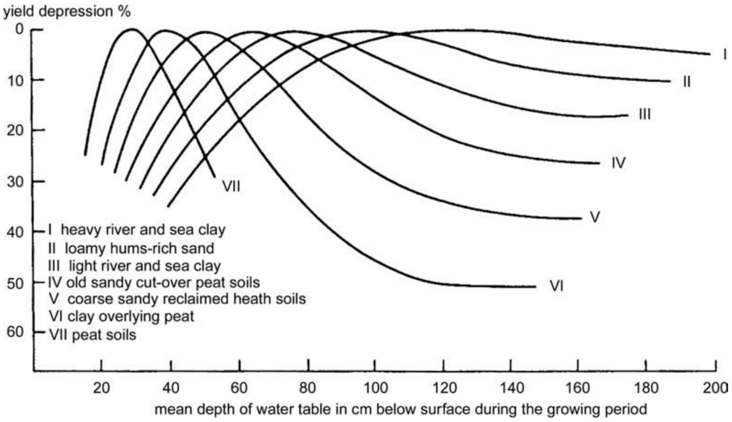


Figure 2.2.: Yield depression as a function of the mean depth of the water table during the growing season for various soil types (after Visser [1958])

Feddes [1971] formulated yield curves in function of groundwater table depth, for five probability of exceedance in clay, sandy loam and clay on sandy loam, for red cabbage, potato and lettuce. Figure 2.3 presents an adapted version of the relationship between yield and groundwater depth for potatoes for a 90 % probability of yield exceedance (every year). The optimal water table depth, meaning the one that allows the maximum yield, is around 90 cm for clay and clay on sandy loam, and 100 cm for sandy loam. At these water table depths, a fresh yield of about 45 ton ha$^{-1}$ or more can occur every year. Shallower water levels would lead to oxygen stress and hence yield reduction. These curves differ largely from the ones in Figure 2.2, especially in the dry section of the curve, because precipitation was not considered, therefore soil water is only provided by capillary rise.

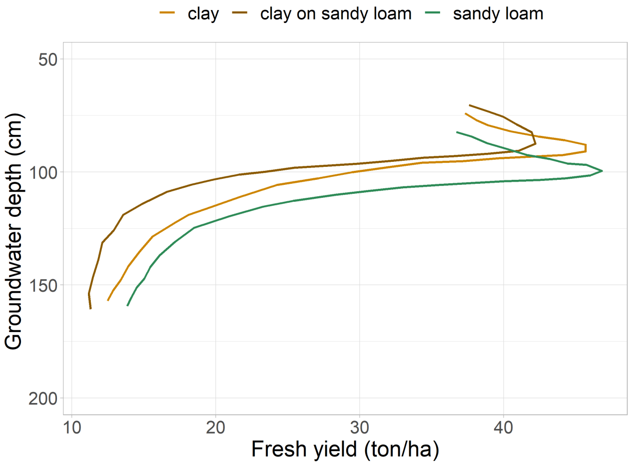


Figure 2.3.: Dependence of potato fresh yield on groundwater table depth over the growing season, for clay, sandy loam and clay on sandy loam, at 90 % probability of yield exceedance. Adapted from Feddes [1971].

Similarly, Valk and Schoneveld [1963] evaluated the influence of groundwater on five crops including cauliflower, onions, gladiolus, cabbage and beetroot, cultivated on three soil types, namely heavy clay on sticky clay and on light fine sandy clay, and light fine sandy clay. In the clayey topsoils, groundwater levels above 60 cm compromised crop yield for most of the crops, except for gladiolus. In the light fine sandy clay, groundwater levels higher than 120 cm already caused a decrease in yield.

During wet growing seasons, areas with a shallow water table depth are more susceptible to have impacts on crop yield than areas where the water table is lower, especially in fine-grained soils. Feddes [1971] makes an overview of the results of previous experiments, which show that the optimal water table depth varies between 60 cm to 80 cm in clayey soils and horticultural crops during dry years, while in wet years, the optimum is about 100 cm. For sandy loamy soils, the optimal values ranges between 100 cm to 120 cm. In contrast, Zipper et al. [2015] found that shallow water tables caused yield losses due to oxygen stress in corn, less frequently than what a deeper water table could cause due to water stress, especially in coarse-grained soils. This was mostly because excessive rainfall in the wet year occurred very early in the vegetative period, allowing most of the plants to recover. In general, there is a trade-off between drought resistance and low oxygen resistance, especially in fine-grained soils.

Keeping the groundwater at an optimum level and hence the oxygen availability in the root zone can help to achieve high and stable yields. Groundwater levels only have an indirect effect on crop growth, the soil moisture and thus the oxygen status in the root zone, is what directly influence crop yield. Static (soil texture) and dynamic factors (groundwater levels and weather); and crop type and their phenological stage, have to be considered simultaneously for decision making. Therefore, the management decisions are entirely crop and field-location specific [Zipper et al., 2015, Bartholomeus et al., 2008].

### Impact on different crop types

Several studies in cereals including maize and wheat, have shown that the peak of yield is obtained at a water depth of 1.5 m on average [Cavazza and Pisa, 1988, Kahlown et al., 2005]. However, this value cannot be generally applicable to all climatic conditions since the “optimal” groundwater level will vary with weather conditions [Feddes, 1971]. The yield of maize can be strongly affected by the water table depth due to more sensitivity to waterlogging, while sunflower and wheat can withstand greater water level fluctuations without large yield variations. Although some crops like rice can develop survival strategies like superficial rooting or development of root porosity (i.e aerenchyma) [Armstrong et al., 1991], most conventional arable crops are sensitive to very wet conditions and yield can be highly reduced, even in very short wetting periods. Tian et al. [2021] estimated that overall waterlogging could cause yield losses of about 30 % due to reduction in grain weight, biomass, and leaf area index. However, the crop yield reduction varied between crops, duration of waterlogging and development stage. In this meta-analysis, wheat yield decreased on average 25 % compared with 60 % in cotton due its higher oxygen stress sensitivity, and overall the reproductive stage was more sensitive than the vegetative stage.

Potatoes and maize are very sensitive to weather conditions. In the US, maize yield was estimated to decrease up to 34 % under excessive rainfall, which worsens in poor drained soils [Li et al., 2019]. Additionally, the negative effects of limited oxygen availability due to waterlogging during the summer months worsen because higher tem-

Table 2.3.: Average yield of main crops in Belgium in 2020 [STATBEL, 2022]

| Crops | Average fresh yield (ton ha$^{-1}$) |
|---|---|
| early potato | 38.3 |
| storage potato | 43.7 |
| grain maize | 10.8 |
| silage maize | 42.2 |
| winter wheat | 8.7 |
| sugar beet | 84.1 |

peratures leads to higher respiration rates and herewith oxygen demand.

Table 2.3 shows the average fresh yield of important arable crops in Belgium in 2020 [STATBEL, 2022]. According to the land use analysis in Flanders (see GIS analysis to identify focus crops ), grassland and maize are the dominant crops in poorly-drained soils, accounting for about 50 % and 23 % of the agricultural land, respectively. Other crops like potato, winter wheat and sugar beet are also found in very small percentages. Belgian agriculture is highly oriented towards meat and dairy production. In 2017, there were 35900 farms in Belgium, from which about 75 % had permanent grasslands and 50 % grew forage crops for cattle [van den Pol-van Dasselaar et al., 2019]. A more detailed description of the effects of too wet conditions on yield in these five crops are presented below.

### Grassland

There are two types of grassland for agriculture in Flanders: permanent and temporary. From a purely technical point of view, the term "permanent grassland" means that a parcel remains under grassland for several consecutive years. However, the term permanent and temporary grassland is also used in the collective application in the context of the common agricultural policy (CAP). More information about this can be found on the website of the Dpt L&V. Permanent grassland is the opposite of temporary grassland which is kept in production for one to a few years before destroying the turf and reseeding or not with grass or another crop. Italian ryegrass (Lolium multiflorum) is the most important species in temporary grassland. Permanent and temporary grasslands are typically a mixture of several grass species mainly perennial ryegrass (Lolium perenne), and sometimes legume species like red and white clover (Trifolium pratense, trifolium repens) [van den Pol-van Dasselaar et al., 2019].

In Flanders, regularly resown grassland and forage maize are the main forage production, while in Wallonia permanent grasslands are the most dominant. The average annual dry matter yield of permanent grasslands fluctuates between 8-12 ton ha$^{-1}$ yr$^{-1}$ while for temporary grasslands, yield ranges between 12-16 ton ha$^{-1}$ yr$^{-1}$ [van den Pol-van Dasselaar et al., 2019].

The Belgian variety list contains four species of permanent grassland and four of temporary grassland, adapted to Belgian conditions and more suitable for mowing (Table 2.4) ILVO [2022c]. Temperate perennial grasses have high tolerance to saturated conditions compared with arable crops, although they require well drained soils for a sustained productivity [Moore et al., 1998]. Perennial ryegrass is the most dominant

Table 2.4.: Permanent and temporary grass species planted in Belgium according to ILVO [2022c].

| Permanent grassland | Dry matter yield (ton $ha^{-1}$ $yr^{-1}$) |
|---|---|
| Perennial ryegrass (Lolium perenne) | 10-15 |
| Timothy (Phleum pratense) | 11-16 |
| Meadow fescue (Festuca pratensis) | 10-15 |
| Tall fescue (Festuca arundinacea) | 13-17 |
| **Temporary grassland** | |
| Festololium (Lolium + Festuca) | - |
| Hybrid ryegrass (Lolium x boucheanum Kunth) | 10-16 |
| Italian ryegrass (Lolium multiflorum) | 12-17 |
| Westerwolds ryegrass (Lolium multiflorum westerwoldicum) | 2 (only one cut per year) |

specie in Flanders. Timothy and Meadow fescue are rather less important and are mostly added to grass mixtures. Tall fescue and Italian ryegrass are the most yielding grasses (up to 17 ton $ha^{-1}$ $yr^{-1}$), also Tall fescue is highly tolerant to dry and wet conditions and less susceptible to diseases, while Timothy grass requires well-drained conditions ILVO [2022a].

Di Bella et al. [2022] showed that reductions in root and shoot biomass were low in some grass species like Koronivia grass (Urochloa humidicola), Dallis grass (Paspalum dilatatum), Tall fescue (Festuca arundinacea) and Perennial ryegrass (Lolium perenne), under 18 to 21 days of waterlogging conditions. Thanks to root porosity or aerenchyma increase (up to 40 %), the biomass reduction was sometimes negligible. Ploschuk et al. [2017] also evaluated the recovery capacity of forage grasses. Bulbous canary grass and Tall fescue fully regained the normal shoot and root grow rate after 15 days of waterlogging, while other grass species had a progressive fall in stomatal conductance and net photosynthesis during the stress period, with minimal root and shoot growth.

### Maize

In Belgium, silage maize is the second most important forage for livestock after grass. The acreage of silage increased from 20000 ha in 1970 to about 183159 ha in 2021, while the area of maize for grain reached 48180 ha in 2021 [ILVO, 2022b, STATBEL, 2022]. Farm yields can go up to 14 ton $ha^{-1}$ of grain under non-limiting conditions (full irrigation and nutrients) but it can be much lower (1-2 ton $ha^{-1}$) in less developed countries [Steduto et al., 2012]. In Belgium, the average grain yield, based on 15 varieties included in the Belgian variety list by 2022, is 13 ton $ha^{-1}$, while silage yield is 21.4 ton $ha^{-1}$ (based on almost 40 varieties) [ILVO, 2022b].

Maize is considered the most sensitive crop to water stress relative to wheat or sorghum [Steduto et al., 2012], because differences in their growing season (e.g. droughts occur more often during the flowering period of maize (summer) than of wheat (winter)).

The most sensitive period to wet conditions and waterlogging in maize is the germination phase [Guoping et al., 1988]. Ren et al. [2014] reported that grain yield decreased more than 30 % under 6-days waterlogging, during this phase. In flooded conditions, the decrease can be higher, going up to 50 % of yield loss under 2 days of flooding [Guoping et al., 1988]. Although the crop resistance to waterlogging increases during the other development stages, the duration of waterlogging intensifies its adverse effects, which can cause up to 80 % yield decrease under 9 days under waterlogging [Tian et al., 2021].

Rainfall can have either positive or negative impact on crop yield, depending on the temperature, intensity, soil drainage conditions, groundwater level, and the development stage of the crop. Excessive rainfall leading to prolonged high soil moisture in the root zone can result in several negative impacts in plant morphology, root activity and respiration, grain amount per cob, and final silage or grain yield [Li et al., 2019]. The year 2018 was unusually dry, while summer 2021 was the wettest ever seen in Belgium. 2016 had exceptional heavy rains in May and June followed by dry months in July and August. The impact on yield in these years can be seen in Figure 2.4. In 2016, silage maize yield was considerably lower than the 2012-2021 average, while in 2021 the yield increased by 5.4 %, whereas corn yield stayed close to the average in both years (Figure 2.4). Based on the Agrometeorological Bulletin, yield reduction in 2016 was mainly due to suffocation of the root system and soil acidification during the rainy months at the start of the season, which made the crop more vulnerable to drought in the next months. The apparent overall yield increase in 2021 can be partially explained by the fact that the extreme rainfall was experienced mostly in the south-east of Belgium, while the North had normal weather conditions. In the regions affected by abundant rainfall and especially in poorly drained soils, corn was yellow and small. Some places also exhibited fungal diseases and lodging.

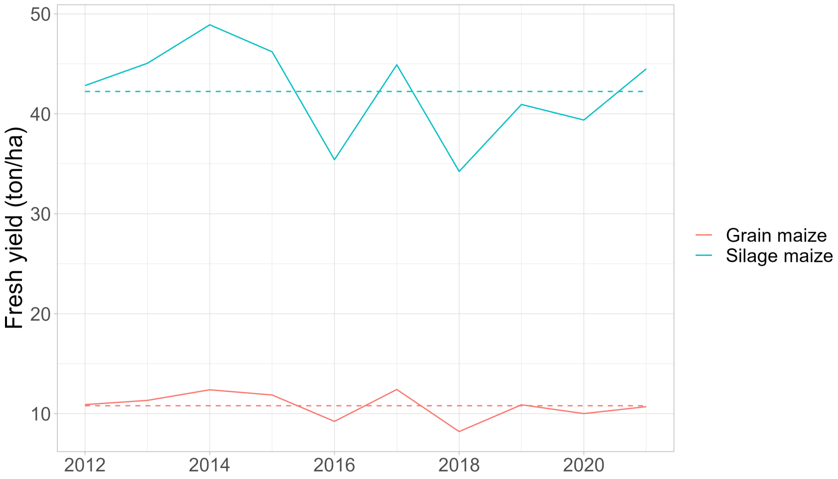


Figure 2.4.: Fresh yield variation for grain maize and silage maize from 2012 to 2021 according to STATBEL. The average yield for that period is depicted in dashed lines.

### Potato

Fresh tuber yield from irrigated fields ranges from 40 to 50 ton ha$^{-1}$, but it can be lower in humid regions due to a higher risk of diseases [Steduto et al., 2012]. In Belgium, potatoes occupy only 5 % of the total farmland but it is a major crop of the country, with an average yield of about 43 ton ha$^{-1}$ [STATBEL, 2022]. Therefore, there have been many efforts to increase potato production in the country. An example is WatchITgrow, which is a geo-information platform that helps to determine and improve potato yields in a sustainable way [Swayer et al., 2019].

Potatoes are equally sensitive to too wet or too dry conditions due to their shallow rooting system, and cannot tolerate more than 24 hours of flooded conditions [Swayer et al., 2019] because tubers are in direct contact with the soil and are more prone to rotting. Drought and heat stress during tuber formation were the dominant factors in 79 % of low-yielding years within the 1947 - 2012 period in Belgium [Gobin, 2018]. Nevertheless, waterlogging conditions played a major role in 49 % of the low-yielding years. The wet summer in 2021 in Belgium did not impact heavily the growing season of potato, evidenced by a yield slightly close to the 2012-2021 average according to STATBEL [2022] (Figure 2.5). However, the Agrometeorological Bulletin and Deronde [2021] reported that quality was lower due to severe disease stress caused by mildew, impossibility to apply phytosanitary treatments due to low trafficability, and growth cracks in the tubers in presence of high nitrogen concentration. In 2016, the persistent wet conditions during spring hampered the proper root development of the crop with an increased risk of water stress during the next dry months. These radical differences in weather conditions caused harvesting problems in the presence of hard mounts. Humid conditions also caused early flowering, and rotting in temporary flooded areas.

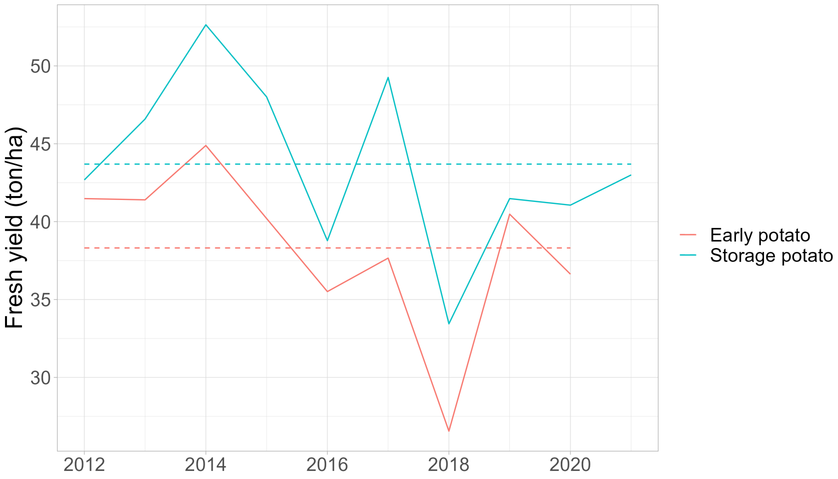


Figure 2.5.: Potato fresh yield variation from 2012 to 2021 according to STATBEL. The average yield for that period is depicted in dashed lines.

### Winter Wheat

Grain yield in rainfed temperate climate can vary from 4 to 10 ton ha$^{-1}$, and can reach up to 15 ton ha$^{-1}$ in cool environments with high solar radiation [Steduto et al., 2012]. In Belgium, the average yield is roughly 9 ton ha$^{-1}$[STATBEL, 2022]. According to the weather risk analysis made by Gobin [2018] from the period 1947 to 2012 in Belgium, periods of waterlogging occurred mostly in spring, which together with low temperatures during the growing season, caused low yields during these years. Projected yield losses due to waterlogging are expected to be around 5 % based on Gobin [2010].

Waterlogging during the vegetative period can cause substantial yield reduction in winter wheat. Oxygen stress for just three days can already damage roots, leading to the displacement of stems (lodging), and reduction of the capacity of nutrient uptake, which decreases tiller numbers [Steduto et al., 2012]. Compared to other winter cereals, winter wheat has the capacity to develop physiological adaptations during transient waterlogging. Ploschuk et al. [2018] reported that winter wheat produced adventitious roots with 20 % of aerenchyma during 14-days of waterlogging, without reducing photosynthetic activity. However, the duration and time at which waterlogging occurs, influence the recovery capacity of the plant. Winter wheat was found to recover almost entirely under waterlogging of maximum 20 days during the early stage (before flowering) according to San Celedonio et al. [2017], while yield loss ranged from 34 % to 92 % if occurring in the flowering stage (Romina et al., 2014). Under prolonged waterlogging duration, roots can be severely damaged and the crop may not recover even if the water conditions improve [Steduto et al., 2012].

Contrary to spring crops like maize and potatoes, the yield of winter wheat decreased by 8.5% in Belgium, in the wet summer of 2021 compared with the average, and by 22 % in 2016 [STATBEL, 2022] (Figure 2.6). According to the reports in the Agrometeorological Bulletin, yield decrease in 2021 was mostly linked to lodging due to strong winds during the extreme rainfall events, harvesting delays and germination of grains. Similar occurred in 2016, where harvesting delays due to wet conditions caused plant to lodge.

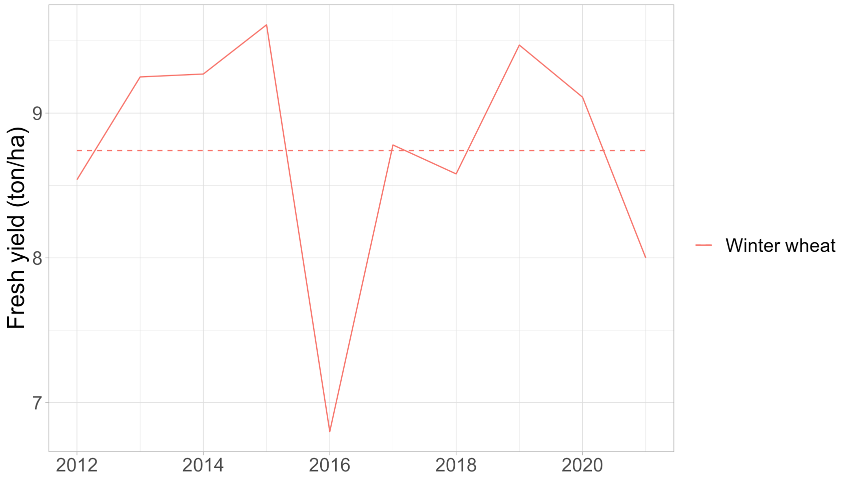


Figure 2.6.: Winter wheat fresh yield variation from 2012 to 2021 according to STATBEL. The average yield for that period is depicted in dashed line.

**Sugar beet**

Fresh yield commonly ranges from 40 to 60 ton ha$^{-1}$ but can go up to 100 ton ha$^{-1}$ under optimal water and nutrient conditions [Steduto et al., 2012]. In Belgium, the average yield is about 85 ton ha$^{-1}$ [STATBEL, 2022]. Sugar beet is very sensitive to water deficit in the initial growing stages. Its peak water requirement occurs at the end of the vegetation period when maximum canopy cover is reached. Early over-watering can inhibit leaf development and promote premature flowering and early production of seeds. Excess water (e.g. overirrigation) near harvest, increases fresh root yield but root sugar concentration may be reduced [Steduto et al., 2012].

In Belgium, periods of repeated waterlogging explained 86 % of the low sugar beet yields during 1947 to 2012 [Gobin, 2018]. In contrast, projected yield losses were estimated to be around 12 % to 27 % due to droughts [Gobin, 2010]. Sugar beet is one of the few crops that has the possibility to recover partly from drought and heat due to their deep roots. This can be seen for example in the dry year of 2018, where the yield was similar to the average in contrast with other spring crops [STATBEL, 2022] (Figure 2.7). In the wet summer of 2021, sugar beet also performed much better than other crops, the Agrometeorological Bulletin reported that despite some diseases like Pseudomonas, leaf development was very abundant and among the highest of the last decade. The heavy rains and the insufficient oxygen in the soil led to a pallidity of the foliage, but gradually restored at the end of the summer. However, the drastic weather changes in 2016 seemed to affect more the growing season of sugar beet, probably because disease pressure in the wet months and subsequent higher vulnerability to droughts.

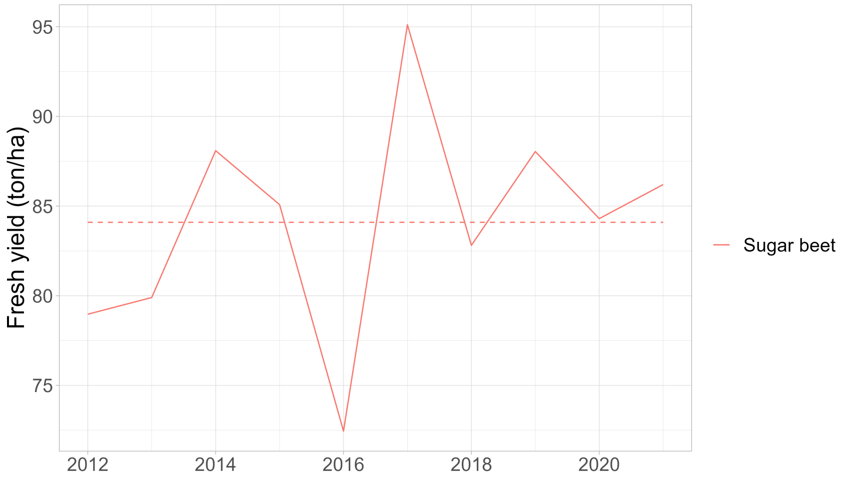


Figure 2.7.: Sugar beet fresh yield variation from 2012 to 2021 according to STATBEL. The average yield for that period is depicted in dashed line

## 2.3. Indirect effects

Indirect crop damage due to excessive wet conditions are related to reduced trafficability and workability, soil degradation, sowing delays and retarded crop growth, pests and weeds. These factors ultimately lead to a reduction in crop yield. In Belgium, 79

% of low yields in maize during 1947 to 2012 were caused by late planting and delayed crop development due to a cold and wet spring, while waterlogging during harvesting explained 29 % of the low yields. In the case of potatoes, 43 % of the low yields were caused by waterlogging, which produced planting delays, tuber damage or difficult harvest operations [Gobin, 2018].

## Limited carrying capacity: trafficability, workability and trampling

Trafficability and workability refer to the capacity of the soil to support agricultural operations involving machinery, without causing structural damage [Müller et al., 2011]. Both qualities are essential for optimal planting, plowing and harvesting activities, and are largely limited by soil moisture conditions. Waterlogged soils can easily collapse by trampling through dispersion of clay particles, especially when concentration of sodium is high. Soil structure can be easily damaged in the presence of machinery or livestock [McDonald, 2021]. In grasslands, cows can damage the soil structure and increase soil compaction (trampling loss) leading to a reduced infiltration capacity or capillary rise, less oxygen available, and root growth restrictions [Bakel and Hoving, 2017]. The magnitude of the damage will depend on the carrying capacity of the soil, and can be reduced by using controlled traffic farming systems.

Knowledge of the type of crop can help to determine the required workability and trafficability, as this determines the weight of the machines used for planting/sowing and harvesting. In The Netherlands, heavier machines are commonly used for planting maize and potatoes while lighter machines are employed for winter wheat or sugar beet [Bakel and Hoving, 2017]. Machines used for harvesting are much heavier than the ones used in planting or sowing, which results in more soil compaction in wet conditions. Too wet conditions during the harvesting period are more severe because not all the field can be harvested or the next crop cannot be sown.

On the other hand, knowledge of the soil type allows to determine its mechanical behavior with changes in soil moisture content. Soil strength is highly dependent on soil water content and density, an this in turn determines the bearing capacity of the soil and energy required for tillage [Müller et al., 2011]. In cohesive soils, the soil strength as a function of water content can be described by the consistency index Ic (Figure 2.8), based on the upper plastic limit (UPL) and lower plastic limit (LPL). A value of 0.75 is commonly considered as a limit for workability but this is not necessarily a threshold for trafficability. Lower values denote that the soil is too wet and easily deformable (not good for trafficability), while higher values represent the soil is too dry and prone to fissures and crumbling (good for trafficability) [Müller et al., 2011]. In Figure 2.8, gravimetric water content ranges from 0.15 kg $kg^{-1}$ to 0.50 kg $kg^{-1}$ for Ic = 0.75. Soils with lower clay content change their mechanical behavior faster with variations in water content.

Since the strength of the soil changes with soil water content, water table depth defines the trafficability and workability in a field. In turn, optimal water tables vary with soil type and climatic conditions. A water table depth lower than 75 cm may be adequate in heavy marsh soils in spring. In peatlands, water tables are commonly high and the soil bearing capacity is low under standard agricultural machinery. The choice of lighter machines can allow the trafficability and workability of these soils [Müller et al., 2011].

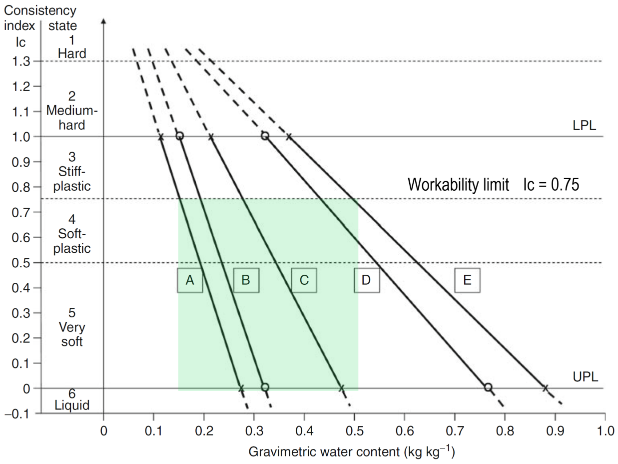


Figure 2.8.: Consistency diagram based on lower plastic limit (LPL) and upper plastic limit (UPL) for five typical topsoil substrates in north-eastern Germany. Soils A, B, C, D and E have 15%, 20%, 30%, 40% and 50% clay content, respectively. Adapted from Müller et al. [2011]

## Sowing or harvesting delay

Soil temperature and moisture content are the dominant environmental factors that determine crop germination. Crops need a certain soil temperature to germinate, which varies highly between species and even within cultivars. For example, maize requires at least 10 °C, which normally occurs in the last week of April, while winter wheat can germinate at lower temperatures of around 5 °C [Singh and Dhaliwal, 1972]. Wet soils warm up at a slower rate than dry soils in spring, and take longer to cool down in autumn due to the large heat capacity of the water [Bakel and Hoving, 2017].

All crops are generally more susceptible to wet conditions during the germination and pre-emergency periods [Moore et al., 1998]. The greater the probability of wet conditions in autumn, the higher the chance of choosing early varieties that yield less. Also, if waterlogging occurs in spring, the sowing date will be delayed and the growing season will be shorter [Van Oort et al., 2012]. Therefore, soil moisture content, affecting both soil temperature and the carrying capacity, is one of the factors that determine the start of the growing season. On the other hand, harvesting delay due to limited carrying capacity cause the next crop planting to be postponed or even cancelled.

In The Netherlands, the largest negative yield anomalies in potato in the period 1951 - 2010 were explained by either a wet start of the growing season or a wet end of the growing season. Most of the low yields were due to late planting, especially when the date exceeded April, 30th [Van Oort et al., 2012].

## Soil quality, nutrient deficiencies and toxicities

The rate of oxygen depletion depends mainly on soil temperature but also organic matter, salinity and pH, and plant factors like growing stage, nutrients and adaptation ability [Moore et al., 1998]. With limiting oxygen, micro-organisms in the soil can compete with plant roots for the available oxygen or hinder the availability and uptake of certain nutrients. Consequently, microbial activity is among the factors determining oxygen stress to plant roots [Bartholomeus et al., 2008].

Nitrogen can be lost from the soil through different paths, either via leaching or via chemical processes. Oxygen deficiency in the soil promotes the breakdown of nitrate (denitrification), possibly resulting in less nitrogen available. Waterlogging usually increases nitrogen leaching beyond the root zone, which can also contribute to nitrogen deficiencies [Irmak and Rathje, 2008]. Changes in redox potential, soil pH and soil temperature ultimately affect nitrogen transformation and availability [Kaur et al., 2020]. It may be required to add nitrogen in the soil to compensate for these losses. However, severely damaged crops may no longer recover and the addition of nitrogen is not profitable.

On the other hand, decreasing oxygen changes the physico-chemical properties of the soil (Figure 2.9). The reduction potential of the soil increases under waterlogged conditions and changes the chemical equilibrium of elements, which enter the soil-water solution in their ionic forms. This is the case of iron and manganese compounds, which can rise to toxic levels under anoxic conditions [McDonald, 2021]. Toxins can accumulate in the soil and anaerobic respiration can produce potentially harmful end products like ethanol. Soil pH is also reduced by the accumulation of volatile organic acids and the high concentration of $CO_2$. These processes cause restricted root growth, because roots are less capable to extract nutrients from the soil and remain close to the surface where there is more oxygen [Moore et al., 1998]. Overall crop growth is compromised due to reduced tillering capacity, and premature leaf senescence and sterile florets [Manik et al., 2019].

More detailed information about the chemistry in saturated or waterlogged soils are explained in the next chapter Impact of changing groundwater level on nutrient mobility.

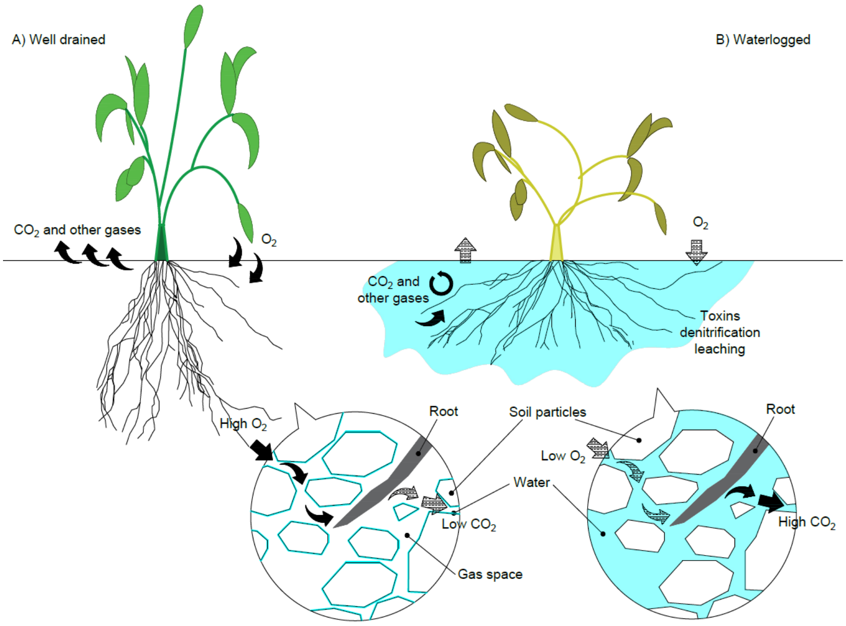


Figure 2.9.: Diffusion of gasses in well drained soils and waterlogged soils. Adapted from [Moore et al., 1998]

## Weeds

Weeds are unwanted plants, highly tolerant to abiotic stress, that interfere with crops and livestock production. They emerge and develop spontaneously when they find a suitable environment. Agricultural weeds compete for resources (light, nutrients, and soil moisture), can physically hinder and inhibit crop growth, host pests and promote diseases [Schonbeck, 2022]. Weeds can cause more crop losses than other biotic factors (animal pests and pathogens); estimates of the potential losses worldwide were on average 33 %, with the highest potential loss in maize (40 %) [OERKE, 2005]. More recent estimates of crop yield losses were about 28 % [Vilà et al., 2021].

Wet conditions can cause an increase of diseases and pests, and can stimulate weed growth. Other plant varieties, more adapted to wet conditions and usually less valued, can take over and reduce crop production. The presence of plants like toad rush (Juncus bufonious), docks (Rumex spp.) and sedges (Carex) are common in waterlogged conditions [Moore et al., 1998]. Many grass species such as Lolium, Brachiaria and Phalaris, considered weeds in arable crops, can tolerate temporary waterlogging better than agricultural crops because they have genes usually found in aquatic plants [Krähmer, 2016]. This characteristic enables grasses to develop root adaptations that allow them to survive under wet conditions. Weeds may thrive around stressed crops since they have to compete less for nutrients and space.

## Pests and diseases

Animal pests include insects, mites, slugs/snails, birds and mammals. Diseases comprise fungi, chromista, bacteria and viruses [OERKE, 2005]. Wet conditions and high temperatures favor the development of diseases on crops caused by fungus-like organisms. Diseases caused by Phytium, Phytophthora and Alternaria are common in wet weather conditions. These pathogens are usually present in many soils but become harmful in excessively wet conditions [IPM, 2017]. Certain insects such as the European crane fly (Tipula paludosa) and the fly pest fungus gnats (Bradysia and Lycoriella spp.) are attracted by moist conditions [Weiland, 2012]. Animal pests and diseases are known to cause a potential crop loss of about 19 % and 13 %, respectively [OERKE, 2005].

Roots and seeds are more susceptible to diseases. Affected plants exhibit a shallow root system, root rot, damping-off, and yellowish or purple appearance of the plant [Folnović, 2014]. Pythium and Phytophthora species produce spores that easily move in water in saturated soils to infect new plants. The Pythium fungus is known to cause root rot in winter wheat when excessive soil moisture conditions are present, as the plant is more vulnerable in the first weeks after emergence. Another disease in flooded conditions is Peronospora sparsa (downy mildew), which can affect submerged wheat leaves [Byamukama and Ali, 2022].

Deronde [2021] reported that the permanent high humidity and moderate temperatures in summer 2021 lead to severe disease stress in potatoes in Flanders, Phytophthora and Alternaria were widely observed in potato fields. The Agrometeorological Bulletin also recorded different bacterial and fungal diseases in crops such us Pseudomona, Cercospora beticola, Rhizoctonia solani, and Erwinia.

### Crop damage and harvest quality

Excess water causes rotting of harvestable products, especially in arable crops like potatoes, where the tubers are in direct contact with the soil. In the case of grass, it restricts grazing for a certain period of time [Bakel and Hoving, 2017]

According to a newspaper article published in August, 2021 Times [2021], the quality of the harvest of different fruits, grains and vegetables was reduced due to a humid spring and constant rainfall events in summer 2021. Wet conditions led to indirect effects like poor pollination of the flowers especially in pears or scab formation in apples, which makes it difficult to meet quality standards. Besides this, long wet periods followed by dry periods enhances secondary tuber formation alongside the main tuber, which modify the size and the shape of the potatoes and look less appealing for customers. Deronde [2021] pointed out that the large amount of precipitation, often in combination with high nitrogen content in 2021 caused a disproportionate tuber growth resulting in growth cracks and hollowness, mainly in the cultivar Fontane. Some Fontane plots also showed new flowering and tuber growth leading to green tubers during harvest.

In grasses, the content of protein and fiber define the quality. The crude protein content, which is more efficiently assimilated for meat and milk production, should be least 7 % to meet the animal requirements. The fiber content, although fundamental for stimulating the rumen function, should be lower than 35 % for acidic detergent fiber (ADF) and smaller than 50 % for Neutral Detergent fiber (NDF), in order to have good digestibility levels [Oregon State University, 2018]. With maturity, protein decreases and fiber increases. Consequently, the optimal harvesting time depends on the desired quality and quantity. Early-harvested grass will be more protein-rich than a late-harvested grass, but with a lower biomass volume. Harvesting time is affected by weather and soil conditions: the soil needs to be dry enough for the machines to enter the field or for the cattle to graze [Oregon State University, 2018]. Therefore, a harvesting delay due to high soil moisture conditions will compromise the quality of the grass and the possibility to storage it.

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# Part II.

# Modeling framework

# 3. GIS analysis to identify focus crops

Diana Estrella, Tom De Swaef, Sarah Garré

## 3.1. Introduction

A GIS analysis based on available soil and crop maps of Flanders was performed to identify areas of interest. The locations where the water levels are naturally high could be more affected by rising groundwater levels due to their poor drainage. **Poorly drained soils were defined according to the drainage classes in the Soil Belgian Map.** The dominant soil types and land cover types in these areas allow to select the most relevant crops and soil types to be modelled. The identification of these areas was also used to target interested parties such as farmers so that we could obtain their valuable feedback on the project methodology.

The dominant crops in poorly drained soils were identified as follows:

1. Define "poorly drained soils" based on the drainage classes given in the Belgian Soil Map.
2. Extract the areas with soils that meet the definition of poorly drained soils.
3. Intersect the land cover map with these poorly drained areas.
4. Combine this resulting map with the map of the Flemish provinces to have the area of crops per province in poorly drained soils.

## 3.2. Materials and Methods

The analysis was done using soil and land cover maps collected from Geopunt Vlaanderen and the software QGIS 3.22. The Digital Soil Map of the Flemish Region [VPO, 2017], scale 1:20000, contains the soil texture according to the Belgian textural classes, drainage status and profile development of the soil. The Agricultural Use Plots map [LV, 2016] contains the overview of the parcels with agricultural use, wooded areas and agricultural infrastructure. Four agricultural use maps for subsequent years; 2018, 2019, 2020 and 2021 were used in order to estimate the average crop surface. All this information is managed by the Database of Subsoils Flanders (DOV) and can be also consulted there.

In addition, we asked the Flemish Environment Agency (VMM) to report the location of areas where rewetting is on the agenda in the context of the Blue Deal plan. They provided us with four Blue Deal flagship projects: Dune complex, Zwarte Beek, Kleine Nete and River recovery Leie.

## Digital Soil Map of the Flemish Region

The soil map of Belgium is defined according to soil texture, drainage status and profile development. The soil series and their notation are established based on the combination of these properties' classes. Soil texture classes are based on the relative clay, silt and sand fractions. The drainage classes depend on the depth of redoximorphic mottling and/or reduction colors occurrence. The soil profile development classes are based on visual identification of soil horizons. The Flemish region has more than 4000 different soil types [Dondeyne et al., 2014].

The seven soil texture classes are wider than the ones defined in the standard USDA Soil Taxonomy system (Figure 3.1). There are also differences in the ranges of particle size for silt and sand categories. In addition of the seven main classes, three extra classes are defined for special cases, **G** for gravel, **V** for saturated peat soils by groundwater, and **W** for saturated peat soils by rainwater.

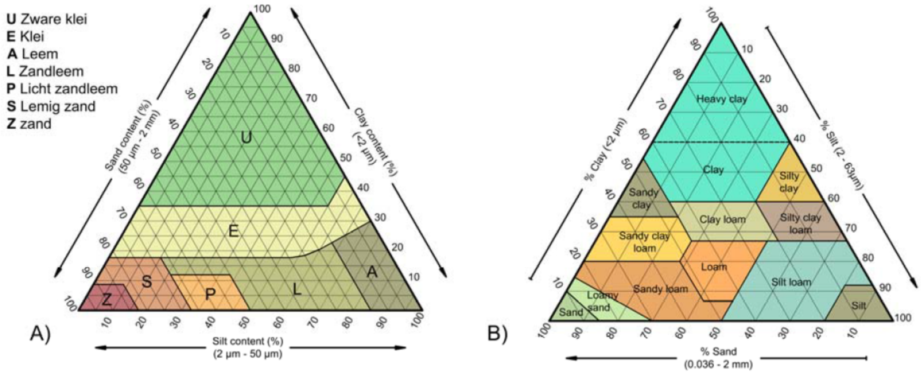

Figure 3.1.: Textural classes according to the Belgian textural classes (A) and USDA textural classes (B). Adapted from Dondeyne et al. [2014]

There are six drainage classes for the cases of deep groundwater and three classes for shallow groundwater (Table 3.1). Distinction in depth of occurrence of mottling and reduction colors is made between the silty and clayey textures and the sandy textures. Finally, there are eleven classes of soil profile development. For example, a soil type **Pca** refers to a light sandy loam (**P**), moderately well drained (**c**) and a profile development corresponding to a B horizon (**a**).

## Agricultural Use Plots

The agricultural use plots map contains thirteen main categories, from which eight correspond to arable crops (Table 3.2). Each category comprises several more detailed subcategories of crops.

## Determination of the dominant soil and crop types in poorly drained soils

All the areas with poor to extremely poor drainage conditions, (classes h, i, e, f , g) and combinations of these classes (Table 3.1), were considered as poorly drained areas

Table 3.1.: Drainage classes and symbols according to the legend of the soil map of Belgium [Dondeyne et al., 2014]

| **Symbol** | **Definition** | **Depth of occurrence (cm)** | | | |
|---|---|---|---|---|---|
| | | **Silty & Clayey textures (A, L, E, U)** | | **Sandy textures (A, S,P)** | |
| | | **Redox-morphic mottling** | **Reduction colors** | **Redox-morphic mottling** | **Reduction colors** |
| **No groundwater within 125 cm of soil surface** | | | | | |
| **a** | Excessively drained | - | - | >120 | - |
| **b** | Well drained | - | - | 90-120 | - |
| **c** | Moderately well drained | >80 | - | 60-90 | - |
| **d** | Imperfectly drained | 50-80 | - | 40-60 | - |
| **h** | Poorly drained | 20-50 | - | 20-40 | - |
| **i** | Very poorly drained | 0-20 | - | - | - |
| **Groundwater present within 125 cm of soil surface** | | | | | |
| **e** | Poorly drained | 20-50 | >80 | 20-40 | >100 |
| **f** | Very poorly drained | 0-20 | 40-80 | 0-20 | 50-100 |
| **g** | Extremely poorly drained | 0 | <40 | 0 | <50 |

Table 3.2.: Crops categories in the agricultural use plots map.

| **Category** | **Crop** |
|---|---|
| Potatoes | Early potatoes, storage (industrial) potatoes and seed potatoes |
| Fruits and Nuts | Pear, apple, strawberries, ... |
| Cereals, seeds and legumes | Winter wheat, summer wheat, winter barley, ... |
| Grassland | Grassland, natural grassland, turf, ... |
| Vegetables, herbs and ornamental plants | Chicory root, onions, cauliflower, brussels sprouts, spinach, carrot, salad sorts, ... |
| Woody crops | Deciduous trees, poplars, forest and edge plants, ... |
| Agricultural infrastructure | Stables and sheds |
| Maize | Silage maize and grain maize |
| Other crops | Cut rye, floral mixture, tobacco, ... |
| Sugar beet | |
| Flax and hemp | |
| Fodder | Grass clover, grass lucerne, alfalfa, fodder beet, ... |
| Water | |

and extracted from the soil map. The land cover map for each year (2018-2020) was intersected with the obtained poorly drained soils layer. Finally, the resulting maps were crossed with the map of the Flemish provinces obtained from the Atlas of Belgium, to have the total area of crops per province.

## 3.3. Results and Discussion

Figure 3.2 shows the areas with poor drainage over Flanders, together with the location of the four Blue Deal Flagship projects. Most of the soils with low drainage capacity or where the groundwater level is shallow, are located in the province of Antwerp, and some parts of West Flanders and Limburg.

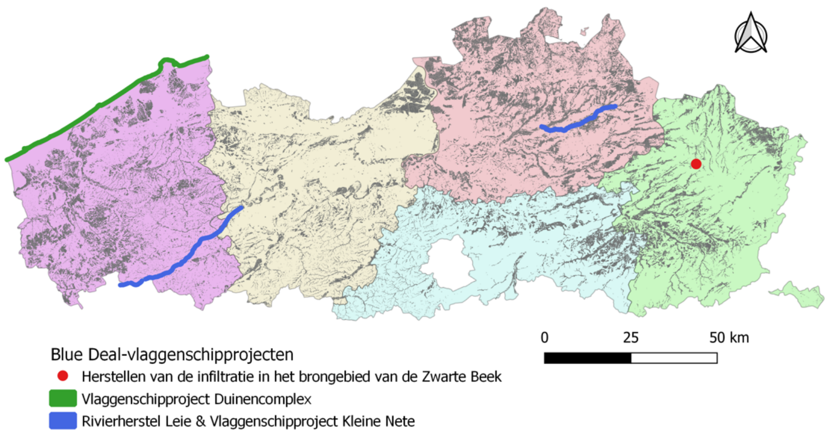

Figure 3.2.: Poorly drained soils (grey) in Flanders and the location of the four Blue Deal Flagships projects.

The dominant soil textures in these soil types are sandy loam (24 %) and loamy sand (20 %) (Figure 3.3). Light sandy loam, sand and clay cover each around 14 % of the area. Other textural classes appear in less than 3 % of the area.

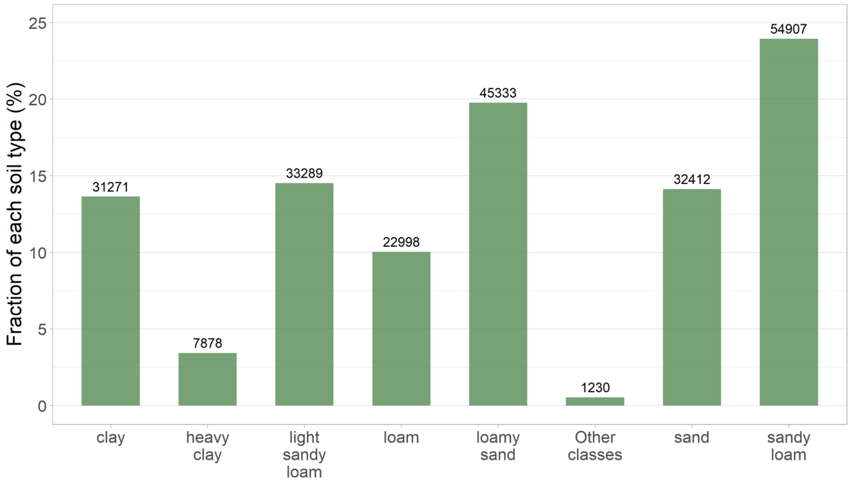

Figure 3.3.: Dominant soil texture classes in poorly drained soils over Flanders. The value on top of each bar represents the area in hectares.

Regarding crop types, Figure 3.4 shows the 4-year (2018 -2021) average area of each crop per province, according to the crop categories shown in Table 3.2. The total cultivated area in poorly drained soils is about 123970 ha. The dominant crop categories in all provinces are grassland, maize and potatoes. Antwerp has the largest area of grassland and maize over Flanders, while potatoes are largely found in West Flanders. Vegetables and cereals are also mostly cultivated in West Flanders.

The 4-year average crop area, according to the crop classification of Table 3.2, also indicates that from the total cultivated area in poorly drained soils, grassland and natural grassland cover almost half of it (Figure 3.5). Silage maize is the second crop grown in these areas (18 %), while industrial potatoes, grain maize, clover and winter

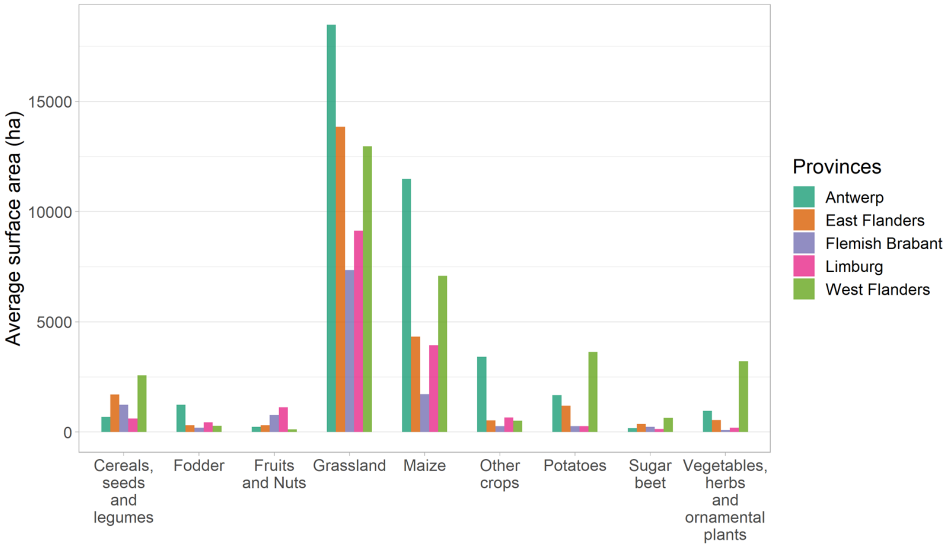

Figure 3.4.: Four-year (2018-2021) average surface area of crops cultivated in poorly drained areas over Flanders per province.

wheat share a similar percentage (4-5 %). Sugar beet and pear are also found in few areas.

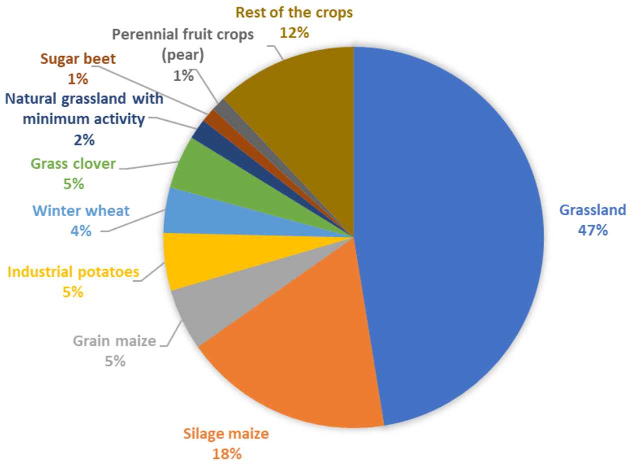

Figure 3.5.: Dominant crops in poorly drained soils over Flanders based on a 4-year average all provinces combined.

In total, 72 % of the area with poorly drained soils is covered with natural or cultivated grass, and forage, which evidences that the main economical activity in these areas is livestock farming. This is logical since arable crops do not grow well in poorly drained soils, where soil saturation or waterlogging may occur (Impact of groundwater levels and waterlogging on cultivation factors). Therefore, the main target group for the agricultural workshops was livestock farmers.

When looking at the location of the Flagships projects, grassland and maize (mostly silage maize) are the predominant crops (Figure 3.6), which also relates to livestock farmers.

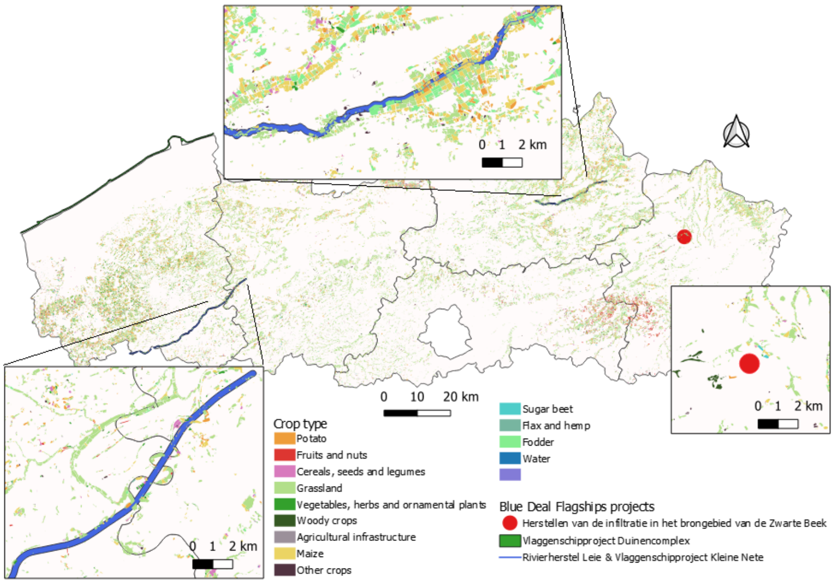

Figure 3.6.: Agricultural use in poorly drained soils in the location of the Blue Deal Flagships projects.

## 3.4. Conclusions

The GIS analysis using available soil and land use maps gave a first idea of the dominant crops and soil types found in poorly drained areas. The most dominant crops were, grassland, maize, potatoes, winter wheat and sugar beet. The dominant soil textures were sandy loam, loamy sand and sand. Since about 72 % of the area is covered with grass and forage, the main economical activity in these areas is livestock farming. These results provide a good overview of the soil characteristics and agriculture in poorly drained soils, for modelling purposes and for targeting interested parties.

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# 4. Model framework to evaluate the suitability of groundwater regime for crop growth

Diana Estrella, Martin Mulder, Tom De Swaef, Ruud Bartholomeus, Sarah Garré

## 4.1. Introduction

The main objective of this project is to determine the impact of the groundwater levels on common crops in Flanders. The model instruments used in this study are the same as those behind the Dutch initiative WaterVision Agriculture: the soil water transport model SWAP coupled to the crop model WOFOST. The coupled instrument does not only take into account drought stress on plants, but also oxygen stress under too wet conditions. In addition, indirect effects affecting sowing, mowing or harvest times can be quantified.

SWAP-WOFOST has been extensively verified in the last decades. The numerical solutions of SWAP were also compared with analytical solutions. An overview of some validation and sensitivity analysis cases can be found in Heinen et al. [2021]. Since the start of the WaterVision Agriculture tool in 2015, the model instruments were continuously developed and improved. A recent validation at regional and local scale for grass and silage maize satisfactorily compared the simulated crop development and transpiration reduction with observed NDVI values [Mulder et al., 2021].

Since the model has been extensively tested in fairly similar Dutch conditions, we focused on adapting the input data to Flemish conditions (weather, soil and groundwater level) and on validating the simulated yields with historic local yield data from various trials. Crop parameters were thereby not altered. The information on the model framework is largely extracted from the SWAP-WOFOST manual [Kroes et al., 2017] and related articles [Werkgroep Waterwijzer Landbouw, 2018]. More information can be found in those sources.

## 4.2. The SWAP-WOFOST model

SWAP (Soil, Water, Atmosphere and Plant) is a one-dimensional, field scale and vertically directed model that simulates the transport of water, solutes and heat in the unsaturated and saturated zone, in interaction with vegetation development [Kroes et al., 2017, van Dam et al., 2008]. SWAP allows to consider water exchange with the surroundings, like discharge to ditches, drains and other surface waters. The crop growth module WOFOST (World Food Studies; De Wit et al. [2020]) is integrated in SWAP to describe the phenological development, growth and yield production of major arable crops.

The main input information consists of weather data, groundwater levels and soil & crop characteristics. The model output comprises time series of water (and solute) balances and crop dry matter development. In addition, the occurrence of different stress types over the growing season is quantified.

SWAP-WOFOST was developed in The Netherlands by Wageningen University and Research and is freely available in `https://www.swap.alterra.nl/`. The model version for this project was provided by Wageningen University and Research from the tool WaterVision Agriculture.

**Important**

The content of this chapter was largely extracted from the WaterVision Agriculture report [Werkgroep Waterwijzer Landbouw, 2018] and the SWAP 4 manual [Kroes et al., 2017].

## Soil water transport

SWAP [Kroes et al., 2017] computes transport of water, solutes and heat in the unsaturated and saturated zone using Richards equation, including root water extraction to simulate the movement of soil moisture in variably saturated soils. The SWAP domain is considered from just above the canopy of the crop to a plane in the phreatic groundwater (Figure 4.1). In this domain, the transport processes are predominantly vertical. Below the phreatic groundwater level (saturated zone), the model can also estimate lateral drainage fluxes. However, this option was not activated in this project. SWAP can simulate discharge to ditches, drains and other surface waters, through drainage and infiltration equations acting as sinks or sources in the 1-D model, completing the vertical water balance.

The top boundary conditions of the system are characterized by the soil surface with or without vegetation and the atmospheric conditions. The bottom boundary condition describes the interaction between saturated shallow soil layers with regional groundwater, while the lateral boundary explains the interaction with surface water systems (Figure 4.1).

The major concepts and assumptions of SWAP-WOFOST used in this study include [Heinen et al., 2021]:

- The evaporation demand of the atmosphere is calculated using the Penman-Monteith equation [Monteith, 1965].
- The water movement is vertical (one-dimensional model) and described by the Richards equation.
- Water retention characteristics of each soil layer are described with Mualem-Van Genuchten functions.
- The porous medium is assumed to be rigid, isotropic and isothermal.
- Soils can be variably saturated and heterogeneous.

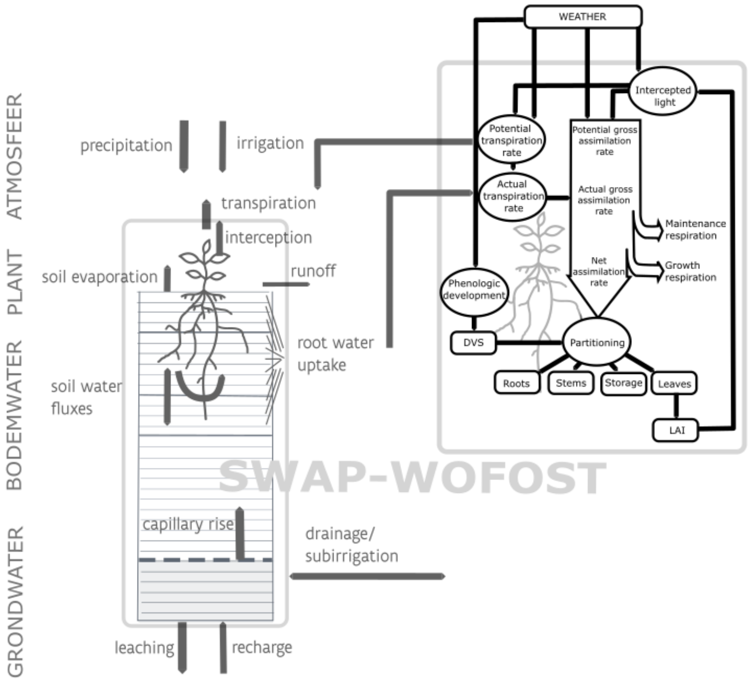


Figure 4.1.: Schematic representation of the functioning of the coupled SWAP-WOFOST model (1-D) used for this study.

- The bottom boundary conditions can be specified as flux or pressure head, and may depend on the phreatic groundwater, or the hydraulic head in the deeper aquifer and resistance of the system.
- Transpiration reduction can be caused by very dry conditions (water stress), very wet conditions (oxygen stress). Salinity stress was not considered.
- Ponding occurs when the soil infiltration capacity is exceeded, and surface runoff takes place only after a threshold ponding height is surpassed (i.e. 0.2 cm).
- Soil temperature is simulated as a diffusion process.
- Irrigation can be considered as fixed applications or chosen according to irrigation criteria. Irrigation was not considered in this study.

The Richards equation for variably saturated soils ( (4.1)) is solved numerically in SWAP for every soil compartment, using specified boundary conditions and relations between $\theta$, h and K, given by the Mualem-Van Genucthen functions:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z} + 1\right)\right] - S_a(h) - S_d(h) - S_m(h) \tag{4.1}$$

In (4.1), $\theta$ is the volumetric water content (cm$^3$ cm$^{-3}$), t is time (d), K(h) is the hydraulic conductivity (cm d$^{-1}$), h is the soil water pressure head (cm), z is the vertical coordinate (cm) taken positive upward. $S_a(h)$ is the soil water extraction rate by roots (cm$^3$ cm$^{-3}$

d$^{-1}$), $S_d(h)$ is the extraction rate by drain discharge in the saturated zone (cm$^3$ cm$^{-3}$ d$^{-1}$) and $S_m(h)$ is the exchange rate with macro pores (cm$^3$ cm$^{-3}$ d$^{-1}$).

In this study, the only sink term considered is the soil water extraction rate by roots ($S_a$).

### Bottom boundary conditions

The bottom boundary is located in the unsaturated zone or in the upper part of the groundwater table. The bottom boundary condition can be determined by an imposed pressure head (e.g. groundwater level), an imposed water flux (e.g seepage ) or a combination of the two (e.g. q-H relation), depending on the application and spatial scale. In total, SWAP offers eight options to prescribe the bottom boundary condition. Option 5 "Prescribed soil water pressure head of bottom compartment" was chosen in this study.

For the selected bottom boundary condition, the pressure head at the bottom of the soil profile (bottom compartment) and date must be specified. For times between observations, SWAP interpolates linearly.

## Crop growth

The dynamic crop growth model WOFOST [De Wit et al., 2020], integrated in SWAP, describes the phenological development, growth and yield formation of major arable crops. The potential transpiration and yield are determined by the incoming radiation, carbon dioxide concentration, air temperature and crop characteristics. The actual transpiration and yield are calculated based on the decreased crop water uptake due to drought and/or lack of oxygen, as calculated by SWAP.

WOFOST calculates how much light and $CO_2$ is intercepted and potentially converted by photosynthesis. The actual photosynthesis is then calculated by reducing the potential photosynthesis for limited availability of moisture for evaporation or oxygen deficiency. Part of the energy produced during photosynthesis is used for maintenance respiration, and other part is converted into dry matter. During this conversion, some energy is lost as growth respiration. The dry matter produced is distributed over the different parts of the crop: roots, stems, leaves and storage organs, depending on temperature and the development stage of the crop. Some simulated crop growth processes like the maximum rate of photosynthesis and the maintenance respiration, are influenced by temperature. Other processes like the distribution of assimilates or senescence of crop tissue are controlled by the phenological stage of the crop. The phenological development stage also depends on temperature.

A dynamic grass growth model "GRASS", derived from WOFOST, is specifically developed for the simulation of grassland [Kroes and Supit, 2011], to consider the differences in the growing stages and cultivation practices between grass and arable crops. Grass is perennial and remains in the vegetative period during most of its growing season. Also, it is frequently mowed or grazed. Mowing and grazing in the model occur when the above ground dry matter exceeds a certain threshold ( value). Grass is simulated as a permanent grassland, and five combinations of mowing and grazing management scenarios are available. In practice, the time of mowing/grazing will depend on the farm management and interaction between different fields. This grass module is experimental and calibrated for Dutch conditions, but several studies have shown its robustness [Mulder et al., 2021].

**Important**
For more information of the required crop parameters and values used in this study, the reader may refer to the crop files published in the PEILIMPACT github repository.

## Direct and indirect effects

Yield reduction due to changes in hydrological conditions distinguishes between direct and indirect effects. Direct effects are linked to water and oxygen stress ( and salinity stress), while indirect effects are related to how prevailing hydrological conditions affect sowing and harvesting.

### Direct effects on yield

Sub-optimal soil moisture conditions (too wet or too dry) have a direct influence on the yield of agricultural crops. Under these conditions, crop transpiration is reduced due to stomatal closure. This also reduces the absorption of $CO_2$, leading to less photosynthesis and less growth.

To determine the uptake of water by plant roots, SWAP first calculates the potential transpiration (i.e. the transpiration at optimal soil moisture conditions). This is calculated based on weather variables (solar radiation, air temperature, humidity and wind speed) and plant characteristics (crop height, reflection coefficient, leaf area index and minimal stomatal resistance). The potential transpiration is distributed over the root zone, proportional to the root density, to determine the potential uptake of water by the roots. Then, based on the soil moisture conditions at different depths in the root zone, the extent of damage due to dry or wet conditions is determined. SWAP uses stress factors (0 - 1) for every sub-optimal condition, at each soil compartment, to calculate the actual plant root water uptake.

$$S_a(z) = \alpha_{rd} * \alpha_{rw} * S_p(z) \tag{4.2}$$

$$T_{act} = \int_{-D_{root}}^{0} S_a(z)\,dz \tag{4.3}$$

$\alpha_{rd}$ and $\alpha_{rw}$ are the stress factors for too dry and too wet conditions, respectively. $S_p(z)$ is the potential root water uptake, $S_a(z)$ is the actual root water uptake at each soil compartment, and $T_{act}$ is the actual transpiration over the entire root zone, or in other words, the sum of individual root water uptakes multiplied by the compartment thickness. The transpiration reduction due to each stress is calculated by multiplying the total reduction in crop water uptake with the proportion of the logarithmic value of the corresponding stress factor ((4.4)).

$$T_{red,j} = [S_p(z) - S_a(z)] * \frac{\log \alpha_j}{\sum_{i=1} \log \alpha_i} \tag{4.4}$$

It is assumed that the relative distribution in transpiration reduction is equal to the relative yield loss.

**Drought stress** Drought stress is calculated by the function of Feddes et al. [1978] (Figure 4.2). Above $h_3$, root water uptake is optimal and no drought stress occurs. Below $h_3$, the root water uptake linearly decreases until zero at $h_4$ (wilting point). Generally, fixed values for $h_3$ and $h_4$ are used. However, the drought stress threshold ($h_3$) depends on crop type, soil texture, root density and atmospheric demand, and the linear decline may deviate from reality. Therefore, a detailed, microscopic root water uptake module for drought has been added in SWAP [de Jong van Lier et al., 2013] and can be chosen as alternative to Feddes et al. [1978].

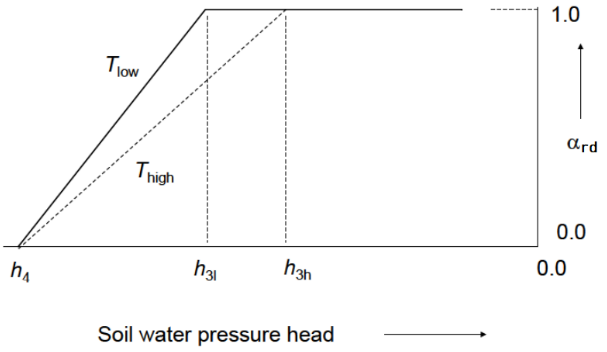


Figure 4.2.: Reduction factor for root water uptake, $\alpha_{rd}$, as function of soil water pressure head (h) and potential transpiration rate ($T_p$) [Feddes et al., 1978]

**Oxygen stress** Oxygen stress influences crop yield via the aeration of the soil, whereby the oxygen supply to plant roots takes place. Under too wet conditions, air in the soil pores is replaced by water and the availability of oxygen becomes limiting for root respiration. Root respiration is determined by the transport of oxygen in the soil and the demand by the roots. Since the transport of gas in water-filled pores is approximately 1000 times lower than that in air-filled pores, the availability of oxygen is determined by the air content at the different soil depths (Figure 4.3). In addition to respiration by roots, the available oxygen is used for respiration by microorganisms. The link with the crop growth model WOFOST makes it possible to describe the oxygen demand of plant roots in detail.

Oxygen transport is calculated in SWAP using the model proposed by Bartholomeus et al. [2008]. In this model, the critical gas filled porosity for oxygen stress depends on several abiotic (soil physical properties, moisture content, temperature) and biotic factors (plant characteristics). Therefore, the model of Bartholomeus et al. [2008] is applied for every soil layer, to calculate the difference between potential and actual root respiration and subsequently, the reduction factor $\alpha_{rw}$ due to oxygen stress (wet conditions).

### Indirect effects on yield

In SWAP, indirect effects refer to restrictions in normal agricultural practices due to too wet or too cold conditions, which ultimately shortens the growing season. These include limited carrying capacity for tillage, sowing/planting or harvesting, delayed

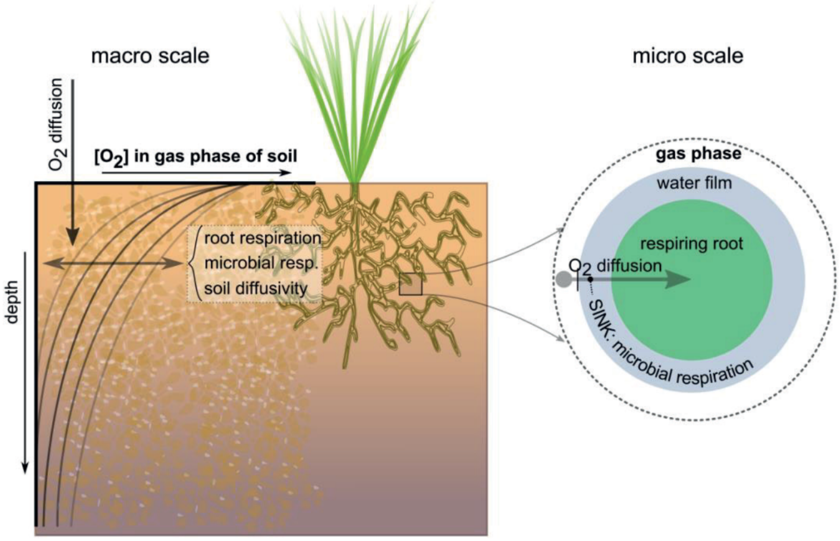


Figure 4.3.: Schematization of the oxygen module for determining daily respiration and transpiration reduction. The module combines physiological processes, root and microbial respiration; and physical processes, diffusion at both macro and microscale. Figure taken from Bartholomeus et al. [2011].

germination, and crop damage [Werkgroep Waterwijzer Landbouw, 2018]. Other indirect effects like quality of harvest, soil quality, pests and diseases are not taken into account. More context about different indirect effects can be found in the chapter Impact of groundwater levels and waterlogging on cultivation factors. Indirect effects like pests and diseases along with nutrient deficiency are accounted for in one single management factor "RELMF", which varies with the type of crop. These factors were obtained from several experiments under Dutch conditions and double-checked by plant scientists, for the WaterVision Agriculture tool, which were maintained in this study. Nutrient deficiency during the growing period is not implemented in this version of the model, but a nitrogen module is available [Groenendijk et al., 2016].

For arable crops, different machinery is used for preparatory works (i.e. tillage), sowing or planting, and harvesting. The start of each of these stages can be delayed if the soil is too wet for the machines to enter the field, or too cold for the seed to germinate. In the model, this is determined based on a pressure head criterion derived from Beuving [1982], and a temperature criterion in case of germination (temperature sum needed for crop emergence). A certain pressure head, at 15 cm depth, has to be met before preparation works, sowing or harvesting can start, which depends on soil and crop characteristics. WaterVision Agriculture distinguishes between two categories for the pressure head criterion: light and heavy. This is a weight category that depends on the weight of the most common machine used for the specific crop (Table 4.1, 4.2, and 4.4 of Werkgroep Waterwijzer Landbouw [2018]). Plowing, always falls under the heavy category. For sowing, maize and potatoes are in the heavy category, while winter wheat and sugar beet fall in the light category. For harvesting, all the five crops fall in the heavy category.

In grass, indirect effects are related to insufficient carrying capacity for mowing or grazing. In this case, when a certain pressure head, at 15 cm for mowing or at 10 cm for grazing, is exceeded, harvest decreases by a certain percentage based on the degree of exceedance. In this study, only mowing was considered since it is the main grass management in Flanders.

In order to find the pressure head values for the Flemish soils, top soils (first soil layer of each soil profile) were first translated to the Dutch soil classification "The Staring series" [Heinen et al., 2020] based on the soil texture and organic matter. Then, the appropriate pressure head was assigned to every soil profile and crop. Table 4.1 presents the different pressure head thresholds used for the Flemish soil types, according to the light and heavy category. This is a rather simple method but allowed to include approximated pressure head values in the model, and calculate indirect effects.

By taking into account the possibility that the growing season may be shifted or shortened, the model actually introduces a "second" calculated potential crop yield associated with a sub-optimal growing season. Figure 4.4 illustrates how indirect effects are calculated in the model. In the absence of indirect effects, the situation would be similar to the figure on the left (reference situation), where just direct effects (water and oxygen stress) are considered, and the potential yield ($Y_{pot,max}$) is the maximum possible. After a wetting measure, the situation can become similar to the figure on the right, where indirect effects now play a role and the growing season is shortened. In this condition, this "second" potential yield ($Y_{pot}$) and actual yield implicitly include the reduction due to indirect effects. To determine the maximum potential crop yield $Y_{pot,max}$, the model assumes a deep groundwater level of 5 m to minimize the indirect effects of excessively wet conditions due to shallow groundwater levels. The difference between these potential yields represents the yield reduction due to indirect effects.

$$RED_{ind}(\%) = \frac{(Y_{pot,max} - Y_{pot})}{Y_{pot,max}} * 100 \tag{4.5}$$

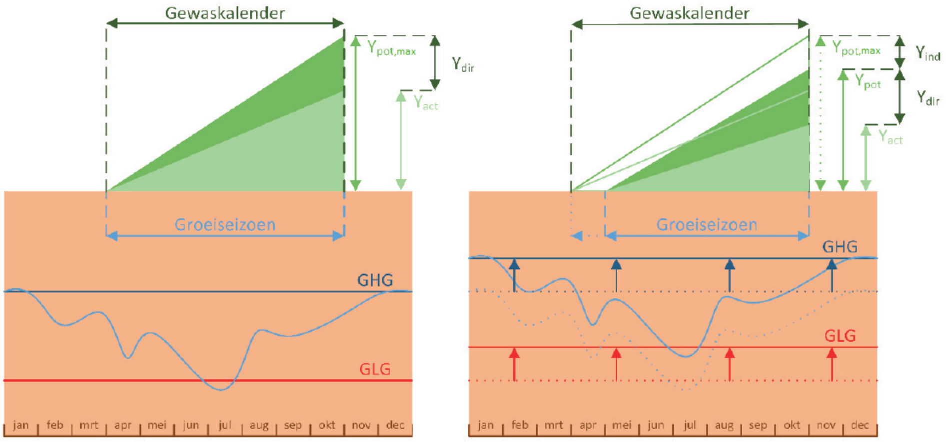


Figure 4.4.: Example of the calculation of the potential and actual yield when taking into account direct and indirect effects. On the left, the reference situation is displayed, and on the right , the situation after a wetting measure. The dark green area represents the potential crop yield and the light green area, the actual crop yield. Figure extracted from Werkgroep Waterwijzer Landbouw [2018].

Table 4.1.: Pressure head criterion at 15 cm depth according to light and heavy category, for different soil types in Flanders. Values are taken from Table 4.1 of Werkgroep Waterwijzer Landbouw [2018].

| Staring building block | Description | Soil Belgian classification | Preparatory works | Pressure head at 15 cm depth (cm) Light category | Pressure head at 15 cm depth (cm) Heavy category |
|---|---|---|---|---|---|
| B01- B04 | Weakly loam to very strong loam with very fine to moderately fine sand | sand (Z)<br>loamy sand (S)<br>light sandy loam (P)<br>sandy loam (L) | spring | -50 | -60 |
| B07 | Very light sludge | light sandy loam (P)<br>loamy sand (S)<br>sandy loam (L)<br>loam (A) | autumn | -60 | -60 |
| B08 | Moderately light loam | sandy loam (L)<br>loam (A) | autumn | -60 | -90 |
| B09 | Heavy sludge | loam (A)<br>clay (E) | autumn | -60 | -90 |
| B10-B12 | Light to very heavy clay | clay (E)<br>heavy clay (U) | autumn | -70 | -100 |
| B13 | Sandy loam | sandy loam (L)<br>loam (A) | autumn | -70 | -100 |
| B17 | Peaty clay | loam (A) | spring | -60 | -80 |

### Yield reduction

The potential crop yield is calculated using the dynamic crop model as function of the $CO_2$ content, solar radiation, temperature, crop characteristics, and based on the pressure head criterion and temperature criterion at the start and end of the growing season. The transpiration reduction due to too dry and too wet conditions is used to calculate the actual crop yield. The total yield reduction ($RED_{TOT}$) in % is defined as the relative difference between the maximum potential yield ($Y_{pot,max}$) and actual yield ($Y_{act}$) ((4.6)). The yield reduction due to direct effects is the difference between $RED_{TOT}$ and $RED_{ind}$ ((4.7)).

$$RED_{TOT}(\%) = \frac{(Y_{pot,max} - Y_{act})}{Y_{pot,max}} * 100 \tag{4.6}$$

$$RED_{dir}(\%) = RED_{TOT}(\%) - RED_{ind}(\%) \tag{4.7}$$

The yield reduction due to each stress ( dry or wet conditions) is calculated by multipliying $RED_{dir}$ with the proportion of each transpiration reduction, $T_{red,j}$ from (4.4).

$$RED_j = RED_{dir} * \frac{T_{red,j}}{T_{pot} - T_{act}} \tag{4.8}$$

The potential and actual crop yield, and transpiration reduction due to each stress were the main model output variables for this study.

## 4.3. Model Input

To get realistic model results, a good estimation of the boundary conditions and soil properties is fundamental. This regional version for Flanders uses freely available datasets and maps for the whole of Flanders (online or on request), obtained from Flemish institutions or from previous projects (Table 4.2). Despite the inherent limitations of such generic and large-scale data, the information is suitable for applying the model in a regional scale. More detailed information about the different input data layers is given below.

Note: For the case study De Zegge-Mosselgoren (Case-study: agricultural land around De Zegge-Mosselgoren ) this input data (weather data and soil information) was combined with the groundwater levels from a locally calibrated groundwater model (preliminary results) from the “Ecohydrological study: basis for restoration measures for Nature Reserve De Zegge” (Witteveen+Bos) instead of the general map of average groundwater levels used for the regional analysis of Flanders. Unfortunately, this study was very behind schedule, which meant that we were unable to work with the final results of the ecohydrological study and to calculate future scenarios to quantify the effects on agriculture.

Extra map layers (e.g. provinces, main rivers) were downloaded from The Atlas of Belgium, for graphical purposes.

To link the input data with its corresponding location (i.e. coordinates) in Flanders, ASCII maps were used. These maps were generated in QGIS 3.22, using the Belgian Lambert 72 (EPSG: 31370) projection system. For the regional analysis, the maps were homogenized to 500 m resolution using a simple upscaling criterion, either “mean

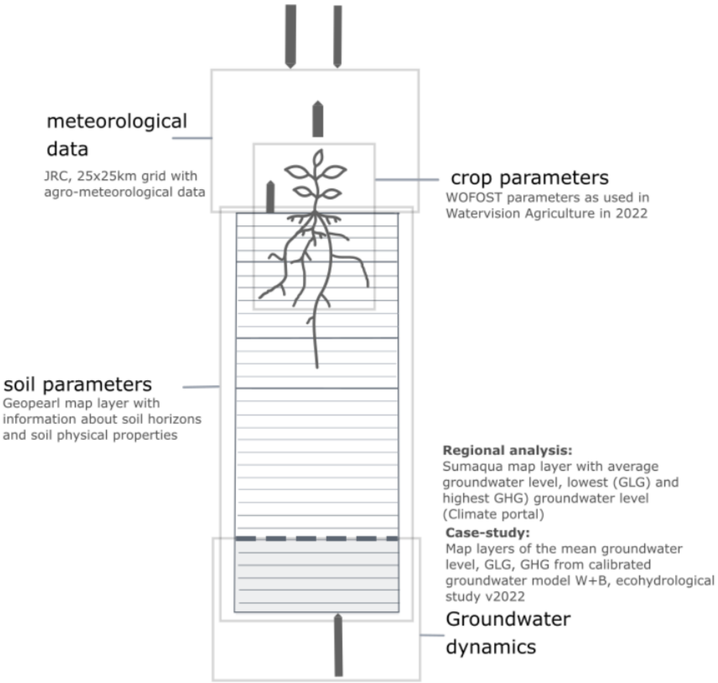


Figure 4.5.: Schematic overview of the information/data used to shape the model parameters and necessary input variables in the model framework of PEILIMPACT. If a user has more accurate data for one or more of these components, they can replace the data layers applied here.

Table 4.2.: Overview of the input data used in SWAP-WOFOST

| Input data | Description | Source |
|---|---|---|
| Meteorological data | Daily interpolated meteorological variables from 01/01/1990 until 31/12/2021, 25 x 25 km resolution. | Joint Research Center (JRC) |
| Crop data | Planting and harvesting dates | ILVO and Dutch crop calendar |
| Soil data | Soil texture, soil hydraulic parameters and vertical discretization of 536 soil profiles over Flanders. | Flemish Institute for technological Research (VITO), from the GeoPearl model [Joris et al., 2017] |
| Groundwater levels (GWL) maps (Regional scale) | Average GWL, average highest GWL (GHG) and average lowest GWL (GLG) maps, 100 m resolution. | Effecten van Klimaatverandering op de freatische grondwaterstanden (Sumaqua) [Franken and Wolfs, 2022] |
| Groundwater levels (GWL) maps (Case study) | Average GWL, average highest GWL (GHG) and average lowest GWL (GLG) maps, 10 m resolution. | “Ecohydrological study: basis for restoration measures for Nature Reserve De Zegge” (Witteveen + Bos) (ongoing study) |

value” or “majority” in the Resampling tool. For the case study, the original resolution was maintained.

## Meteorological data

The Joint Research Center (JRC) contains daily interpolated agro-meteorological data for Europe and neighboring countries, with a 25 km resolution, from 1979 to the last calendar year completed. Up to the date of this project, data from 01/01/1979 until 31/12/2021 is available. Table 4.3 presents the meteorological information provided in JRC and used in the model. Units conversion and formatting was done before using it in the model.

Table 4.3.: Meteorological variables and their units as given in JRC.

| Variable | Units |
|---|---|
| Maximum air temperature | °C |
| Minimum air temperature | °C |
| Mean daily wind speed at 10 m | m s$^{-1}$ |
| Vapour pressure | hPa |
| Sum of precipitation | mm d $^{-1}$ |
| Total global radiation | kJ m$^{-2}$ d$^{-1}$ |

The meteorological ASCII map was built based on the coordinates ( blue points in Figure 4.6) of the meteorological grids as given by JRC, and applying voronoi polygons in QGis. In this way, the corresponding region for each point could be determined, which is similar to a grid of 25 km x 25 km resolution (Figure 4.6). Finally, the map was exported to 500 m resolution.

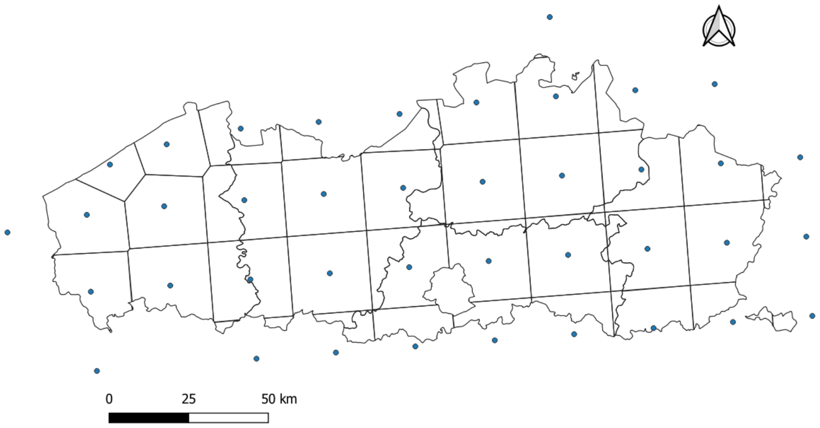
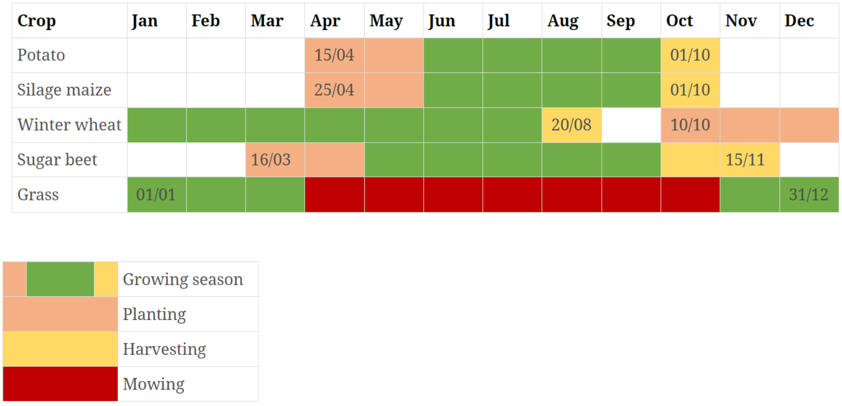


Figure 4.6.: Raster map showing the location of the JRC meteorological grids.

## Crop data

Typical planting and harvest dates in Flanders were determined with the help of ILVO experts. These dates are similar to the ones assumed in WaterVision Agriculture.

Table 4.7 shows the growing season for the 5 crops modeled in this study, together with their period of planting, harvesting and mowing (in the case of grass) in Flanders. The dates in the table indicate the planting and harvesting dates used in the model.



| Crop | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Potato | | | | 🟧 15/04 | 🟧 | 🟩 | 🟩 | 🟩 | 🟩 | 🟨 01/10 | | |
| Silage maize | | | | 🟧 25/04 | 🟧 | 🟩 | 🟩 | 🟩 | 🟩 | 🟨 01/10 | | |
| Winter wheat | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟨 20/08 | | 🟧 10/10 | 🟧 | 🟧 |
| Sugar beet | | | 🟧 16/03 | 🟧 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟨 | 🟨 15/11 | |
| Grass | 🟩 01/01 | 🟩 | 🟩 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 🟩 | 🟩 31/12 |

| | |
|---|---|
| 🟧🟩🟨 | Growing season |
| 🟧 | Planting |
| 🟨 | Harvesting |
| 🟥 | Mowing |

Figure 4.7.: Crop calendar of the 5 crops simulated with SWAP-WOFOST. Colored cells represent the time span for planting, harvesting and mowing (in case of grass) in Flanders, while the specific dates are the planting and harvest dates used in the model.

## Soil data

Soil texture, soil hydraulic parameters and characterization of the soil profiles over Flanders were provided by the Flemish Institute for technological Research (VITO), from the GeoPearl model [Joris et al., 2017]. There are in total 536 dominant soil units defined over Flanders. Soil texture, organic carbon, and pH for each soil horizon are extracted from the Aardewerk database 2010 [VPO, 2011] and the Belgian soil map [VPO and IWT, 2014]. Soil hydraulic properties are calculated using the extracted soil properties and the pedotransfer functions of Wösten et al. [1999]. Soil profiles are defined to a depth of 3 m and subdivided into 5 to 7 horizons. In this study, the depth of the soil profiles was extended to 6 m.

Bulk density (BD) was calculated according to the formula of Vereecken [1988], shown in (4.9), which depends on the percentage of organic carbon ($C_{org}$) . This formula applies for sand (Z), loamy sand (S) and light sandy loam (P) textures. For other textural classes, bulk density is assumed equal to 1.48 g cm$^{-3}$. This is obviously a simplification of reality. The bulk density in SWAP is especially important for determining the maximum rooting depth of the crops.

$$BD = 1.634 - 0.0948 * C_{org} \tag{4.9}$$

$$BD = 1.48 \tag{4.10}$$

### Soil texture according to the Belgian Soil Classification system

The soil texture according to the Belgian Soil Classification system [Dondeyne et al., 2014, Van De Vreken et al., 2009] for each of the 536 soil units, was determined based on the clay and sand content of the first top soil layer. Figure 4.8 shows the soil textural classes in Flanders according to this classification, based on the soil properties used in the model.

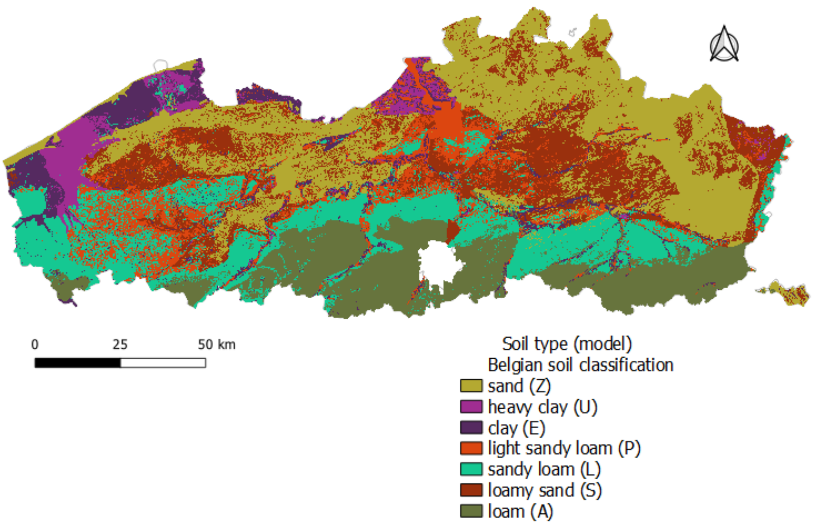


Figure 4.8.: Soil texture according to the Soil Belgian Classification System, based on the textural information used in the model.

This map is less detailed than the Belgian Soil Map since the classification was based just on the clay and sand content of the first layer and mainly serves to visualize trends between crop yield, groundwater and soil types.

### Maximum rooting depth allowed by the soil

The maximum rooting depth depends on plant and soil characteristics. Ranges of maximum rooting depth for different crops can be found in the FAO guidelines [Allen et al., 1998]. We defined the maximum rooting depths for each plant as in the WaterVision Agriculture tool (Table 4.4), which slightly differ from values provided by the FAO. However, normal root growth can be restricted in the presence of hard soil layers, compaction, and boundaries in the soil (e.g. rocks) [Moore et al., 1998]. Therefore, root growth restrictions were considered when:

- pH <4.0
- BD >BD calculated by linear interpolation for its respective clay content, between points: BD = 1.6 g $cm^{-3}$ and clay = 20 %, and BD = 1.2 g $cm^{-3}$ and clay = 65 %.

**Important**
Correctly estimating the maximum rooting depth is important for quantifying both drought and oxygen stress. The deeper the roots can grow, the more access they have to water in the deeper part of the soil. This will (quickly) cause less stress during drought. On the other hand, deep-rooted crops are also more likely to suffer

Table 4.4.: Maximum rooting depth according to crop characteristics assumed in the model.

| Crop | Maximum rooting depth (cm) |
|---|---|
| Potato | 50 |
| Silage maize | 100 |
| Winter wheat | 125 |
| Sugar beet | 120 |
| Grass | 40 |

from oxygen stress at high groundwater levels. If local information is available on root depths, it is therefore advisable to see whether or not the assumptions above need to be adjusted.

For comparison: for the calculations of water absorption in the Flemish Reactive Assessment Framework for Water Scarcity, the Soil Service of Belgium assumed the following root depths: Potato - 45 cm, Silage maize - 60 cm, Sugar beet - 60 cm, Grassland - 60 cm.

The check of the BD was done for each soil layer and when the BD is exceeded or PH is lower than 4, roots cannot grow deeper, even though this is still theoretically possible. The minimum rooting depth is 10 cm for grass and 20 cm for other crops. If no restrictions were imposed by the soil, the maximum rooting depth would be the one given in Table 4.4. The spatial variability of the maximum rooting depth allowed by the soil is shown in Figure 4.9.

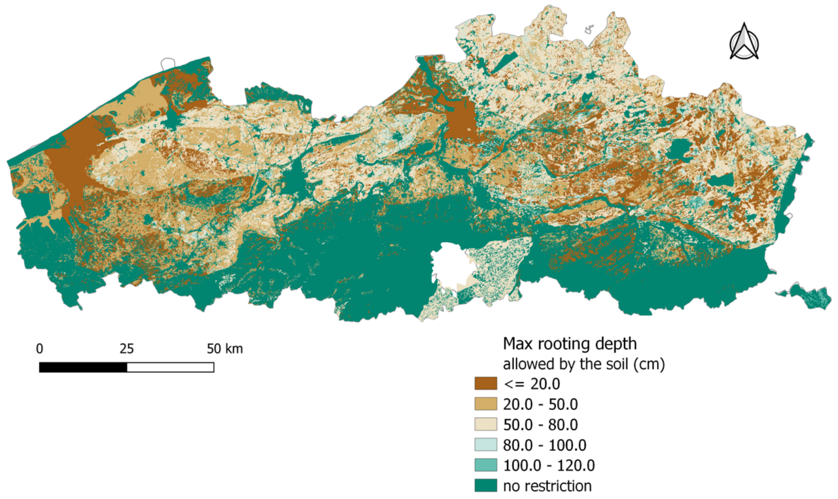


Figure 4.9.: Spatial variation of the maximum rooting depth allowed by the soil as given in the model.

### Soil discretization

To get realistic simulations of the water infiltration in the soil matrix, especially at the soil surface, the grid cells or soil compartments for numerical solution of the Richards equation have to be small enough. The SWAP manual [Kroes et al., 2017] provides some guidelines to define the thickness of the soil compartments, which are shown in Table 4.5. The initial discretization from the GeoPearl soil input was therefore adapted to comply with these guidelines.

Table 4.5.: Vertical discretization of the soil profile for numerical solution of Richard's equation.

| Depth of the soil profile (cm) | Compartment thickness (cm) |
|---|---|
| 0 - 50 | 1 |
| 50 - 80 | 2 |
| 80 - 140 | 5 |
| 140 - 200 | 10 |
| 200 - 300 | 20 |
| 300 - 600 | 25 |

### Phreatic groundwater levels

Average groundwater levels (Figure 4.10), and average highest (GHG) and lowest groundwater levels (GLG) maps, with 100 m resolution, were provided by Sumaqua in the context of the project "Actualiseren grondwaterstandsindicator en berekening effecten van klimaatverandering op de freatische grondwaterstanden" [Franken and Wolfs, 2022]. The average groundwater levels for all pixels were obtained from Machine Learning (ML) trained with a large number of observations in Flanders (5673 locations). The GHG and GLG maps were approximated using ML based on the results of 217 long term SWAP simulations, for points in which some correlation between precipitation and groundwater was observed. GHG & GLG maps do not contain information in the locations closer to watercourses where said correlation does not exist. Note that the generated maps are predictions and are not necessarily valid in locations where drainage or GWL extractions are present without a data point nearby to train the algorithm.

Different natural factors are involved in the groundwater level (GWL) fluctuations and the response time of the groundwater system to a certain precipitation event (time lag). One factor is the cumulative precipitation deficit (precipitation - reference evapotranspiration, P-ET0), which is highly correlated with GWL. However, the time response of the system can vary from less than a month to even years. This time delay is mainly influenced by the depth of the GWL [Wossenyeleh et al., 2020, Londot and Huysmans, 2021], which also defines how strong the seasonal effects of the precipitation in GWL are. Shallow GWL normally have more correlation with $P\text{-}ET_{ref}$ than deep GWL. Wossenyeleh et al. [2020] found that in relatively shallow GWL (<10 m), the delay ranges between 0-2 months. In places close to rivers, ditches or drains however, the GWL fluctuations will be more influenced by the surface water levels instead of the $P\text{-}ET_{ref}$. Another factor is soil texture, which defines the storage capacity of the soil. Additional to these natural factors, there are also anthropogenic conditions like unknown GWL abstractions and sewers, which also affect the GWL fluctuations.

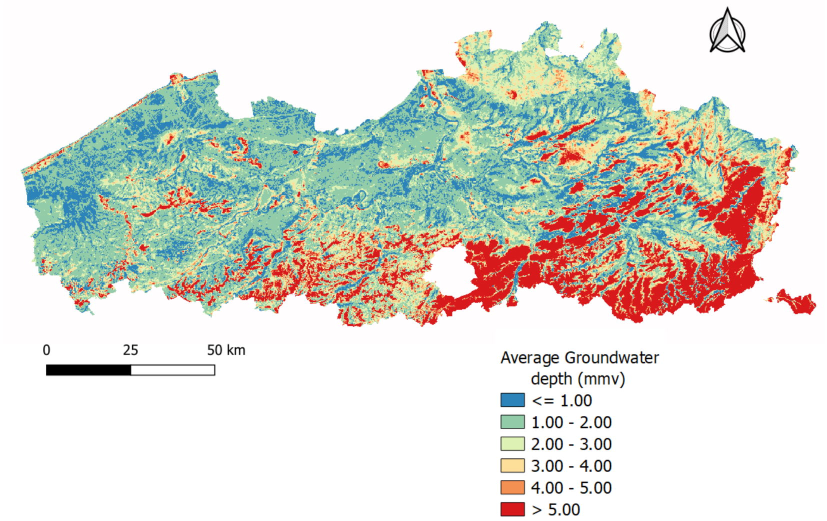


Figure 4.10.: Spatial variation of the groundwater levels in Flanders [Franken and Wolfs, 2022]

### Description of the phreatic groundwater dynamics

The seasonal fluctuations of the GWL are crucial to predict its impact on the growth of arable crops. Yet, the available information in Flanders does not describe these dynamics. In this study, GWL fluctuations were approximated by the sinus function of (4.11). This sinus curve was calculated in every location and varies according to the average highest (GHG) and lowest groundwater levels (GLG), but keeps constant through the years (Figure 4.11). The shape of the curve is based on the monthly P-ET$_{ref}$ over Flanders for the period 1979-2021.

$$GWL = GHG - Amp + Sin((days + 80) * \frac{\pi}{180}) * Amp \tag{4.11}$$

$$Amp = abs(GLG - GHG)/2 \tag{4.12}$$

Since GHG & GLG maps were developed assuming some correlation between precipitation, evapotranspiration and GWL, defining the locations where this correlation occurs is also important in order to use adequately the information available. Areas which depict some correlation could be modeled using the sinus function based on GHG and GLG, while areas without correlation could be simply modeled with the average groundwater levels.

Therefore, a correlation analysis was done to identify said areas. For this purpose, groundwater levels observations (2732) were downloaded from DOV using the python package pydov. These observations were compared with the monthly precipitation deficit (P-ET$_0$), according to their specific location. The results of the correlation analysis and location of these observations in Flanders is shown in Figure 4.12. Locations showing some correlation (>0.25), have GWL mostly shallower than 3 m (depicted in orange).

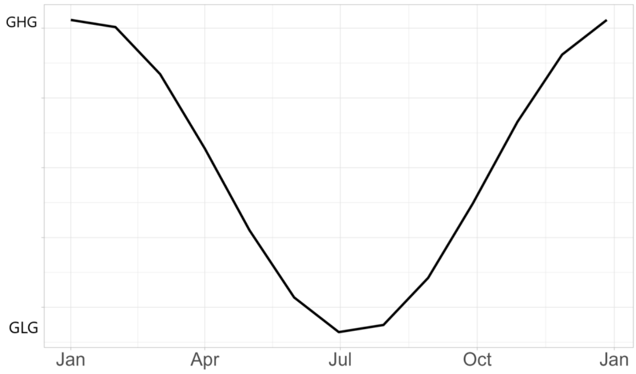


Figure 4.11.: Average groundwater regime approximated with the sinus function based on the GHG and GLG.

Therefore, the sinus function was used just in these locations, where the average GWL was shallower than 3 m.

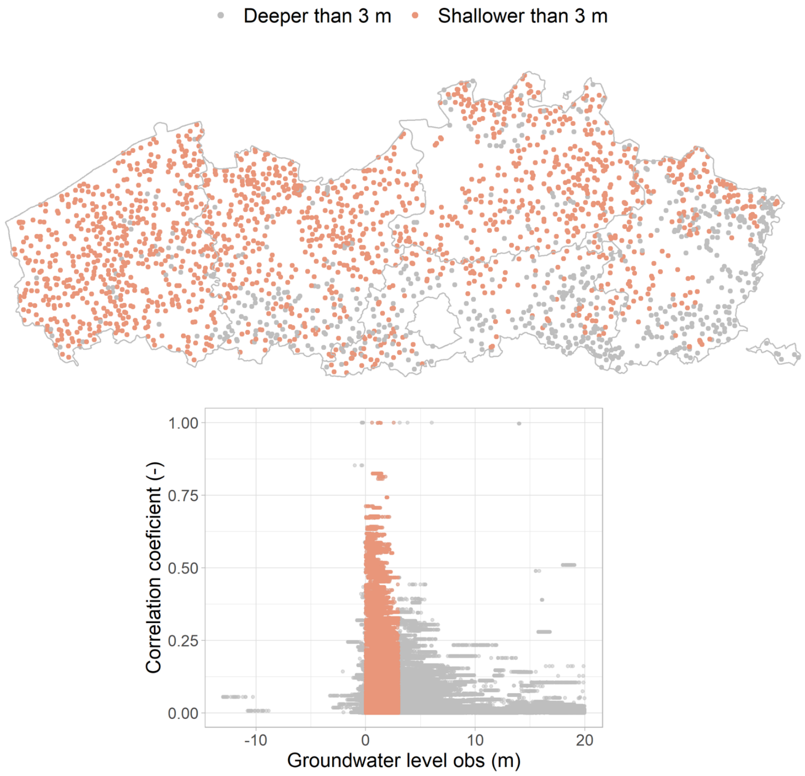


Figure 4.12.: Correlation between precipitation deficit and groundwater levels. GWL shallower than 3 m are depicted in orange. Positive groundwater levels are below the soil surface.

Groundwater levels (GWL) served as bottom boundary condition in the model. GWL were converted to pressure heads in order to use the option 5 in SWAP. Pressure heads were obtained based on the reference located at 600 cm depth, which is the extent of the soil profile.

## 4.4. Model setup and running

Model running and analysis of model simulations involved three main steps, which are illustrated in Figure 4.13.

1. Input data generation
2. Model run
3. Postprocessing

In synthesis, the model needs three main input files: meteo files (.met), crop files (.crp) and the main swap file (.swp). These files are supplied with information from the Sqlite database. The model runs using the model executable and these input files. The file "result_output.csv" is the main output of the model, that contains output variables like daily crop transpiration and biomass, which is previously defined in the sqlite database. During postprocessing, the potential and actual dry matter yield for each year, and yield reduction due to water stress and/or indirect effects are calculated.

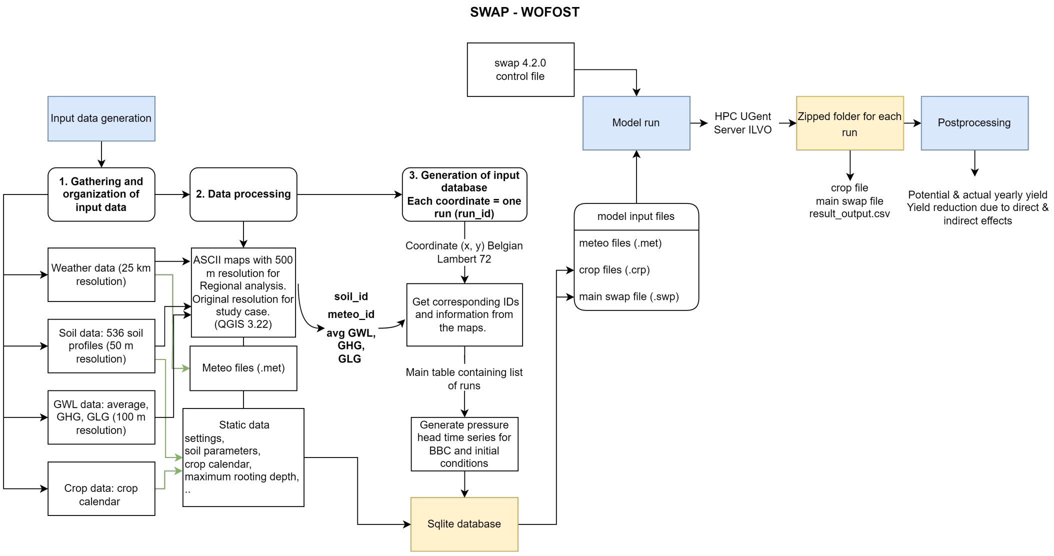


Figure 4.13.: Flowchart of the input data generation, model run and model results processing using SWAP-WOFOST.

The first step to run the model is the generation of input data. The structure of the input data folders is showed in Figure 4.14. The **crop** folder contains the crop files (.crp), where detailed crop parameters for simulating crop growth and biomass assimilation are specified. The file **location.csv** has the coordinates (in Belgian Lambert 72) of every location where the model will be run. The **input_data** folder comprises most of the input data for each run, such us soil parameters, crop management parameters, and other input variables, which are stored in the Sqlite database. The **maps** folder contains the ASCII maps for meteo and soil IDs, and average GWL, GHG and GLG values.

This information is also included in the database. Sqlite databases are then saved in the folder **database**. Five main Sqlites databases were created for each crop type, assuming that each crop covers the whole area.

The **meteo** folder holds the weather time series for each 25 x 25 m grid, in the correct format (.met), and CO2 emissions (.co2) until 2021. The **source** folder contains the model executable, version 4.2.0. The folders **libraries** and **R scripts** have the R libraries and R scripts for generating the databases and running the model.

The **swap.swp** file is the main swap file, containing general information regarding simulation, meteorology, crop rotation, irrigation, soil water flow, heat flow and solute transport. The main swap file draws the required information from the sqlite database. The control file **control.inp** contains directories and paths of the input data files.

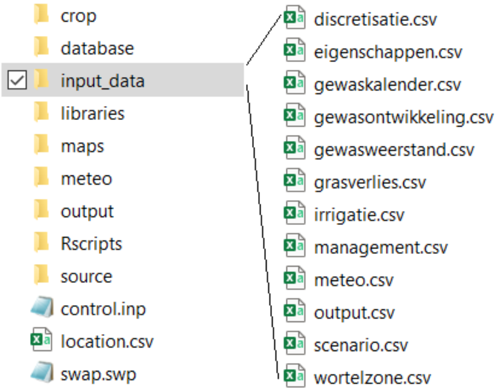


Figure 4.14.: Organization of input data folders for running SWAP-WOFOST.

The next step involves running the model. This can be done directly in R studio or through a batch file. For the Regional analysis, simulations were executed in the UGent Super computer and/or the ILVO server. In the regional analysis, each simulation corresponds to a grid cell with 500 m resolution. In the case-study, each simulation corresponds to the center of an agricultural parcel.

The model output is available in a zipped folder containing the crop file, the main SWAP file and the result_output.csv file. The result_output.csv file contains the daily simulated potential and actual transpiration, transpiration reduction due to dry and wet conditions, potential and actual yield, and groundwater levels.

The final step is the postprocessing of the model results, where the yearly yields and total yield reduction due to direct (i.e. water stress) and indirect effects, and average GHG and GLG are determined.

The model instruments and general input data layers for Flanders can be freely downloaded from the PEILIMPACT github repository.

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# 5. Use of the model framework

Sarah Garré

The current model framework can be used to answer different types of questions. It is important to clearly distinguish different ways of using the modeling framework, so that the most appropriate level of detail and accuracy is used/respected for these inherently different applications. Below we outline a number of possible uses of the modeling framework and briefly describe how this can be applied in those cases.

## Analysis of suitability and trends across Flanders

The impact of groundwater levels on yield is a complex interaction of climate, soil, groundwater dynamics and crop. It is therefore interesting to look at the scale of Flanders to see whether certain trends or spatial patterns can be found. Such a regional analysis for the whole of Flanders then broadly reflects the suitability of certain regions/areas for certain crops, enables us to identify and quantify types of stress and to highlight major trends in space and/or time.

The basic data layers as shown in the Model framework to evaluate the suitability of groundwater regime for crop growth are suitable for this. These data layers, which cover Flanders, can of course always be improved, but the level of detail is sufficient for a regional analysis.

Attention!: Since the timing of drought in the growing season can be decisive for crops, we applied a sine function based on the average highest (GHG) and average lowest (GLG) groundwater levels at locations where groundwater dynamics are correlated with rainfall. Where this was not the case, we worked with an average groundwater level that remains constant throughout the year.

## Exploratory analysis of contrasting groundwater levels at a given location

In recent years, there have also been more and more small-scale actions in Flanders that can have an impact on the groundwater levels: level-controlled drainage, dams, wetting of a part of the stream valley, etc. Also there, people would like to be able to estimate how these interventions will affect one or more agricultural plots. One then looks for a rough, exploratory simulation of harvesting at a certain location where no additional information is yet available (i.e. local groundwater measurements/models, local weather data, accurate soil data).

The basic data layers described in the Model framework to evaluate the suitability of groundwater regime for crop growth are also suitable for this. Users should be aware that this is a rough approximation of reality, but it can be used to compare contrasting situations. If it is possible to install a monitoring well to check the current groundwater level and its dynamics or if monitoring well measurements are already available on `https://www.dov.vlaanderen.be/`, it is advisable to use this information or at least check whether the measured groundwater levels correspond on average with the general groundwater map layer.

### Detailed impact analysis in large-scale rewetting projects

Finally, large-scale rewetting projects are planned in some areas that will bring about substantial changes in groundwater levels for a larger area. Ecohydrological studies are usually also carried out in these types of projects. Here too, it is important to estimate the impact of the rewetting on agricultural activities in order to evaluate whether the plans are feasible and what accompanying policy can be developed for the affected farmers if a negative impact is indeed expected.

For this type of customization, the model can be used to calculate the impact of current and future groundwater levels for all plots in the affected area. In this case, the input data for the model must be more detailed than the general Flemish data layers, especially with regard to groundwater levels. This can come from local groundwater measurements or from real groundwater models for that area that are calibrated with local data. Such models are then often available, precisely because an ecohydrological study is also being set up.

# Part III.

# Results

# 6. Regional analysis and plausibility check

Diana Estrella, Ruud Bartholomeus, Tom De Swaef, Sarah Garré

## 6.1. Approach

To have an overall idea of the yield variability due to wet or dry conditions across Flanders, a regional analysis was performed. The regional model was constructed by defining a 500 m resolution grid covering the extent of Flanders (Figure 6.1). This resulted in a set of more than 54000 SWAP-WOFOST simulations. The model was run in these locations for each of the five focus crops: grass, silage maize, potato, winter wheat, and sugar beet. For further analysis, pixels not classified as agricultural land were excluded from the analysis. In reality there are of course rotations and more possible crops. The resulting maps do not represent the real situation in any given year but serve to identify potentially problematic areas for different crop types on a regional scale (conditions that are too wet or too dry).

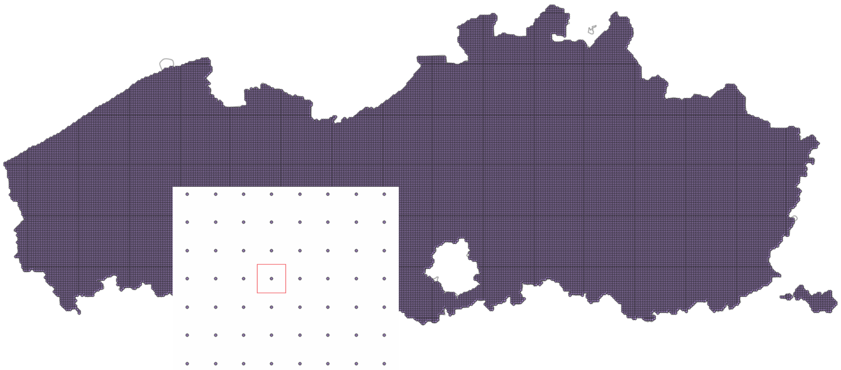

Figure 6.1.: Raster with 500 m - resolution of the Regional model in Flanders. The red square illustrates one 500 m - resolution grid cell and every dot represents one simulation.

The simulation period was from 01/01/1990 to 31/12/2021 (31 years), to take into account variability in weather conditions. Soil salinity, lateral drainage, and irrigation were not considered in the model, but can be activated for dedicated studies.

## 6.2. Results Regional Analysis

The following results illustrate the effects of the temporal and/or spatial variation in weather, soil, plant and groundwater level conditions on crop yield. All these variables are closely linked to each other and together determine the crop yield in a certain year and location.

## Temporal variation

Precipitation deficit (precipitation - reference evapotranspiration, P-ET0) is a commonly used indicator to assess meteorological drought. It indicates whether there was enough precipitation since the beginning of the hydrological season to cover the evaporation demand of the atmosphere. Positive values mean excess or sufficient water availability, and negative values indicate insufficient water availability, from the meteorological perspective. Years with low precipitation, and usually higher temperatures, have a greater precipitation deficit, expressed as a negative value of P-ET0. Figure 6.2 shows the variability of the average P-ET0 in the last ~30 years in Flanders, cumulated from January to January. The precipitation deficit can also be computed from April to April, which is considered as the hydrological year. Weather conditions vary substantially between years, and different dry and wet periods can be identified. For example, the period 1998 - 2002 was quite wet, while the period 2017-2020 was very dry. Apart from the overall precipitation deficit, the timing of long dry periods is also crucial to estimate its impact on specific crops.

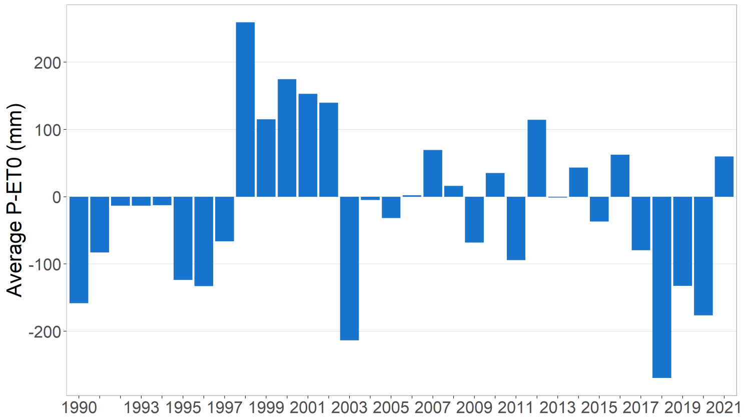

Figure 6.2.: Average precipitation deficit (P-ET0) from 1990 to 2021 in Flanders, showing periods of dry and wet years. Precipitation deficit is calculated from January to January.

Figure 6.3 shows the average temporal variation of the yield in agricultural areas in Flanders for the five focus crops (on the left), and the average yield reduction due to water and oxygen stress, and indirect effects (on the right). Years 2015, 2018 and 2021 are highlighted in the plots, which are considered “normal”, “dry” and “wet” years, respectively. The potential yield ( maximum potential yield) depicted in grey color, represents the yield that would be produced under optimal conditions of water and nutrients, and if crops are completely protected against weeds, pests and diseases. The actual yield (light green) represents then the estimated yield under the actual meteorological conditions of that year, assuming that nutrients and other reducing factors are not posing any problem so that we can isolate the effects of water stress (too wet or too dry). The red dashed lines represent the average yield from 2012 to 2021 for that crop in Belgium, based on the Belgian statistics “STATBEL” or the Belgian variety list in the case of grass.

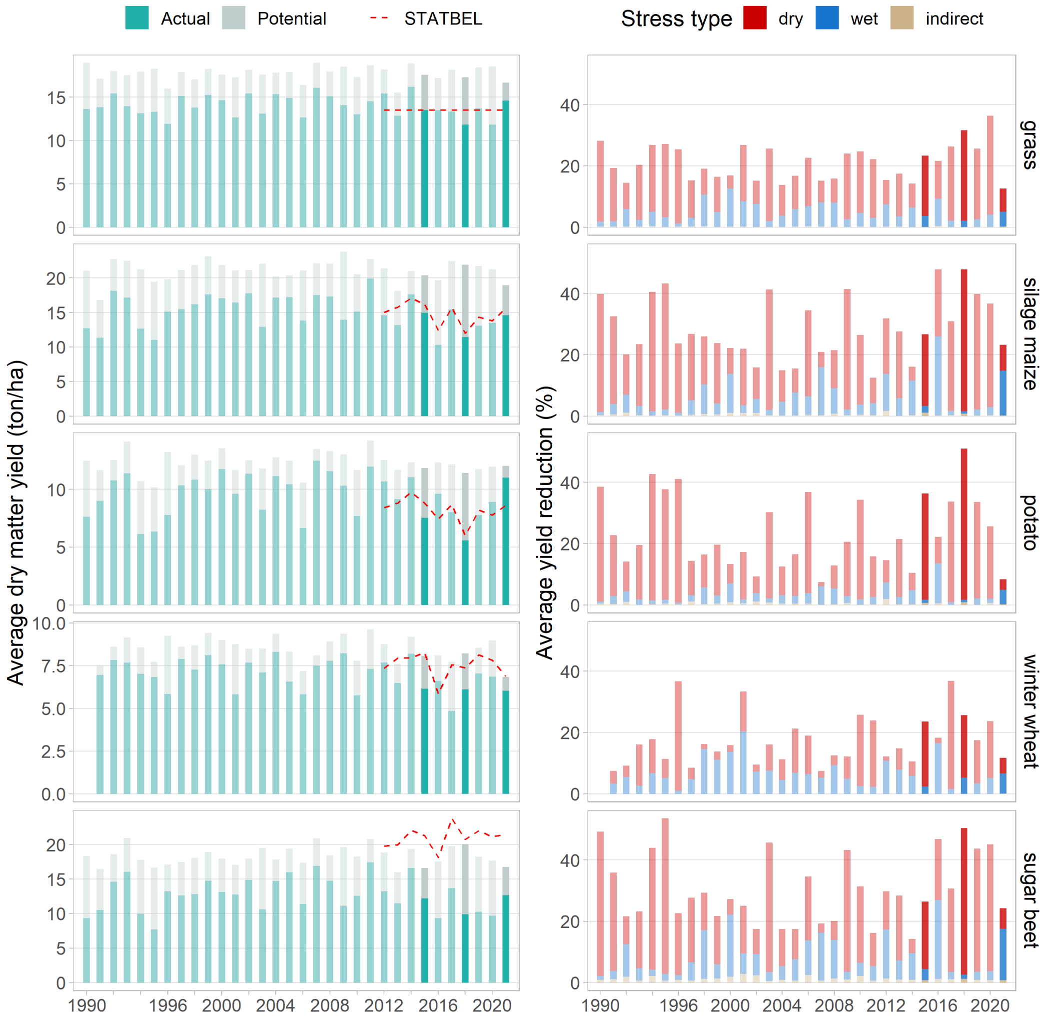

Figure 6.3.: Average simulated yield and yield reduction of grass, silage maize, potato, sugar beet and winter wheat in agricultural areas in Flanders from 1990 to 2021. The graphs on the left show the average potential ($Y_{pot}$) and actual ($Y_{act}$) yield in ton ha$^{\backslash-1}$ from all simulations. $Y_{pot}$ represents the maximum potential yield (see section 2.3.2 of the modelling framework). The average measured yield based on the Belgian statistics “STATBEL” and the Belgian grass variety list is depicted in red dashed line. The figure on the right show the relative yield reduction ($RED_{TOT} = RED_{dir} + RED_{ind} = (Y_{pot} - Y_{act} / Y_{pot}) * 100 + RED_{ind}$) expressed in %. The colors represent the relative share of the different stress types in the yield reduction. For this we assume that the yield reduction is proportional to the reduction in transpiration (T). The yield reduction expressed in % for each stress type is then $(T_{dry}/(T_{pot}-T_{act})) * RED_{dir}$ (drought stress, red), and $(T_{wet}/(T_{pot}-T_{act})) * RED_{dir}$ (oxygen stress, blue).

The temporal weather variability partially determines the inter-annual yield variability of the crops. Yield decrease is higher in years with more precipitation deficit (e.g. 2018, 2003, 2020) than in very wet years (e.g. 1998, 2021). Among crops, some are more sensitive to dry or to wet conditions. Potato, silage maize and sugar beet are almost equally affected by either dry or wet conditions, but **potato shows more yield reduction in dry years**, probably because of its shallower root system. **Grass presents more stable yields through the years** compared with the arable crops. Perennial grasses are known to have higher tolerance to oxygen stress compared to arable crops as explained in the chapter Impact of groundwater levels and waterlogging on cultivation factors. **Overall, drought stress causes higher yield reduction than oxygen stress, for all the crops except for winter wheat**. Winter wheat differs from the other crops in its growing season, which also covers winter and early spring. Furthermore, winter wheat matures quite early in summer, and therefore is often not impacted by summer droughts. Therefore, wet conditions or oxygen stress are the predominant cause of yield reduction in this crop. On average, indirect effects are very low and do not cause high yield losses.

When comparing the simulated yield with the average yield in Belgium depicted in red dashed line (Figure 6.3), overall, yield variability trends throughout the years are rather well captured for most crops. **Yields are systematically underestimated in sugar beet**, but relatively, the yields follow the variability over the years. Underestimations can originate from the use of outdated crop parameters in the model ( from cultivars in the 90s) or due to specific field management practices not included in the model, like irrigation events that may be applied in dry years. Overestimations like in 2016 and 2021 for potato, or 2016 for winter wheat, may be also attributed to the presence of pest and diseases that can proliferate in wet conditions, or other indirect effects like root rotting or lodging, which are not accounted for in the model. For example, these indirect effects were mainly the cause of yield reduction in 2021 according to the Agrometeorological Bulletin, and not necessarily oxygen stress. More details about the different factors affecting each of the five crops were described in the chapter Impact of groundwater levels and waterlogging on cultivation factors.

## Spatial variation

Precipitation in Flanders varies in space and in time (Figure 6.4). Consequently, a year considered on average wet or dry, does not cause the same effects everywhere. For example, the province of Limburg was drier in 2018 and wetter in 2021, compared to the rest of Flanders, resulting in a higher yield reduction in this region for both years (Figure 6.5).

The spatial variability of the yield expressed as percentage of yield reduction, in agricultural areas, is shown in Figure 6.5, for the five crops and for the characteristic years 2015, 2018 and 2021. The maps show the combined effect of the variable weather conditions, the soil heterogeneity and the average water table. Dry conditions lead to more yield loss in silage maize, potato and sugar beet in agricultural areas in Flanders than wet conditions. In the valleys, oxygen stress is the cause of significant yield loss, especially in wet years.

Soil type is another important factor affecting yield in the model, because soil hydraulic properties control water retention and infiltration rate, and root growth, and

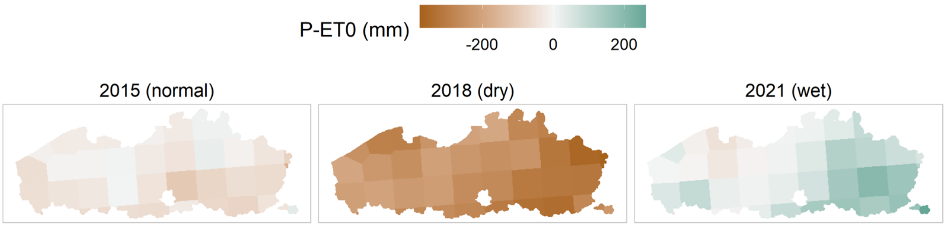

Figure 6.4.: Spatial variability of the precipitation deficit during 2015 (normal year), 2018 (dry year) and 2021 (wet year). Precipitation deficit is calculated from January to January.

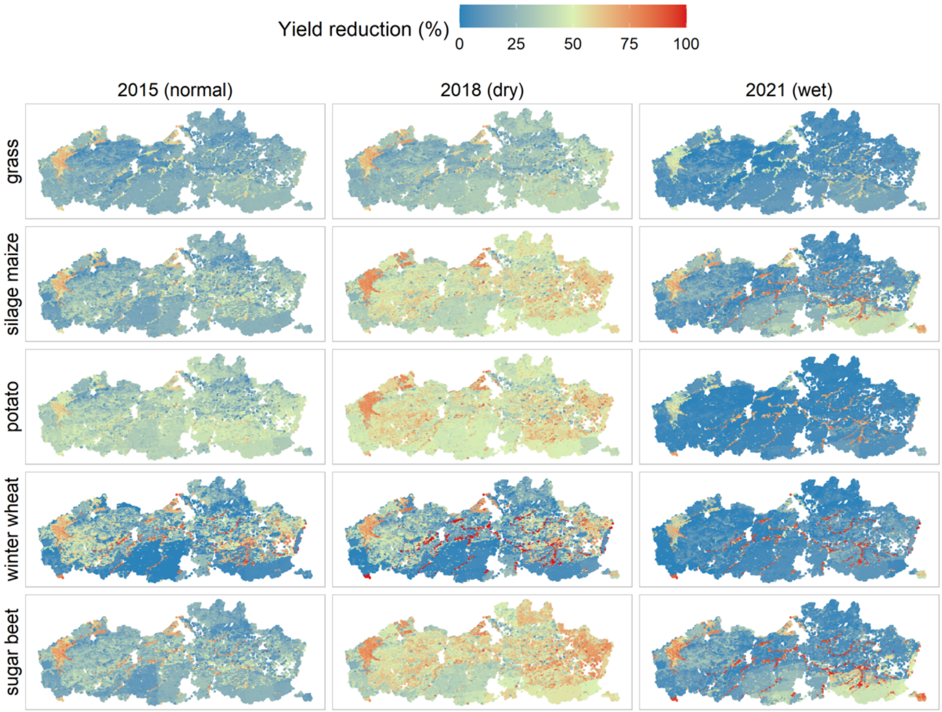

Figure 6.5.: Suitability maps in agricultural areas for grass, silage maize, potato, winter wheat and sugar beet, during 2015 ( normal year), 2018 (dry year) and 2021 ( wet year), based on the regional model.

thus, determining plant water uptake. The soil texture map link to the soil properties used in the model can be seen in section 3.3.1 of the previous chapter. The model takes into account root growth restrictions based on the clay content, bulk density and pH. Bulk density was approximated with the function of Vereecken [1988], since this information was not available at the regional scale. This function assumes an average value of 1.48 g cm$^{-3}$ for clayey soils, sandy loam and loam soils. In reality, bulk density can substantially differ from this value. Because of the relationship between bulk density and maximum rooting depth in SWAP-WOFOST, the maximum rooting depth in clay and heavy clay soils is sometimes limited to 10 cm or 20 cm, depending on the crop type (the minimum rooting depth that can be assumed in the model). In general, sandy loam and loamy soils do not limit root growth in the model, and the maximum rooting depth depends on the crop.

The yield reduction maps presented in Figure 6.5 are closely related to these assumptions. For example, the clayey soils of the polders systematically result in lower yields, because rooting depth was assumed shallow. This is probably not what happens in reality everywhere in the polders. Anthropogenic compaction is another feature which is not represented with approach based on general public data layers. It is therefore important to acknowledge the limitations of models and the data layers they work with, to avoid misinterpretation of the results. For focussed studies on clay soils for example, the link between bulk density and rooting depth could be refined and improved.

Figure 6.5 shows that areas closer to streams, where groundwater is naturally shallow, always present suboptimal yields (reddish colours). This is exacerbated in wet years. In reality, these areas are mainly used for grass production or grazing, where these shallow groudnwater levels are often already taken into account in current farming practices, since grass is typically more tolerant to wet conditions than other conventional crops.

Franken and Wolfs [2022] studied the potential effect of the increased occurence of droughts due to climate change on groundwater levels in Flanders. According to their predictions, the average highest groundwater level (GHG) will slightly increase due to more precipitation in winter months, in locations with deep groundwater level and a thick aquifer (higher buffering capacity). However, the average lowest groundwater level (GLG) will strongly decrease due to less precipitation in summer months (less water availability) and higher temperatures (more water demand), especially in locations with a thin aquifer, shallow groundwater level and limited lateral flow (lower buffering capacity). According to their predictions: the GLG will drop more than 25 cm in about half of the agricultural land (58 %) and groundwater-dependent nature areas by 2050. In contrast, during winter, the average GHG will increase by maximum 10 cm in 78 % of the agricultural areas. It should be noted that this study is mainly based on data from phreatic aquifers with a clear correlation to meteorological variables, but it is still a good indication of the fact that we can expect an impact of climate change on groundwater regimes. Increasing groundwater buffering capacity is therefore a priority for the government to reduce the increasing water stress-related problems in crops due to climate change.

### Effect of groundwater levels and soil texture on crop yield

Figure 6.6 illustrates the relationship between average groundwater levels and yield across Flanders for the different soil types and for a normal (2015), dry (2018) and wet year (2021). The plots emphasizes the effect of the meteorological conditions and soil type on crop yield, given a certain average water table. This can be seen in the distribution of the point cloud in a certain year and how that probability spreads over the years. In the regional analysis, we use the same average groundwater level or groundwater dynamics ( sinus function) for each year as the bottom boundary condition in the model (so no fluctuating groundwater level throughout the years).

Areas with very shallow groundwater levels (>1m) are negatively affected in wet years, but benefit in dry years. The opposite occurs in deeper groundwater levels, where more precipitation could compensate for the low groundwater contribution. But how positive this effect is, will depend also on the soil texture.

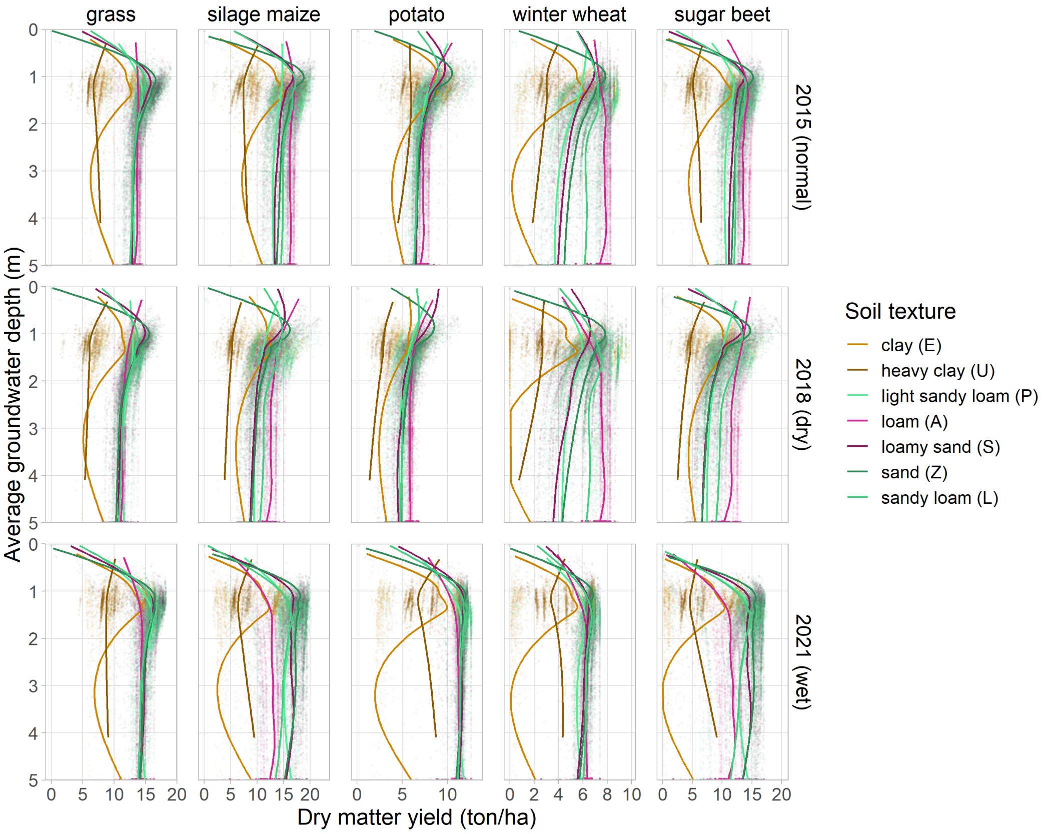

Figure 6.6.: Effect of groundwater, soil type and weather conditions on the yield, for the five focus crops. In the background, the scatter plots contain all simulations of the regional model, and the curves in front represent a trend line for each soil type.

On average, the optimal groundwater level is around 1 m in normal and dry years, and 1.5 m in wet years. However, they also clearly show the large scatter around these averages, which shows it is meaningfull not to work with such simple rules of thumb, but rather consider the variability introduced by crops, soils, groundwater dynamics and weather. Shallow groundwater levels cause oxygen stress, while deep water tables lead to drought stress in periods without rainfall. These thresholds are the result of the physical principles included in the drought and oxygen stress functions in the model.

## 6.3. Plausibility Check

SWAP-WOFOST has already been extensively reviewed in the context of the Waterwijzer Landbouw tool in The Netherlands, and in other projects [Heinen et al., 2021, Mulder et al., 2021, Bertram et al., 2017]. However, a plausibility check in Flanders is important, to test whether this model can give plausible or acceptable results in the Flemish context. Model validation is not always possible because often the necessary data is lacking. In addition, it becomes even more complex for models incorporating a wide variety of processes and associated parameters like SWAP-WOFOST [Heinen et al., 2021]. In Flanders, yearly and spatially explicit yield data for model validation or check is not readily available. Therefore, we collected yield data from different experimental institutes across Flanders (Figure 6.7).

Besides model validation or "plausibility check", the yield database could serve for:

1. Future crop model calibration or validation efforts by any researcher, ILVO and external, respecting the confidentiality level of the datasets ( Open reference yield database in Flanders ).
2. Providing an user-friendly tool to keep collecting yield information from various trials in Flanders and compare it with historical evolutions. This could, for example, be used for the Agricultural Impact Report (Landbouweffectenrapport, LER) of the Flemish government.

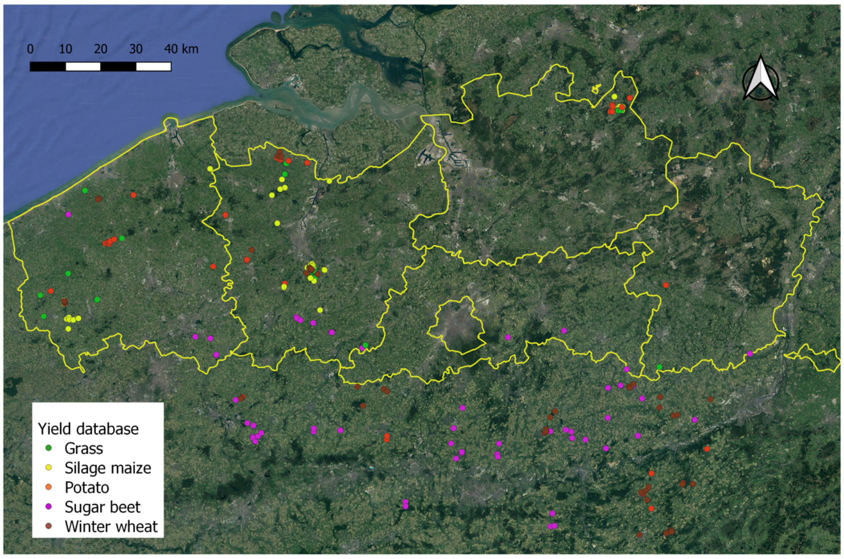

Figure 6.7.: Locations of the yield measurements included in the database. The information outside Flanders was not used in the plausibility check.

The yield database can be accessed in the https://doi.org/10.5281/zenodo.7541363. Unfortunately, the majority of the data is situated in West- and East-Flanders. The database is freely available and can grow with new input by researchers and professionals collecting yield data.

**Important**
Feel free to contact us if you have data available that can contribute to better coverage in Flanders.

## A first step towards a Flemish yield database

The yield database contains yearly yield data at field level for different arable crops in Flanders, under 'conventional' farming practices, along with its coordinate. When available, it also includes the planting/sowing and harvest dates. At the moment, only yield of the five focus crops in this research are included in the database, namely grass, silage maize, potato, winter wheat and sugar beet. The data was collected from different research departments at ILVO and other governmental and private Flemish institutions such us CRA-W and IRBAB KBIVB. Most of the data is the result of variety trials, without irrigation and under normal pest control and fertilizer applications according to the crop's needs. Only few potato observations come from experimental fields with irrigation or from variety trials performed within farmer fields using irrigation. This yield database would help to represent the spatial and temporal variability of yield in Flanders.

## Model setup for plausibility check

The previous chapter (Model framework to evaluate the impact of groundwater levels on agricultural practice) describes the input data and procedures which we followed to generate the simulations for the model check. There is one difference here: site-specific planting/sowing and harvest dates were specified in the model instead of using a generic sowing and harvest date. No indirect effects were calculated in this part.

Before comparing simulated and observed yields, the following should be noted:

**Note**
Since the observed yields were sometimes provided as fresh yield exclusively, a dry matter content was estimated for every crop based on relationships published in the literature: 20 % for grass [van den Pol-van Dasselaar et al., 2019, Eurostat, 2020] and potato [Van Oort et al., 2012], 86 % for winter wheat [Eurostat, 2020], 35 % for silage maize (ILVO variety list 2022) , and 25 % for sugar beet ([FAO, 2009], variety trials in the yield database). In this way, observed and modeled yields could be compared for all crops and between experiments and sites in the same way.

**Note**
We reduced the observed yield from variety trials and experimental fields by 15 % before comparing with the model results. Results from scientific experiments are known to be higher than yield from farmer fields due to smaller plots, reduced edge effects, less field variability, etc. This reduction value is of course an approximation and based on expert advice.

## Results

Figure 6.8 shows the relation between measured and simulated yield for grass, silage maize, potato, winter wheat and sugar beet. The black line represents the 1:1 line between observed and simulated yield. In the case of a perfect model, the points would follow the bisector line. More observations are available for grass and silage maize, while for the other crops, especially winter wheat and sugar beet, data is quite limited.

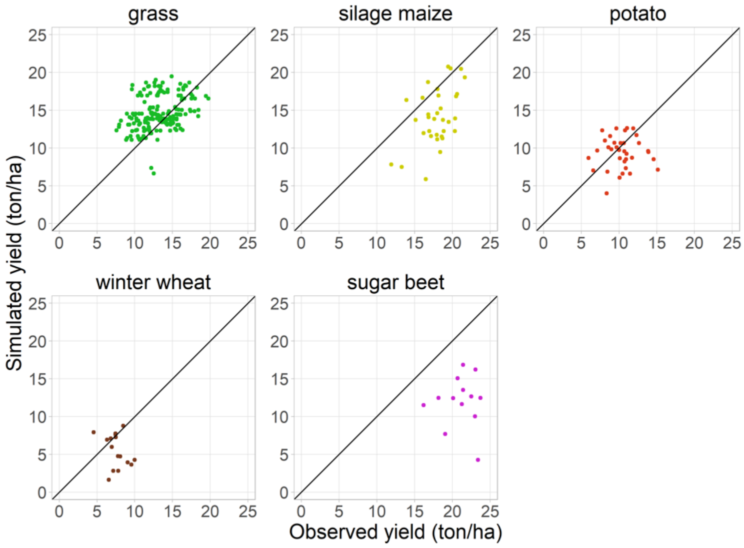

Figure 6.8.: Observed yield (dry matter yield) vs simulated yield for the five crops. The black line is the 1:1 line or bisector line that indicates a perfect fit.

In general, the model tends to underestimate the crop yield, except for grass, even after the 15 % reduction of the experimental yields. The worst underestimation occurs in sugar beet, which is in line with the regional comparison for sugar beet.

One reason can be attributed to the fact that crop parameters used in the model are derived from cultivars in the 90s, and crop yield in modern cultivars have improved substantantially. Allard de Wit, one of the developers of WOFOST, pointed out that crop parameters clearly need an upgrade with recent experimental data.

Another reason can be linked to the preprocessing of the data before model comparison. The crop reduction is currently based on expert advice and applied in the same way for all crops. This should be verified by comparing research data with data from farmers for the same crops.

A third reason is related to the fact that the model used in this study does not take into account all the management practices (like irrigation) occurring in a field; therefore, the knowledge of these practices is important for better simulation and interpretation of the model results.

Table 6.1 shows some statistical indices such us the Root Mean Square Error (RMSE), the relative root mean square error (RRMSE) and coeficient of determination ($R_2$). The RMSE is a measure of the average deviation of the simulations from the observed values. By dividing RMSE by the average observed yield for every crop, it is possible to get a normalized RRMSE, which is dimensionless and comparable across crops. The

Table 6.1.: Metrics for model check

| | RMSE (t ha$^{-1}$) | RRMSE | $R_2$ |
|---|---|---|---|
| grass | 3.07 | 0.23 | 0.12 |
| silage maize | 4.98 | 0.28 | 0.26 |
| potato | 3.07 | 0.30 | ~0 |
| winter wheat | 3.43 | 0.45 | 0.095 |
| sugar beet | 9.36 | 0.43 | ~0 |

$R_2$ measures how good the variation of the observed values from the mean value is explained by the linear regression model. These indices give an estimation of how well the model (SWAP-WOFOST) is able to simulate the target value, in this case, crop yield. These values indicate that the model can simulate the crop yield variability of grass and silage maize reasonably well, but it is not able to simulate all the yield variability of potato, winter wheat and sugar beet, with the limited data and model simplifications. It is to be expected that if local information on soil, weather data, groundwater level, and cropping practices were available and used in the model, the results would improve a lot more. Therefore, for a real validation, a (detailed) crop database with a good spread over Flanders should be established.

The yearly variation of the observed and simulated yield is presented in Figure 6.9. There is a high variability between years, and within the same year between locations. For example, observed grass yield in 2014 varies between 11 ton ha$^{-1}$ and 19 ton ha$^{-1}$, and potato yield varies between 10 ton ha$^{-1}$ and 15 ton ha$^{-1}$ in 2019. These differences can be attributed to differences in soil type, and in field-specific management practices such as pest control and nutrient application, but also in local meteorological conditions.

High differences between simulated and observed yield in potato in 2019 can be partially linked to irrigation in the experimental fields, which was not included in the model. In sugar beet, the model strongly underestimates the yield in all years, especially in the dry year 2018, based on this small set of observations. In this case, a recalibration of the crop parameters as compared to what was used in WaterVision Agriculture, based on targeted field experiments to calibrate and validate the model is required. Also, a check of the conversion from fresh to dry yield and an assessment of the relationship between experimental yield and farmer yield is needed to improve the model results. Despite all the crop yield variability, the model is able to describe most of these dynamics, although, absolute values are sometimes strongly underestimated like in sugar beet.

Overall, one must not forget no site specific information was used to simulate yields for the experimental sites in order to test whether existing data layers yielded acceptable results. Apart from improving model calibration, significant improvements can be expected if one can work with accurate data on soil horizons and hydraulic properties and local weather data.

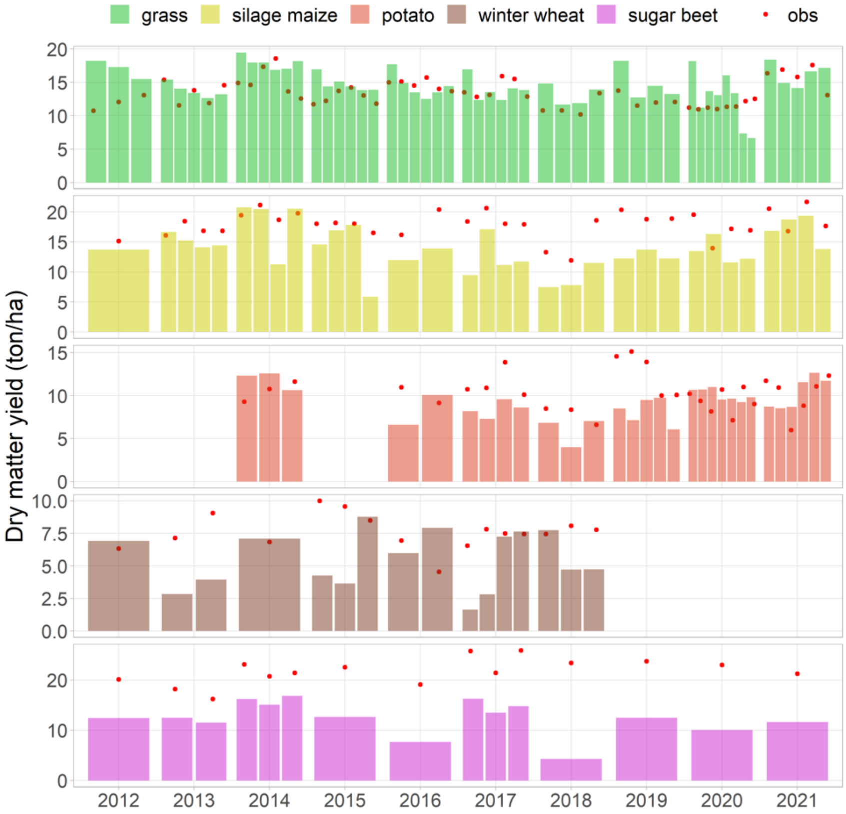

Figure 6.9.: Yearly variation of the observed (red dots) and simulated yield (bar plots) from 2012 until 2021, for the five crops.

## 6.4. Conclusions

We applied the model SWAP-WOFOST at regional scale to describe the crop yield variability due to wet or dry conditions in Flanders. We used historical weather data from 1990 to 2021 and estimated average groundwater levels to simulate the yield of five conventional crops, namely grass, silage maize, potato, winter wheat and sugar beet.

The weather variability between years causes variability in annual crop yields. Simulated yield is on average lower in dry years than in wet years. Potato, silage maize and sugar beet are more sensitive to water stress compared to grass and winter wheat. Grass presents more stable yields throughout the years as compared to the arable crops. Winter wheat is more affected by wet conditions, because a large part of its growing season falls in the rainy months. Spatially, the yield variability is highly influenced by the regional weather variability, soil heterogeneity and water tables. Overall, droughts have more impact on silage maize, potato and sugar beet yields than wet conditions. Areas with sandy loam and loamy soils have normally higher yields than clayey soils, due to less root growth restrictions by the soil.

In general, shallow groundwater levels (less than 1 m below the surface) negatively affect yield in wet years, but benefit in dry years. Just as the yield decreases with deeper groundwater levels, it also decreases when groundwater levels get too shallow. Deeper groundwater levels result in higher yields in wet years, since more precipitation compensates for the low groundwater contribution to crop root water uptake. The extent of this effect depends on the soil texture and the crop rooting pattern.

Based on a dataset with experimental yield observations in Flanders, we demonstrated the model performance. The current model was able to describe general multi-annual trends in average crop yield, despite many limitations in the input data and model simplifications. Although, absolute values are sometimes underestimated, like in sugar beet, where calibration of the crop parameters may be needed to get more accurate results.

This modelling framework is openly available for the research community and efforts should be continued to improve its performance in the future.

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# 7. Case-study: agricultural land around De Zegge-Mosselgoren

Diana Estrella, Tom De Swaef, Ruud Bartholomeus, Sarah Garré

## 7.1. Background and objectives

The nature reserve De Zegge is the only remnant of the low moor ”Geels Gebroekt” in the Kleine Nete valley. In the 60s, most of this area was drained using a network of ditches to make it suitable for agriculture. The Kleine Nete river was straightened, and the Roerdompstraat was built as a barrier between De Zegge and the agricultural land. Since then, groundwater is pumped out of the agricultural land, so that the water level is deeper than the Kleine Nete river [De Becker, 2019]. However, in De Zegge and the nearby nature reserve Mosselgoren water tables should be kept as high as possible. Therefore, an auger pump was installed to pump water from the agricultural areas to a peripheral canal to De Zegge [Van Diggelen and Grootjans, 2019], where water is kept at an almost constant level. Over the years, the nature reserves became hydrologically isolated from the rest of the Kleine Nete valley. The Kleine Nete valley was characterized by thick peat layers that were gradually reclaimed since the Middle Ages [De Becker, 2019] or extracted as an energy source, which was gradually replaced by coal and petroleum [Vanierschot, 2014]. After land drainage in the 60s, most of the remaining peat was decomposed and lost as Co$_2$ [Van Diggelen and Grootjans, 2019].

The nature reserves De Zegge and Mosselgoren are part of the Habitats Directive area ”Valleigebied van de Kleine Nete met brongebieden, moerassen en heiden” (BE2100026) and the Birds Directive area ”De Zegge” (BE21000424) [De Becker, 2019]. De Zegge consists of 115 ha, which are mostly owned and fully managed by the Royal Zoological Society of Antwerp (KMDA) [Van Diggelen and Grootjans, 2019]. The Flemish government has established a number of conservation objectives and priorities for the protection of these areas. However, concern was raised recently that the nature reserves are gradually deteriorating. In addition, climate change is causing an increased occurrence of droughts, further causing pressure on the species depending on wet conditions. Van Diggelen and Grootjans [2019] and De Becker [2019] pointed out to the pumps and canals for land drainage as the reason of deterioration, although Wyseure [2022] asked for a thorough geohydrological study to substantiate a number of assumptions.

Such a study was previously commissioned by the Agency for Nature and Forests and was awarded to the Witteveen+Bos engineering office (”Ecohydrological study: basis for restoration measures for De Zegge Nature Reserve” ). This study first develops a numerical geohydrological groundwater model in order to simulate phreatic groundwater levels, among other things. That model is calibrated with measurements in monitoring wells in the area. When this calibration has been completed, it can be assumed that such a model is the best estimate of the current groundwater flows and level in the entire area, as it is currently managed, with the uncertainties that are always associated with it. Subsequently, this numerical model can also be used to predict the consequences of changing one or more water management measures in the area: switching off pumps or installing or removing weirs. In this way, predictions can be made of the impact of certain measures on groundwater levels.

Full hydrological isolation of the nature reserves from the activities the agricultural areas is not possible in practice, since groundwater remains connected between the two areas via the subsurface. A hydrological isolation would be a very expensive project with underground hydrological screens or other very far-reaching engineering measures, which is not desirable from a practical and financial point of view In order to restore and conserve the nature reserves, De Becker [2019] proposed to rewet the area in the north of De Zegge and the Mosselgoren by raising the average groundwater level by ± 60 cm. Van Diggelen and Grootjans [2019] recommended to stop the pumping in the agricultural polder in the North of De Zegge and raise groundwater levels to ground level. Both studies concluded that agriculture would not be possible anymore under these remediation strategies.

That is why the Department of Agriculture and Fisheries of the Flemish government commissioned this study in 2022 to develop a model framework to assess the impact of groundwater levels on agricultural activities in the area around De Zegge - Mosselgoren. Unfortunately, an analysis of different future groundwater level scenarios was ultimately not possible within the foreseen time due to strong delays in the "Eco-hydrological study: basis for restoration measures for Nature Reserve De Zegge", carried out by the engineering office Witteveen+Bos, commissioned by the Agency for Nature and Forests. However, we used the preliminary results of their calibrated groundwater model ( version December 2022) for the current situation, to showcase how the modelling framework can be used in this area.

## 7.2. Methodology

### Study area

The study area covers approximately 2802 ha and is located in the northeast of the province of Antwerp, in the surroundings of Geel (Figure 7.1). Hydrologically, the area is located in the Kleine Nete valley, with the Bocholt-Herentals canal in the south. The study area includes the Habitats Directive Area 'Valleigebied van de Kleine Nete met brongebieden, moerassen en heiden" (BE2100026), where the nature reserves De Zegge and Mosselgoren are located. These reserves are surrounded by agricultural land. A central pumping station located at the north border of De Zegge ( 51° 11' 52.62" N, 4° 54' 26.98" E) allows the drainage of the agricultural lands, and an auger pump ( 51° 12' 2.06" N, 4° 56' 8.53" E) pumps the water from the agricultural ditches back to the nature reserve De Zegge (Figure 7.1, Figure 7.2). The average monthly precipitation ranges from 30 mm in April and to 78 mm in August, and the average temperature varies between 19 °C in July and 4 °C in January (Joint Research Center (JRC), 2010-2021).

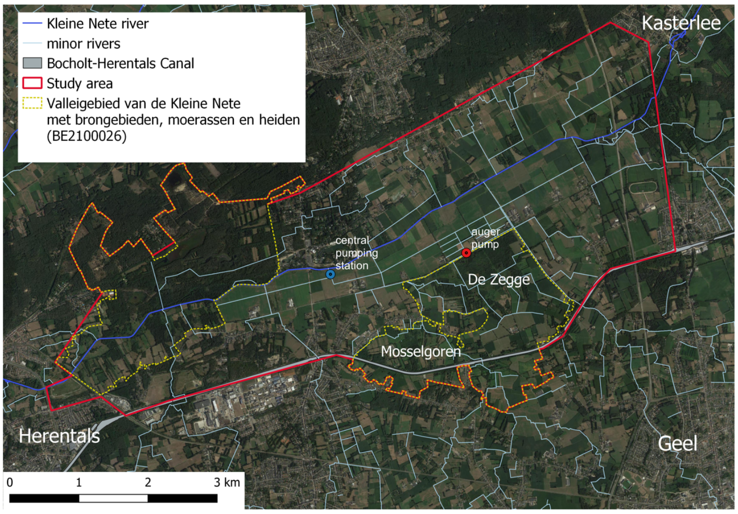

Figure 7.1.: Location of the study area, which includes the Habitats Directive Area 'Valleigebied van de Kleine Nete met brongebieden, moerassen en heiden" (BE2100026), canals, rivers and location of the central pumping station and auger pump.

Figure 7.2.: Overview images of the agricultural land, central pump house, auger pump and water level measurement at the auger pump.

### Agriculture

According to the 'agricultural use map' of 2021 [LV, 2021], the main crops cultivated in the study area are grass (41%), silage maize (24%), clover (11%), grain maize (7%), and potato (6%).

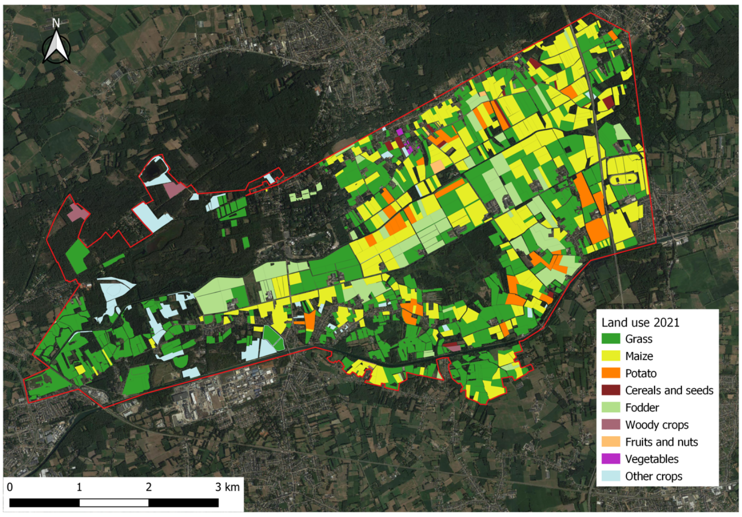

Figure 7.3.: Agricultural use in 2021 in the study area.

### Soil texture

The soil texture in the study area is dominantly sand and loamy sand according to the Digital Soil Map of the Flemish region [VPO, 2017]. Before the drainage of the area in 1960, the soil was mainly sand/peat or peat [Van Diggelen and Grootjans, 2019]. After drainage of the land, most of the peat was decomposed, and currently, peat still exists in the nature reserve De Zegge. For detailed mapping of peat extent and thickness, radiometric data could be combined together with optical satellite data, as in O'Leary et al. [2023]. The soil profiles available for modeling, presented in the chapter Model framework to evaluate the suitability of groundwater regime for crop growth section 3.3.1, have a lesser level of detail and do not contain information of peat in this area (Figure 7.5).

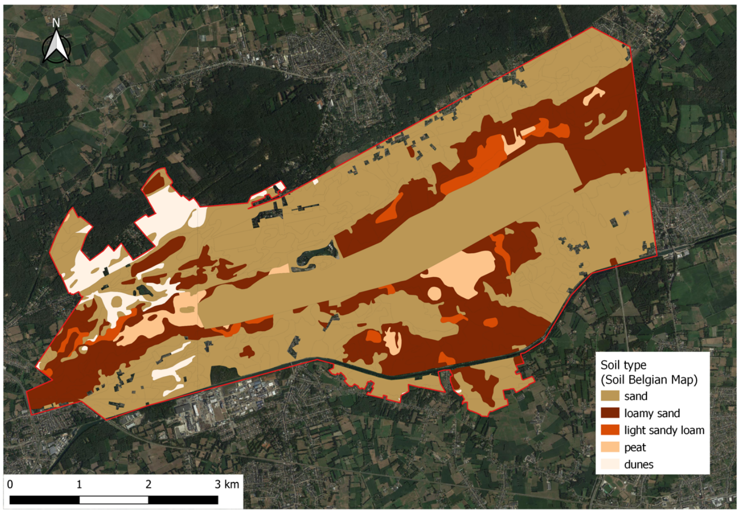

Figure 7.4.: Soil texture in the study area according to the Digital Soil Map of the Flemish region.

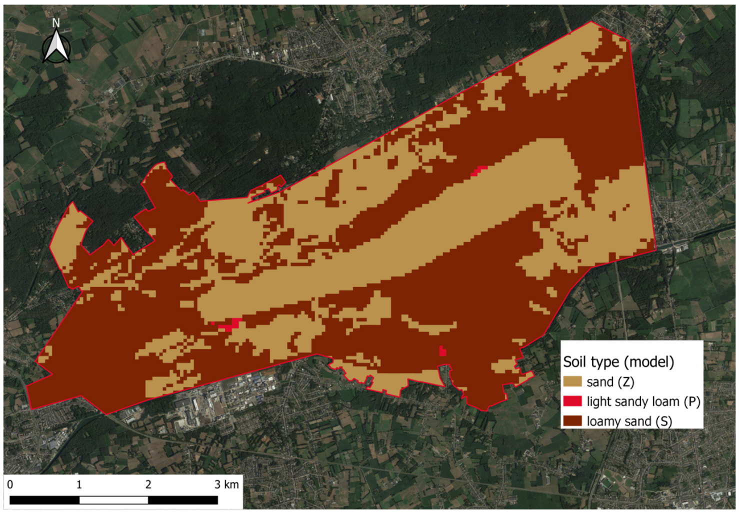

Figure 7.5.: Soil texture in the study area according to the soil properties used in the model.

### Groundwater

The map below (Figure 7.6) shows the average groundwater level in the study area (preliminary results of the ecohydrological study by Witteveen+Bos, December 2022). It shows that in the current state, average groundwater levels in the natural areas are shallower than 50 cm (dark green). In the agricultural area north of the Zegge predominantly between 50 cm and 100 cm deep (light green) and in the higher agricultural area also deeper than 100 cm (light orange). This corresponds to the observations from a previous study by Backx et al. [2012] in the period 2005-2010, where the measured average groundwater levels in the agricultural areas were between 90 cm and 150 cm, and less than 30 cm in the nature area De Zegge. Throughout the study area of the ecohydrological study, average groundwater levels do not go deeper than 300 cm anywhere, fluctuating on average between 50 cm in winter and 110 cm in summer based on the average highest groundwater levels (GHG) (Figure 7.7) and average lowest groundwater levels (GLG) (Figure 7.8).

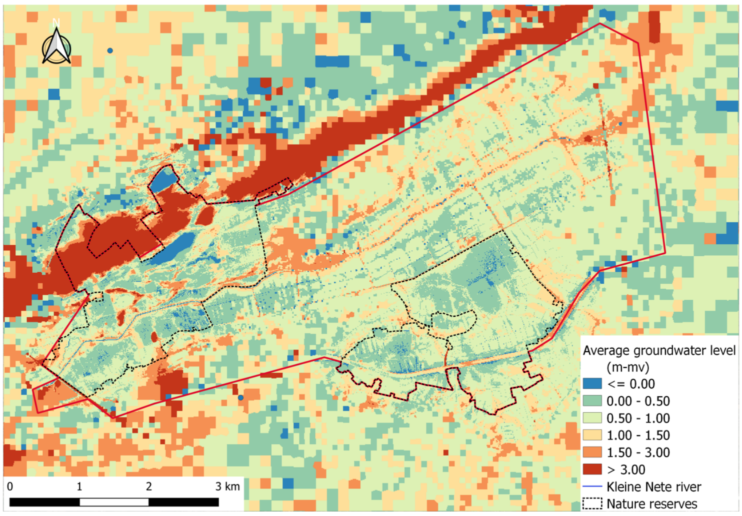

Figure 7.6.: Average groundwater levels in the study area based on the preliminary results of "Ecohydrological study: basis for restoration measures for Nature Reserve De Zegge" (Witteveen+Bos). Please note that these are not final results and the report of this study should be consulted for further use.

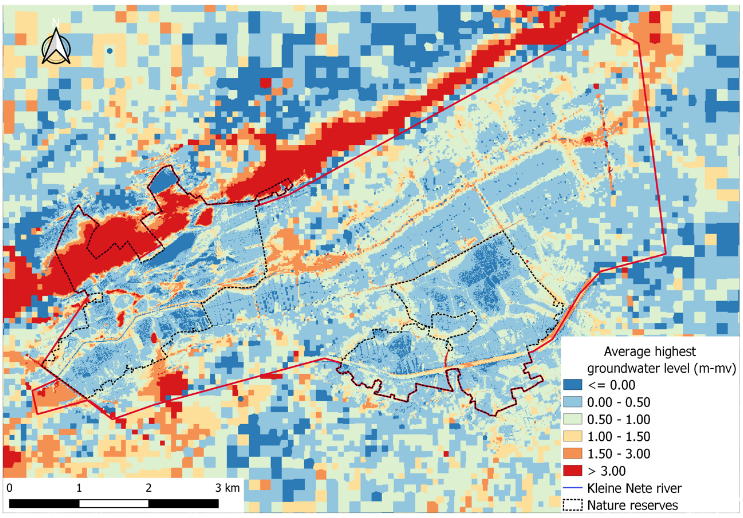

Figure 7.7.: Average highest groundwater levels (GHG) in the study area based on the preliminary results of "Ecohydrological study: basis for restoration measures for Nature Reserve De Zegge" (Witteveen+Bos). Please note that these are not final results and the report of this study should be consulted for further use.

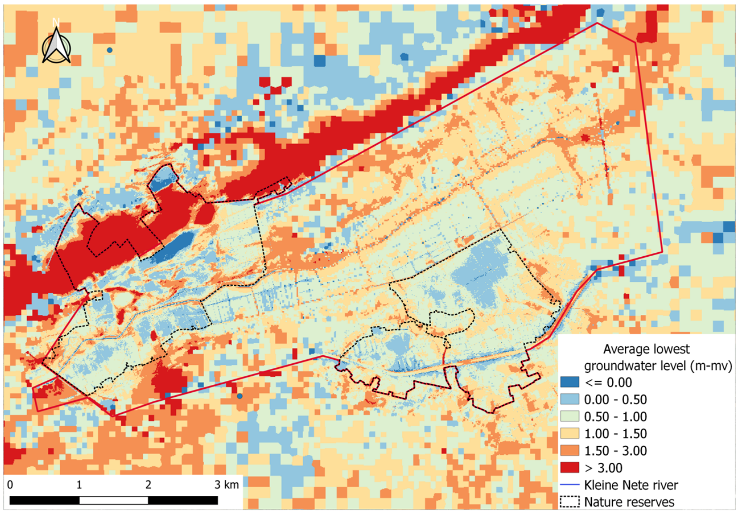

Figure 7.8.: Average lowest groundwater levels (GLG) in the study area based on the preliminary results of ”Ecohydrological study: basis for restoration measures for Nature Reserve De Zegge” (Witteveen+Bos). Please note that these are not final results and the report of this study should be consulted for further use.

The detailed rewetting scenarios were not yet available at the end of this study. It is clear that if a groundwater rise of 60 cm is realized over the entire agricultural area north of the Zegge (as proposed in De Becker [2019]), this would result in a groundwater level just below or even above the soil surface. In the western part of the agricultural area around the Roerdompstraat, this would locally even result in water more than half a meter above the soil surface. It is therefore necessary to obtain more realistic and detailed scenarios for the area in order to subsequently estimate the impact on agriculture.

Van Diggelen and Grootjans [2019] reported 20 groundwater extractions in close proximity to De Zegge. Most of these abstractions are small, in the order of 10000 m$^3$ yr$^{-1}$, and a few are larger than 25000 m$^3$ yr$^{-1}$. According to the information of the licenses granted for the extraction of groundwater available in the DOV webportal, there are curently 27 active groundwater extractions inside the study area, mostly smaller than 20000 m$^3$ yr$^{-1}$. More information on this will probably be available in the ecohydrological study.

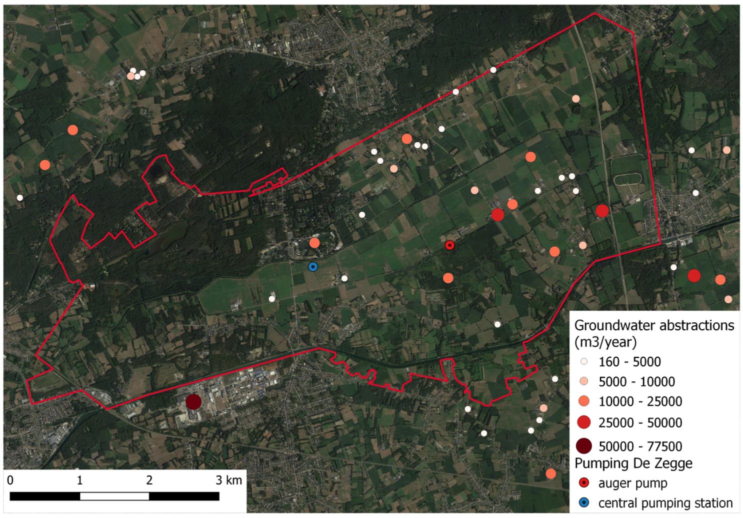

Figure 7.9.: Current groundwater abstractions in the study area. Source:DOV

## Model framework

The model SWAP-WOFOST was applied at field level, following the methodology and using the input data layers described in the chapter Model framework to evaluate the suitability of groundwater regime for crop growth. We could not carry out a model calibration and validation, since no historical data series of yield are available for this area. In total, 1282 simulations were performed for a homogeneous crop cover over the study area (Figure 7.10), every one corresponding to each agricultural parcel. These simulations were conducted for grass and silage maize, which are the dominant crops in the area (65 % of the agricultural area). The model output variables of interest were crop yield and yield reduction due to water stress (too wet or too dry) and indirect effects attributed to wet conditions such as reduced workability and machinability, and planting and harvest delays, which causes a shortening of the growing season.

Figure 7.10.: Location of the SWAP-WOFOST simulations. Each dot represents one model run.

## 7.3. Results and Discussion

The following results include the analysis of the current average situation, based on historical weather conditions and soil information as in the regional analysis, but with groundwater levels simulated with a locally calibrated groundwater model (Ecohydrological study Witteveen+Bos) for the period 2010 - 2021 (following the methodology explained in section 3.4.1 of the modeling framework). More details about how the current groundwater levels were obtained can be found in the ecohydrological study of Witteveen+Bos. In principle, this represents the current situation, including the operation of the pumps, canals and central pumping station in the agricultural area north of De Zegge up to the Kleine Nete.

### Meteorological conditions

The precipitation deficit (P-ET0) in the study area from 2010 until 2021 is presented in Figure 7.11. Positive values mean excess or sufficient water availability and negative values indicate insufficient water availability. In general, more precipitation falls in this region compared with the average in Flanders. Therefore, 2016 and 2021 are wetter, and the period 2018 -2020 is less dry.

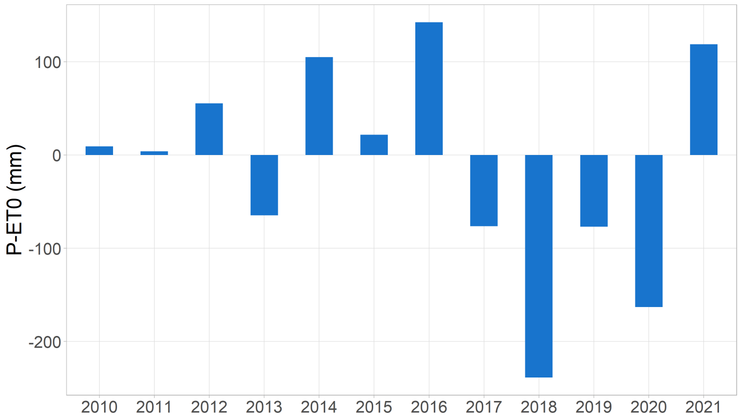

Figure 7.11.: Yearly precipitation deficit (P-ET0) in the study area, for the period 2010 - 2021.

### Yield, yield reduction and type of stress

Figure 7.12 shows the average simulated dry matter yield for grass and silage maize for the period 2010 - 2021, together with the standard deviation of the actual yield ($Y_{act}$) depicted with black bars, and the yield reduction due to water stress and indirect effects. The simulated potential yield (grey) represents the yield in that year under prevailing weather conditions, but ideal soil moisture conditions (no stress). The simulated actual yield (green) represents the harvest with the prevailing groundwater level on a particular plot (here the current situation as obtained with the calibrated groundwater model of the ecohydrological study). On the right we see the relative yield reduction ( $RED_{TOT} = RED_{dir} + RED_{ind} = (\frac{Y_{pot} - Yact}{Y_{pot}}) * 100 + RED_{ind}$ ) expressed in %. The colors represent the relative share of the different stress types in the yield reduction of a specific year. For this we assume that the yield reduction is proportional to the reduction in transpiration (T). The yield reduction expressed in % for each stress type is then $\frac{Tdry}{(Tpot-Tact)} * RED_{dir}$ (drought stress, red), and $\frac{Twet}{(Tpot-Tact)} * RED_{dir}$ (oxygen stress, blue). For example, in 2015 for the case of silage maize, the maximum potential yield and actual yield were respectively 17.9 ton ha$^{-1}$and 14.2 ton ha$^{-1}$. The difference between these two values expressed in percentage results in 20.5 %, which is accounted for by 4.1 % in dry-drought stress, 10.4 % in wet-oxygen stress and 6.0 % in indirect effects.

The model simulations shows a high yield variability through the years, specially in 2011-2012, 2014-2016 and 2021. For the critical years 2015 (normal), 2018 (dry), and 2021 (wet), the grass dry matter yield is on average 11.9 ton ha$^{-1}$, 13.8 ton ha$^{-1}$, and 12 ton ha$^{-1}$respectively, and the silage maize yield is 14.2 ton ha$^{-1}$, 16.6 ton ha$^{-1}$ and 13.7 ton ha$^{-1}$, respectively. The average dry matter yield in Belgium, all soil types mixed, is around 13.5 ton ha$^{-1}$ for grass [ILVO, 2022], and 14.8 ton ha$^{-1}$ for silage maize (with 65 % dry matter yield) [STATBEL, 2022].

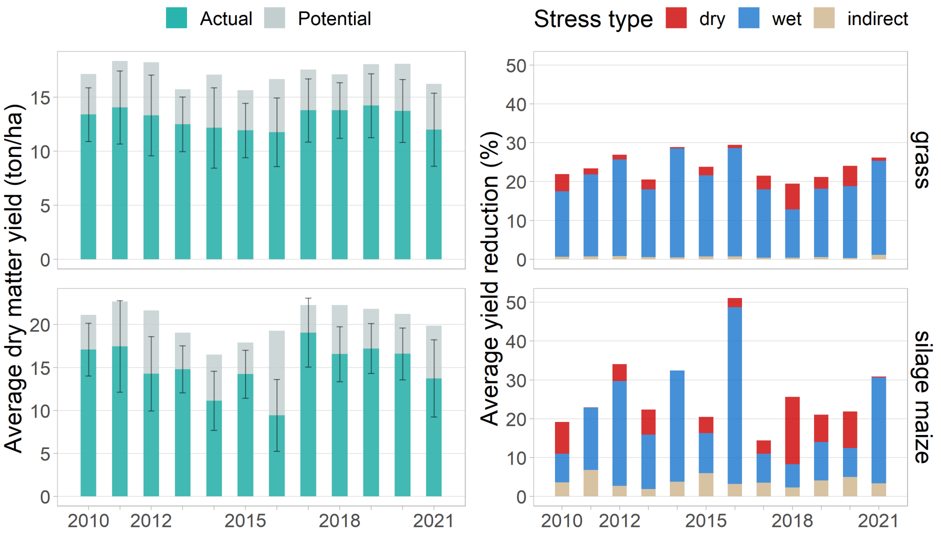

Figure 7.12.: Inter-annual yield variation and yield reduction for grass and silage maize as simulated by SWAP-WOFOST. The graphs on the left show the average potential ($Y_{pot}$) and actual ($Y_{act}$) yield in ton ha$^{-1}$ from all simulations. $Y_{pot}$represents the maximum potential yield (see section 2.3.2 of the modelling framework). The black bars represent the standard deviation of the actual yield between the different plots. The figure on the right show the relative yield reduction ($RED_{TOT}$= $RED_{dir}$+$RED_{ind}$ =($Y_{pot}$-$Y_{act}$ / $Y_{pot}$)*100+$RED_{ind}$) expressed in %. The colors represent the relative share of the different stress types in the yield reduction. For this we assume that the yield reduction is proportional to the reduction in transpiration (T). The yield reduction expressed in % for each stress type is then ($T_{dry}$/($T_{pot}$-$T_{act}$))*$RED_{dir}$(drought stress, red), and ($T_{wet}$/($T_{pot}$-$T_{act}$))*$RED_{dir}$(oxygen stress, blue).

There is a high temporal yield variability, especially in silage maize, which has to do mainly with the high yearly variability in weather conditions in the region (and in Flanders). The actual or attainable yield (light green) is quite high when compared with the potential yield (light grey) in most years, and the overall yield is higher in dry years than in wet years. This shows that the agricultural water management provides optimal conditions for this activity in most situations, which is consistent with what local farmers experience. However, it is a delicate equilibrium. Reductions in wet periods are related to the shallow water table in the study area, which causes oxygen stress (blue color in the figure) in crops when there is excess rainfall. In grass, the average yield reduction is always below 30 % and is largely caused by oxygen stress (too wet conditions). In silage maize, yield losses rise up to 50 % in 2016, and around 30 % in 2021, and are also predominantly caused by oxygen stress. The growing season in 2016 was characterized by wet conditions during spring and dry conditions during the next months (Figure 7.13) which caused suffocation of the root system and soil acidification at the start of the season and made the crop more vulnerable to drought in the next months. Indirect effects ( brown) in silage maize are more significant than in grass, although they do not cause more than 7 % of yield reduction.

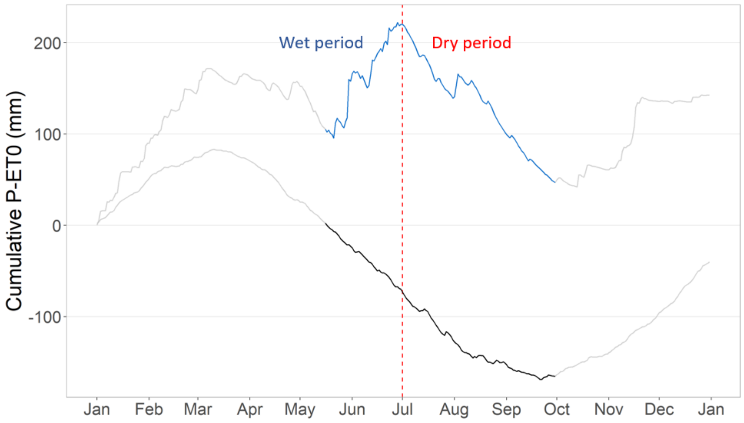

Figure 7.13.: Cumulative precipitation deficit (P-ET0) during 2016. The period May - October is highlighted in the plot. The blue line represents the cumulative P-ET0 in the study area while the black line indicates the average cumulative P-ET0 in Flanders of all years combined (2010-2021).

## Relation between yield reduction and groundwater level

Figure 7.14 shows the relation between the average groundwater levels on each individual parcel (as simulated by the calibrated groundwater model of the ecohydrological study for current water management) and total yield reduction for 2015, 2018, and 2021, for grass and silage maize. The dots in the back denote the simulation results for the three years in all parcels. The colored lines describe the average relation based on the simulations of each year (2015-green/normal, 2018-red/dry, 2021-blue/wet). This makes it clear that the optimum groundwater level is not only determined by the soil and cultivation, but also by the weather. In the wet year 2021, for example, the maximum yield occurs with a lower groundwater level than in the dry year 2018. The yield decreases sharply in all years with groundwater levels above 80 cm.

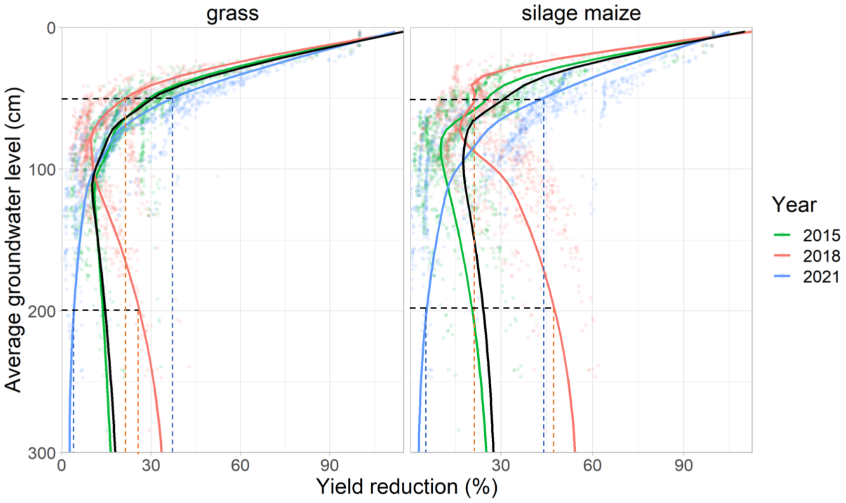

Figure 7.14.: Correlation between average groundwater levels and total yield reduction, in 2015, 2018 and 2021, for grass and silage maize. The dots in the back denote the simulation results for the three years, and the colored lines represent the average relation based on the simulations of each year. The black line represents the average relation of all simulated years combined from 2010 to 2021.

The intersections between the colored line of each year and the horizontal black dotted lines illustrate the effect on yield in dry and wet years, for the situations of shallow groundwater (50 cm) and deeper groundwater (200 cm). For a shallow groundwater level of 50 cm, the yield reduction is lower in a dry year and higher in a wet year. The opposite occurs with a deeper water table of 200 cm, where the yield reduction is much lower in a wet year. In many locations where the water table is shallower than 50 cm, crop yield is still significant but with low rentability. With small increases in groundwater level, yield is drastically reduced to levels where cultivation is not profitable anymore. These relationships can slightly vary for different weather conditions and also depend on the specific properties of distinct crop varieties. In this study, we did not distinguish between varieties within a crop and only compared crops among themselves.

In the current situation, based on the results of a ~10-year period, field management and groundwater level control in the area are optimal for agricultural activities (grass and silage maize), especially in dry years, but already results in limitations in wet years. This is evident from the simulations, but also from discussions with the farmers themselves during workshops in 2022. Should the water table rise due to rewetting measures like the ones proposed in previous studies [Van Diggelen and Grootjans, 2019, De Becker, 2019], this will certainly have consequences for the profitability of the current crops on the agricultural lands north of the Zegge. After all, the above figure clearly shows that when groundwater levels exceed 50 cm, the harvest decreases drastically.

### Next steps: impact of rewetting scenarios

In the future, the modeling framework developed in this study can be used to assess the impact of different groundwater level scenarios on conventional agricultural crops. In concrete terms, these scenarios will be generated with the calibrated groundwater model from the ecohydrological study. After all, this model can be used to calculate the impact of shutting down pumps or other measures and to simulate how this will affect groundwater levels in the entire area. The simulated groundwater levels for different scenarios can then be used to calculate the impact on agricultural crops with this model framework.

## 7.4. Conclusions

The SWAP-WOFOST model was applied at field level in the study area around De Zegge-Mosselgoren to evaluate the yield variability of grass and fodder maize. This was done using the current groundwater levels as obtained with the calibrated groundwater model from the ecohydrological study, and with the same model input as described in the Model framework to evaluate the suitability of groundwater regime for crop growth.

Differences in meteorological conditions between the years cause a large yield variability over the years, especially for silage maize. Shallow groundwater levels in the study area cause oxygen stress in crops in wet years, but are beneficial for crop production in dry years. In general, oxygen stress is the main cause of yield reduction in this area. The total yield reduction due to too dry or too wet conditions and indirect effects (shorter growing season) is up to 30% for both crops at the current groundwater levels and the current climate, except for silage maize in 2016 where there was up to 50 % yield reduction, mainly due to oxygen stress.

In the current situation, agricultural water management in the area is optimal for agricultural activities in dry years, but already causes restrictions in wet years. This corresponds to the practical experience of the farmers involved in the area. Detailed conclusions about the effect of rising groundwater levels as a result of rewetting strategies on agriculture in the study area cannot yet be drawn from this study, as the scenarios were not yet ready. This can be evaluated in the future on the basis of the groundwater level scenarios from the ”Ecohydrological study: basis for restoration measures for Nature Reserve De Zegge” with the model framework elaborated here. The model SWAP-WOFOST adapted for the Flemish conditions and corresponding documentation is freely available in the PEILIMPACT github repository.

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## Part IV.

# Additional considerations regarding rewetting in agricultural areas

# 8. Impact of changing groundwater level on nutrient mobility

Diana Estrella, Fien Amery, Sarah Garré

### Abstract

One of the major concerns in rewetted wetlands is the increase of nutrient concentration in groundwater and the possible contamination of adjacent aquatic ecosystems (i.e. eutrophication). The increase of phosphorus solubility (mobilization) and diffusion are indeed the most important changes of rising groundwater levels. But also, the increase of polluting gases like methane, which may hamper climate change mitigation purposes.

With an increase in groundwater levels, and hence soil moisture, soils shift to anaerobic conditions because of the lack of oxygen. In these conditions, specialized soil bacteria dominate and break down the organic matter at a slow rate. Decomposition of the organic matter (mineralization) into mainly methane and carbon dioxide, and nutrient intake (assimilation), are therefore very slow processes, which cause plant residue accumulation. At the same time, changes in pH alter the amount of soluble nutrients and chemicals in the soil. Inorganic phosphorous is usually bonded to clay particles, iron, aluminum and calcium. The altered pH in anaerobic conditions increases the solubility of these elements, and the adsorbed phosphorous and organic carbon substances are released to the soil solution. Nitrogen on the other hand is mostly lost from the soil as nitrogen gas. These nitrogen losses cause less soluble nitrogen to be available for plants.

**Key points**

Higher groundwater levels lead to insufficient oxygen in the soil, which drastically changes its physical and electrochemical characteristics. In these new conditions, adsorbed phosphorus and organic carbon substances are more mobile, and can be diffused to surface waters. This will depend on the phosphorous availability in the soil. Leaching of soluble nitrogen is typically lower and mostly lost as gas, with less of it available in the soil.

## 8.1. Introduction

Rising groundwater levels causes drastic changes in the ecosystem, and to the physical and electrochemical characteristics of the soil [Harpenslager et al., 2015]. Depending on the intensity of rewetting, conventional agriculture may no longer be possible. The increase in nutrient mobilization in soils previously under agricultural use can cause contamination of the surface water, with undesirable effects in aquatic environments (i.e. eutrophication) [Zak and Gelbrecht, 2007, Johnston et al., 2005]. Rewetting of drained agricultural peatlands is especially critical due to the high amount of nutrients and organic matter content [Zak and Gelbrecht, 2007]. Numerous studies highlight the capacity of wetland vegetation like cattail (Thypa sp.) to remove excess nitrogen and phosphorous from surface and pore water. As such, they prevent nutrient accumulation and transport, and mitigate methane ($CH_4$) emissions, which are known to increase in flooded conditions [Vroom et al., 2018, Belle, 2021, Geurts et al., 2020].

The extent and duration of soil under saturated conditions, and the presence of microbiological activity, define whether waterlogged conditions (anaerobic conditions) may occur [Moore et al., 1998]. These conditions are present in rewetted wetlands, where the water level is kept above or slightly under ground surface. The oxygen from the underlying water column can reach a small portion of soil surface before it gets depleted, creating a thin aerobic layer on top of a thicker anaerobic layer. The depth of this aerobic layer depends on the oxygen supply and the consumption rate in the soil, being even inexistent in soils with high decomposable organic matter at the soil surface [Buresh et al., 2008]. Therefore, the chemical processes in the anaerobic layer are the main interest in this chapter.

In Flanders, both soil phosphorus (P) and nitrogen availability are high due to intensive livestock farming and agriculture. Substantial P-reserves have been developed over the years in the Flemish farmland, and nitrogen emissions (mainly ammonia) from agricultural activities have remained alarming, being the focal point of manure and fertilizers legislations [Bomans et al., 2005, Departement Omgeving, 2022]. Phosphorous is normally very strongly bound to soil particles, erosion and surface runoff are the main transport mechanisms of particulate P to surface waters [Bomans et al., 2005]. Under anaerobic conditions, part of the bounded phosphorus enters the soil solution and can be transported through surface runoff and also as soluble or dissolved P [Ponnamperuma, 1972], with a serious risk of eutrophication in nearby water bodies. Similarly, excessive nitrogen emissions and later deposition in the soil cause eutrophication and soil acidification [Departement Omgeving, 2022]. It is therefore important to investigate the possible impacts of rising groundwater levels on nutrient mobilization, gas emissions and availability.

This chapter will describe the main chemical and physical transformations of nutrients and other linked elements in waterlogged soils (anaerobic conditions) with a main focus on phosphorus, and their possible impacts on the ecosystem.

## 8.2. Chemistry of submerged soils under anaerobic conditions

A rising water table causes a fast shift from aerobic to anaerobic soil processes [Harpenslager et al., 2015]. Under anaerobic conditions, soils are in a reduced state instead of an oxidized state, which cause several electrochemical changes such as decrease in redox potential, changes in pH, drastic shifts in mineral equilibria, and sorption and desorption of ions (Figure 8.1) [Ponnamperuma, 1972]. Reduction is the gain of electrons by an oxidizing agent or acceptor while oxidation is the loss of electrons by a reducing agent or donor. Redox potential represents how easily electrons are transferred to or from chemical components in a solution. Under anaerobic conditions, facultative and obligate anaerobic microorganisms use the organic matter as substrate or donor, and oxidized soil components like nitrate ($NO_3^-$) or manganese dioxide ($MnO_2$) as electron acceptors in their respiration. The reduced components during anaerobic respiration are normally carbon dioxide ($CO_2$), methane ($CH_4$), ammonium ($NH_4^+$), ammonia ($NH_3$), hydrogen sulfide ($H_2S$), ethylene ($C_2H_4$) and other residues [Ponnamperuma, 1972]. Under anaerobic conditions, soil has a low oxidation-reduction potential because anaerobic bacteria work at low energy levels due to incomplete decomposition of carbohydrates [Zak and Gelbrecht, 2007, Ponnamperuma, 1972, Buresh et al., 2008]. Therefore, decomposition and assimilation are very slow processes and plant residues accumulate in waterlogged or poorly drained soils (e.g. peatlands).

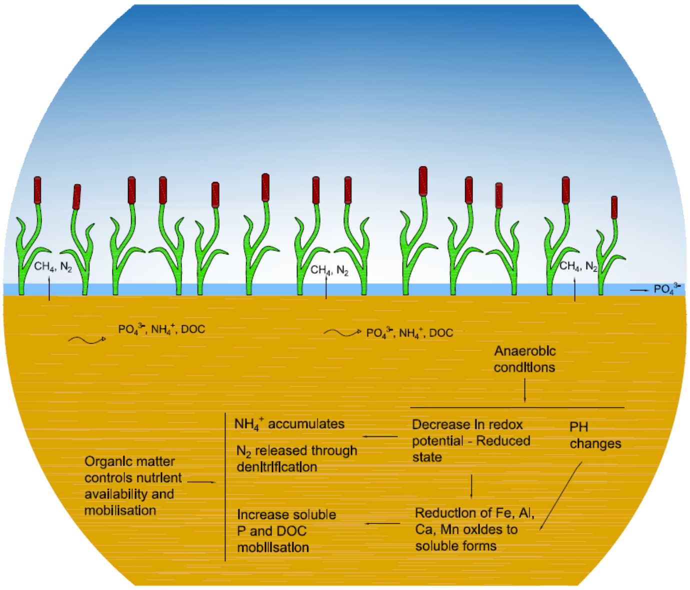

Figure 8.1.: Main electrochemical transformations in soil under submerged conditions.

## Sequential reduction

During the shift from aerobic to anaerobic conditions, oxygen is quickly depleted and other soil compounds are used as electron acceptors for anaerobic bacteria. The choice of these electron acceptors occurs roughly in the sequence shown in Table 8.1, according to the redox potential or electron activity (pe) [Ponnamperuma, 1972, Amery, 2012]. The more negative pe is, the stronger the reduction potential is.

After oxygen depletion, $MnO_2$ ($Mn^{4+}$) or $NO_3^-$ are first reduced to $Mn^{2+}$ and $N_2$ respectively. $NO_3^-$ reduction begins only after the oxygen concentration has dropped to a very low value, and their presence slow down the reduction of the next oxides in the sequence. $MnO_2$ has less influence than $NO_3^-$ because its insolubility in water and it is used as electron acceptor by only a few distinct bacteria. Next in the sequence is ferric iron $Fe(OH)_3$ ($Fe^{3+}$), which is reduced to ferrous iron ($Fe^{2+}$). Under very reduced conditions, sulphate ($SO_4^{2-}$), $CO_2$ and $H^+$ are used as electron acceptors for bacterial respiration [Ponnamperuma, 1972, Boyd, 1995].

Table 8.1.: Sequence of half reduction reactions in submerged soils with pe values predicted for equal concentrations of the reduced and oxidized species in solution [Amery, 2012]

| | **pe*** | |
|---|---|---|
| | **pH 5** | **pH 7** |
| 1) $1/4O_2 + e^- + H^+ = 1/2H_2O$ | 15.6 | 13.6 |
| 2) $1/2MnO_2 + e^- + 2H^+ = 1/2Mn^{2+} + H_2O$ | 12.8 | 8.8 |
| 3) $1/2NO_3^- + e^- + H^+ = 1/2NO_2^- + 1/2H_2O$ | 9.3 | 7.3 |
| 4) $Fe(OH)_3 + e^- + 3H^+ = Fe^{2+} + 3H_2O$ | 4.8 | -1.2 |
| 5) $1/8SO_4^{2-} + e^- + 5/4H^+ = 1/8H_2S + 1/2H_2O$ | -1.0 | -3.5 |
| 6) $1/8CO_2 + e^- + H^+ = 1/8CH_4 + 1/4H_2O$ | -2.1 | -4.1 |
| 7) $H^+ + e^- = 1/2H_2$ | -5.0 | -7.0 |
| 8) $1/4CO_2 + e^- + H^+ = 1/4CH_2O + 1/4H_2O$ | -6.1 | -8.1 |

*for solid-phase/solution equilibria: concentrations of dissolved species of $10^{-4}$ M. Atmospheric gas composition assumed: partial pressure of $O_2$ of 0.21 bar, $N_2$ of 0.778 bar, and $CO_2$ of 3.2 $10^{-4}$ bar.

## Oxygen and other gases

In saturated conditions, oxygen and other gases can transport through the soil only by molecular diffusion in the interstitial water. This process is much slower than diffusion through gas-filled pores (about 10000 times slower), and therefore the oxygen diffusion rate falls sharply when the soil reaches saturation. In just few hours after saturation, all the available molecular oxygen present in the water or trapped in the soil is depleted by microorganisms. In these anaerobic conditions, apart from carbon dioxide ($CO_2$), other intermediate gases like methane ($CH_4$) and ethylene ($C_2H_4$) are also produced during respiration and alcoholic fermentation, and accumulate in the soil [Moore et al., 1998].

## pH

Soil pH is a measure of the concentration of hydrogen ions in the soil solution. Its value ranges from 0 to 14, being 5.5 to 8.0 considered ideal for plant growth. Soil with low pH values (<5.5) are considered acidic, while soils with high pH values (>8.0) are classified as alkaline [Rengasamy, 2022]. pH increases in saturated acidic soils while it decreases in saturated alkaline soils, until both reach a relatively stable value of about 7 [Ponnamperuma, 1972]. This can be seen in several experiments done in rewetting projects [Zak and Gelbrecht, 2007, van de Riet et al., 2013]. The increase in pH in acidic soils has to do with soil reduction processes while its decrease in alkaline soils is because $CO_2$ accumulation. However, this phenomenon can change depending on the organic matter and iron contents. Organic matter and iron enhance the pH decrease in basic or alkaline soils while restricting the increase of pH in acidic soils [Ponnamperuma, 1972].

pH highly influences the hydroxide, carbonate, sulfide, phosphate, and silicate equilibria in submerged soils. This equilibria regulates their chemical and physical transformations, including precipitation and dissolution of solids, sorption and desorption of ions [Ponnamperuma, 1972]; and ultimately, their availability in the soil solution, and for the plants.

### Temperature

Soil temperature mainly determines the oxygen depletion rates in submerged soils. At low temperature, the biological activity of plants and soil microorganisms is low and therefore the oxygen demand is also low. The oxygen demand however increases exponentially with temperature. At higher temperature, plants grow faster and microbiological activity increases, causing a fast oxygen depletion in warm conditions [Moore et al., 1998]. Temperature has therefore a strong effect on soil reduction processes in flooded soils [Ponnamperuma, 1972].

## 8.3. Phosphorous transformation

In the soil, phosphorus (P) is present attached to soil particles, as minerals like Fe-Al oxides and Ca-carbonates, as part of organic matter and a very small percentage dissolved in the soil solution [Bomans et al., 2005]. Phosphorus (P) is a limiting nutrient for crop growth, especially during the vegetative stage. In Flanders, critical P values range from 59 mg P/kg dry soil in winter wheat up to 164 mg P/kg dry soil in maize [Stijn Martens et al., 2020]. Soluble forms of P like orthophosphates ions ( $H_2PO_4^-$ and $HPO_4^{2-}$)are absorbed by the plants and allocated to the fruits and seeds during reproductive stages [Bomans et al., 2005]. Excess soluble P is lost by surface runoff and leaching. Figure 8.2 explains the main transformations of phosphorous in the soil.

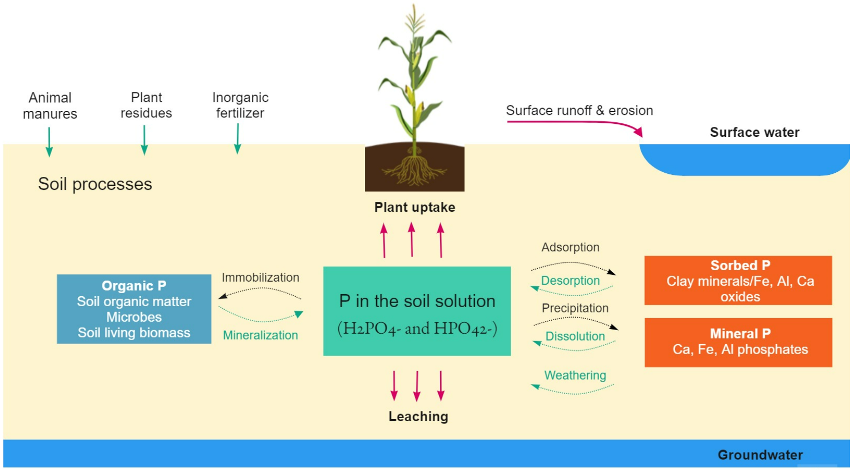

Figure 8.2.: Phosphorous pathways and transformations in the soil. Adapted from Prasad and Chakraborty [2019].

### The role of clay content and soil mineralogy

Inorganic P has high affinity with clay particles, iron (Fe), aluminum (Al) and calcium (Ca) oxides in the soil [Prasad and Chakraborty, 2019, Zak and Gelbrecht, 2007]. Iron and aluminum phosphates predominate in acidic soils and sediments, while calcium phosphates are present in alkaline soils [Ponnamperuma, 1972]. In anaerobic conditions, due to the increase in pH in acidic soils and decrease in alkaline soils, insoluble iron, aluminum or calcium oxides are reduced to soluble forms ($Fe^{2+}$, $Al^{2+}$, $Ca^{+}$), which can move readily in the soil solution [Ponnamperuma, 1972]. Adsorbed phosphorous is then released and becomes part of the soil solution. Clayey soils or soils with high concentrations of Fe, Al or Ca oxides, have a greater P adsorption capacity and therefore P availability will be larger when a bigger portion of the soil becomes saturated [Prasad and Chakraborty, 2019]. van de Riet et al. [2013] found that P values in rewetted peat- and clay-covered peatlands were up to 11.7 mg P-PO4/l, being higher in peat due to larger availability of iron-bond phosphorous. Under saturated conditions, manganese dioxide ($Mn^{4+}$) is also reduced to soluble manganese ions ($Mn^{2+}$). High concentrations of $Fe^{2+}$and $Mn^{2+}$ ions can be toxic for plants [Ponnamperuma, 1972].

### Mineralization and transport processes

Mineralization is the process through which nutrients present in organic matter (C, P, N, K) are converted into inorganic compounds easily available for plants. This process is intensified at higher soil moisture content, because soil microorganisms prefer wetter environments [Whalen et al., 2001], but it slows down under anaerobic conditions because anaerobic bacteria work at a slower rate. Clearly, with higher organic matter content (i.e. peatlands), more available forms of P can be released into the soil [Prasad and Chakraborty, 2019]. Further, organic molecules like humic acids can hinder sorption and precipitation processes of phosphate, leading to more availability of soluble P in the soil [Amery and Vandecasteele, 2015, Prasad and Chakraborty, 2019]. Zak and Gelbrecht [2007] found that the highest soluble P concentration in pore water (143  M) was measured in highly decomposed peat, while negligible increases were found in slightly decomposed peat.

Surface runoff is the main hydrological pathway of phosphorus loss from soils to surface waters [Prasad and Chakraborty, 2019], particularly in agricultural and livestock areas. Runoff water transports particulate P within eroded soil particles, and dissolved P. Diffusion of the soluble P depends greatly on the soil moisture content since soluble P moves through the soil pores by water, thus it can be more easily transported and lost by surface runoff when increasing groundwater levels [Amery and Vandecasteele, 2015]. Surface runoff during rainfall events is higher in saturated soils, and the risk of P losses increases in areas with a high P surplus like is the case of the Flemish region.

## 8.4. Nitrogen transformation

Just like phosphorus, nitrogen is an essential nutrient for crop growth, development and reproduction [Moore et al., 1998]. It is present in soils and sediments mainly as complex organic substances (which are not readily available for plant uptake), ammonium ($NH_4^+$), molecular nitrogen ($N_2$), nitrite ($NO_2^-$), and nitrate ($NO_3^-$) [Ponnamperuma, 1972]. The transformations depend largely on microbial activity controlled by physical and chemical characteristics of the soil such us organic matter, temperature, soil moisture and pH. Ammonium and nitrate are soluble forms of nitrogen, readily available for plants. In anaerobic soils, the main transformations are the accumulation of $NH_4^+$, denitrification and nitrogen fixation [Ponnamperuma, 1972]. Most of the nitrogen is lost from the soil in the form of nitrogen gas; these nitrogen losses cause less soluble nitrogen to be available for plants. Figure 8.3 shows the main transformations occurring in nitrogen.

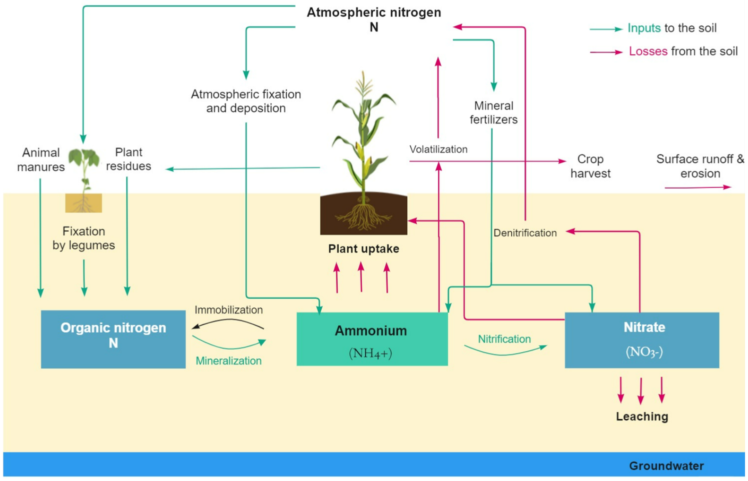

Figure 8.3.: Nitrogen pathways and transformations. Adapted from ESN [2020].

## Accumulation of ammonium

After increasing groundwater levels until soil saturation, microorganisms quickly deplete the remaining oxygen. Due to lack of oxygen, chemical transformation of organic nitrogen (mineralization) cannot go further in the conversion to $NO_3^-$, and consequently $NH_4^+$ accumulates in the soil [Buresh et al., 2008]. The fact that anaerobic bacteria have low nitrogen requirements also contributes to a faster ammonium release and accumulation [Tusneem, 1971]. van de Riet et al. [2013] reported that high ammonium release (4.8 mg N- $NH_4^+$/l) was observed in rewetted peatlands. Also, Zak and Gelbrecht [2007] found that the upper highly decomposed peat layer was mostly responsible for the high mobilization of ammonium after rewetting, due to availability of decomposable organic matter. Ammonia volatilization is another pathway of nitrogen loss from fertilized flooded soils with urea. High pH (7.5 to 10) and temperature favors the loss of added fertilizer through ammonia volatilization [Buresh et al., 2008].

## Denitrification and nitrogen fixation

Denitrifying bacteria use $NO_3^-$ instead of oxygen as the oxidizing agent to transform nitrogen into nitrogen gas ($N_2$or $NO_2$), which finally escapes to the atmosphere [Ponnamperuma, 1972]. In presence of high nitrate availability (i.e. through fertilization, plant residues), incomplete denitrification due to shortage of oxygen can induce nitrous oxide ($N_2O$) emissions [Vroom et al., 2018, IPV, 2022]. Nitrous oxide has been found to be negligible in rewetted wetlands [Vroom et al., 2018]. In flooded soils, ammonium can be converted to nitrate in the thin upper aerobic layer and diffuse down to the anaerobic zone, where it is denitrified [Tusneem, 1971].

The depletion of oxygen and high amount of dissolved organic carbon also promote the biological nitrogen fixation by cyanobacteria. This process occurs typically in paddy rice [Buresh et al., 2008].

## 8.5. Other transformations

### Carbon transformation

The main transformation of carbon in waterlogged conditions is the decomposition of the organic matter (e.g. carbohydrates) by soil microorganisms during respiration [Ponnamperuma, 1972]. This transformation is much slower than in aerobic conditions because the energy released in these transformations is much lower. Methane ($CH_4$) is the typical end product of the anaerobic decomposition of organic matter, accompanied usually by smaller amounts of carbon dioxide ($CO_2$), organic acids and hydrogen [Ponnamperuma, 1972]. $CH_4$ emissions are one of the main concerns in rewetted peatlands because it is a highly polluting gas. In soils rich in organic matter, $CO_2$ can accumulate in the porewater and potentially dissolve carbonates [Zak and Gelbrecht, 2007].

Besides P, iron oxides are also bonded to organic carbon substances. The reduction of these oxides under anaerobic conditions releases dissolved organic carbon (DOC) in the soil solution [Zak and Gelbrecht, 2007, Harpenslager et al., 2015, Maranguit et al., 2017].

### Sulphate transformation

In very poorly drained soils, sulphate ($SO4^{2-}$) is reduced to sulphide ($S_2^-$) and sometimes hydrogen sulphide ($H_2S$) [Moore et al., 1998]. $H_2S$ can react with heavy metals to produce insoluble sulphides, or provide hydrogen to photosynthetic sulfur bacteria [Ponnamperuma, 1972]. Zak and Gelbrecht [2007] identified that sulphate concentration increased sharply after rewetting, but had a rapid decrease in the upper highly decomposed peat horizon.

## 8.6. Effects on water quality and biodiversity

An increase of nutrient availability in the soil solution, especially phosphorous (P), can lead to contamination of local semi-aquatic ecosystems. This increase is insignificant agronomically because phosphorus and nitrogen are limiting nutrients for crop growth, but small concentrations in the water (20 $\mu$g/l) can already deteriorate aquatic ecosystems and reduce water quality [Bomans et al., 2005]. The amount of P release in the water is dependent on its availability in different forms in the soils, either in the organic matter, attached to iron (Fe), aluminum (Al) and calcium (Ca) particles, or as phosphate minerals. Also, the Fe/P ratio determines the export of P from eutrophic wetlands to nearby water bodies [Zak et al., 2004]. Soil nitrogen pollution due to nitrogen gases deposition is less probable under waterlogged conditions because emissions of contaminant gases such us ammonia and nitrous oxides are very small.

In the case of rewetting of peatlands, the removal of the highly decomposed top layer, has been considered as a mechanism to reduce carbon losses, P and N mobilization, and ultimately eutrophication problems [Zak and Gelbrecht, 2007, Harpenslager et al., 2015]. Top soil removal can also avoid that fast-growing plants in nutrient rich water (e.g. cattail, reed) take over and decrease the biodiversity of the wetland [Harpenslager et al., 2015]. However, this method can be expensive [Klimkowska et al., 2010]. An alternative solution is the use of wetland plants to absorb excess nutrients and prevent nutrient diffusion and accumulation [Vroom et al., 2018, Geurts et al., 2020]. This is explained in more detail in the next chapter (Potential of paludiculture crops in Flanders) .

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# 9. Potential of paludiculture crops in Flanders

Diana Estrella, Sarah Garré

## Abstract

Paludiculture is the productive use of rewetted wetlands from the perspective of conserving an essential ecosystem that is currently being used for conventional agriculture, but with the benefit of being economically attractive. Paludicrops or wet crops can provide several productive uses and environmental services. Their biomass can be used for building materials, animal feed, horticultural substrates, and biofuel production. Paludiculture restores a valuable habitat for endangered species, while offering possibilities for animal husbandry and pharmaceutical industries. Environmental services include water purification and retention, carbon sequestration and greenhouse gas emissions mitigation.

Countries like The Netherlands and Germany have significant experience with paludiculture. Cattail (Typha sp.), reed (Phragmites australis) and peat moss (Sphagnum sp.) are the most promising crops because they have multiple uses and offer several market opportunities. In Flanders, paludiculture is poorly known and most of the research has been focused on Miscanthus (Miscanthus x giganteus) as bulk material for sustainable growing media, or for biofuel production. Miscanthus seems to be more productive and persistent under Belgian conditions compared to other paludicrops, although propagation is still costly due to rhizome preparation. Willow (Salix sp.) has also showed their potential in Flanders within Agroforestry for animal shelter, and is under ongoing research with the purpose of being used as a natural barrier.

Although there is certainly potential in these ‘new’ crops, paludiculture is an emerging and not very well known type of farming, and therefore there is still lack of knowledge and awareness from governments, farmers and customers about their benefits. Most of the limitations are related to cultivation practices and adapted machinery, market opportunities, and regulations and incentives. Nonetheless, there is a growing ideology towards more sustainable practices and bio based alternatives within industries, and the EU missions (Horizon Europe) have ambitious goals to reduce net GHG emissions from drained peatlands. This certainly opens big opportunities for paludicrops in the future.

Experience gained in neighboring countries can be used in Flanders as a baseline for continuing research and creating appropriate market opportunities according to the Flemish context. In Flanders, fragmentation of the agricultural area can be a limiting factor for paludiculture to become profitable in industrial applications. In that case, the focus in Flanders could be on local processing and use and circular agricultural models.

**Key points**

Paludiculture can be used as an alternative to conventional agriculture in areas where rewetting projects are required. These crops can guarantee the production of biomass for various industrial purposes and can also form a transition between cultivated land and wet nature, and also provide water purification and water buffering.

Knowledge of cultivation practices and adapted machinery, along with market opportunities are crucial to encourage farmers to make a transition towards these crops. In Flanders, paludiculture is not well known and more research/pilot projects are needed to determine which paludicrops are more suitable for the Flemish conditions and which market opportunities are available before it is a viable option for farmers.

The relative small-scale agricultural areas in Flanders can be a limiting factor for paludiculture to become profitable at industrial levels, processing and use at local scale can be more suitable.

## 9.1. Introduction

Paludiculture (Latin 'palus' = swamp), is the productive use of rewetted wetlands, from the perspective of conserving an essential ecosystem but being economically attractive. Peatlands are a special type of wetland characterized by having a naturally accumulated peat soil layer in the surface, formed from the slow plant decomposition over the years under waterlogged conditions [De La Haye et al., 2021]. The peat soil is therefore a huge carbon storage, which is known to release roughly 1.9 gigatonnes of $CO_2$ annually to the atmosphere due to their degradation [IUCN, 2021]. Instead of draining peatland areas to make way for conventional agriculture or extracting peat soil for substrate in horticulture or garden use, paludiculture aims to keep the productive function of the peatland [De La Haye et al., 2021]. This is achieved by cultivating crops that can thrive in temporarily or permanent wet or even flooded conditions, and thus preserving the ecosystem services of wetlands [Wichtmann et al., 2016].

Plants can adapt to wet conditions (oxygen stress) in different ways; by developing aerenchyma to provide gas exchange between aerobic shoots and anaerobic roots, by stem enlargement (hypertrophy), producing a radial root oxygen barrier or by adventitious root formation [Kaur et al., 2020]. Most of the arable crops are sensitive to very wet conditions (see previous chapter) as they cannot develop those adaptations. Perennial grasses and pasture legumes can be more tolerant to transient waterlogging compared to arable crops, but they do not resist permanent soil saturation or flooded conditions [Moore et al., 1998]. Paludicrops are rather more appropriate for rewetted wetlands. Their cultivation for biomass production and new market opportunities has been largely explored in Europe, under mainly the framework of climate change mitigation [De La Haye et al., 2021, Duursen and al., 2016].

Wet crops can deliver a wide range of productive and environmental services. In rewetted wetlands, greenhouse gasses emissions depend on oxygen and nutrient availability in the soil [Collins et al., 2019]. Under aerobic conditions (water levels below the soil surface), carbon dioxide ($CO_2$) and nitrous oxide ($N_2O$) are emitted, resulting from the decomposition of the organic matter. In anoxic conditions (water levels above the soil surface), $CO_2$ and $N_2O$ emissions are reduced significantly but part of the organic matter is broken down to methane $CH_4$) due to methane-producing bacteria [Emsens et al., 2019, Wilson et al., 2016]. Despite $CH_4$ emissions are low compared to CO2, this gas is about 25 times more potent than CO2 [Emsens et al., 2019]. Some paludicrops like cattail (typha sp.) and reed (phragmites) can release oxygen in the soil under flooded conditions which can reduce $CH_4$ formation. Other crops like peat moss (sphagnum sp.) can sequester $CO_2$ producing even negative greenhouse gases rates [Collins et al., 2019]. Cattail and reed also need high nutrient availability; therefore, they can act as water purifiers and increase the water retention capacity in the wetland [Collins et al., 2019, Vroom et al., 2018]. The biomass of most paludicrops can be used for several purposes: building materials, insulation, animal feed, growing substrates, raw material for paper production, composting and biofuel [Collins et al., 2019].

Paludiculture presents however some limitations regarding cultivation practices, market opportunities, and regulations. There have been proposed different business models including horticultural substrates production, adapted dairy farming combined with paludiculture, and carbon-credit schemes [Collins et al., 2019]. However, this new type of farming is still new and currently under ongoing research. There is currently a lack of certainty regarding market opportunities and regulations, with which farmers have to struggle [Collins et al., 2019, De La Haye et al., 2021]; however, this will likely improve as the system develops.

In this chapter, we give an overview of paludiculture crops with potential in the Flemish context. We start with a general overview and ongoing research, and then zoom in on the most promising crops for the Flemish context. We finish with a discussion on the knowledge gaps for further research.

## 9.2. Overview of paludiculture crops

The Database of Potential Paludiculture Plants (DPPP) [Abel et al., 2013] lists more than 1100 plants suitable for paludiculture, from which 469 are considered "good" because they can be economically valuable. Most of the crops are perennial and grow in soils with a water table of about 20 cm below soil surface. Examples of these crops are peat moss (sphagnum sp.), cattail (typha sp.), reed (phragmites), and willow (salix sp.). Collins et al. [2019] presents a nice overview of potential paludicrops, their products and opportunities for Carbon and Blue credits, based on an extensive literature review (Table 9.1), in the framework of the Carbon Connects project.

As Table 9.1 shows, each crop requires a specific groundwater regime to obtain maximum growth and environmental benefits. For most paludicrops, a water level that fluctuates around -20 cm or even higher is more efficient from the $CO_2$ emission point of view. Optimal water level can be around 40 cm below the soil surface for peat moss or giant cane, while it can be up to 1 m above soil surface in the case of cattail and reed. Other crops like cranberry and willow do well in a wider range of water levels and can tolerate soil water fluctuations [Bestman et al., 2019].

Table 9.1.: Overview of important paludicrops, products and potential for C-credits and Blue-credits. C-credits potential is based on estimates of GHG-emission reductions: ++ very high potential, + high potential, 0 little potential, - no potential. Potential for blue credits is based on water purification and storage [Collins et al., 2019].

| Crop | Water level (cm) | Products | Carbon credits | Blue credits |
|---|---|---|---|---|
| Alder (Alnus sp.) | -40 to +5 | Wood | ++ | Storage:++ |
| Cattail (Typha sp.) | 0 to +20 | Animal fodder<br>Insulation and building material<br>Potting soil<br>Feed for pest-controlling predatory mites<br>Food | + | Purification:+<br>Storage: ++ |
| Giant cane (Arundo donax) | -40 to 0 | Building material<br>Combustion/biogas | 0/+ | Purification:++<br>Storage:++ |
| Peat moss (Sphagnum sp.) | -15 to -5 | Substrate in horticulture | ++ | Purification:+<br>Storage:+/0 |
| Reed (Phragmites) | -20 to +20 | Roofing material<br>Combustion/biogas | ++ | Purification:++<br>Storage:++ |
| Reed canary grass (Phalaris arundinacea) | -30 to +10 | Combustion/biogas | + | Purification:+/0<br>Storage:+ |
| Sedge (Carex sp.) | -40 to +20 | Combustion/biogas | ++ | Purification:+<br>Storage:+ |
| Sundew (Drosera sp.) | -20 to 0 | Medicine | ++ | Purification:0<br>storage:0/+ |
| Sweet flag (Acorus calamus) | -30 to +10 | Herb and medicine | + | Purification:+<br>Storage:+ |
| Water fern (Azolla sp.) | >+5 | Animal fodder<br>Protein | 0 | Purification:+<br>Storage:++ |
| Wild rice (Zizania sp.) | 0 to +20 | Food | + | Purification:++<br>Storage:+ |
| Willow (Salix sp.) | -40 to +20 | Wood | 0/+ | Purification:+<br>Storage:++ |
| Yellow iris (Iris pseudacorus) | -40 to +10 | Flowers | + | Purification:++<br>Storage:+ |

## Benefits and shortcomings

In Europe, there are different ongoing projects focused on peatland restoration and paludiculture as an innovative and profitable alternative for natural vegetation upon rewetting of wetlands, such as Carbon Connects, Care-Peat, DESIRE, LIFE Peat Restore and CANAPE [De La Haye et al., 2021]. This goes in line with the goals of the European Green Deal, which aims to reduce net greenhouse gas emissions by at least 55 % by 2030. Many benefits exist from the cultivation of paludicrops. The most promising crop is cattail (Thypa sp.) for building materials, biofuels, animal feed [De La Haye et al., 2021, de Jong et al., 2021] and peat replacement in horticultural substrates [Leiber-Sauheitl et al., 2021, Hartung and Meinken, 2021, , EDR]. From the Climate Change perspective, cattail cultivation has the potential to reduce CO2 emissions due to peatland conservation [de Jong et al., 2021]. Cattail has extra environmental benefits compared to other bio-based materials because it can be used to absorb pollutants and purify water Belle [2021], and therefore is more preferred in the market. However, CH4 emissions may be high in cattail since water levels have to be kept above ground level (0-20 cm) to have optimal yields [IPV, 2022]. Another crop being explored for water purification is duckweed fern (azolla sp.) in the project Innovatie Programma Veen [Duursen et al., 2016] in North Holland. Nutrients removed from the water and converted into crop biomass can be used as compost or animal feed [Belle, 2021]. Peat moss has also being researched as an alternative to peat substrate in the project MOOSzucht in Germany, and for increasing the carbon storage capacity of the peat [De La Haye et al., 2021], also as a decorative material Duursen and al. [2016] and lining for exotic animal terrariums in the project CANAPE.

Ziegler et al. [2021] stated that paludiculture is an emerging and science-driven innovation around the world and especially in Europe; however, it has to face several limitations regarding lack of economic viability, knowledge, subsidies and regulations. Although considerable research has been devoted to maximize the potential of paludiculture with the purpose of increasing agriculture sustainability and contribute to a bio-based economy, governments, farmers and customers are still not fully aware of this new technique and their environmental benefits [Collins et al., 2019]. The market is still new and developing, adapted machinery is missing, and therefore, most of the production is at small scale or within research/pilot projects. Paludiculture is not competitive with traditional drained-agriculture and subsidies and incentives are fundamental to make this market profitable [Ziegler et al., 2021]. The lack of regulations and clear prospect of paludiculture discourage farmers to adopt this new type of farming and companies to use paludicrops as raw material [Collins et al., 2019, De La Haye et al., 2021].

Figure 9.1 summarizes the main benefits and shortcomings of paludiculture encountered in several pilot projects and studies across Europe [Collins et al., 2019, Ziegler et al., 2021, Duursen et al., 2016, Geurts and Fritz, 2018].

**Benefits**

- Productive uses: building materials, energy production, horticultural substrates.
- Carbon fixation and storage, and reduction of greenhouse gas emissions.
- Peat conservation and reduction of land subsidience.
- Improvement of the water quality and quantity.
- Wetland habitat protection and biodiversity preservation.

**Shortcomings**

- Change of management practices and machinery is required.
- Small-scale production and still not economically viable
- High initial investments costs
- Lack of subsidies, incentives and regulations
- Still in research and not very well known

Figure 9.1.: Benefits and shortcomings of Paludiculture

## Potential uses of paludicrops

Wet crops can provide several productive uses and environmental services that can be economically attractive (Figure 9.2). Their biomass can be used for building materials, insulation, animal feed, growing substrates and composting, and biofuel production. Environmental services include water purification, carbon sequestration and water retention capacity increase in the wetland [Wichtmann et al., 2016]. Paludiculture also recreates a valuable habitat for endangered species [Greifswald Mire Center, 2015]. Paludiculture offers the possibility to be combined with other industries, like meat with water buffalo, or medicine with medicinal plants [Greifswald Mire Center, 2015]. While these potential services have already been identified in the literature, the viability of the crops for farmers depends on the available markets and their stability as well as on investments necessary to cultivate and harvest those crops.

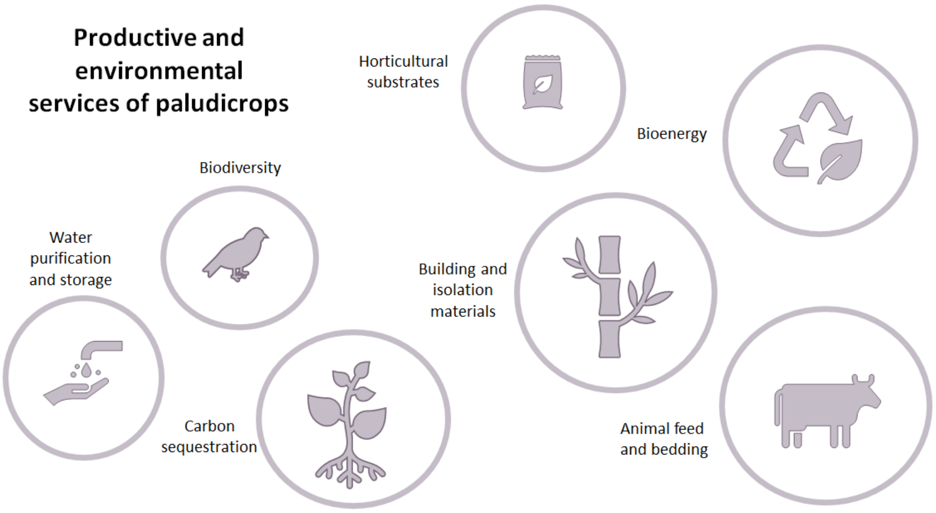

Figure 9.2.: Main productive and environmental services from paludicrops.

## Productive uses

**Building and isolation materials** Wet crops can be used as raw products for building and isolation materials. The main requirements for bio based constructions and insulation materials are light weight, fire retardance, resistance to biotic factors like mold and fungus, and not to emit harmful substances [Bestman et al., 2019]. Different products can be produced based on crop fibers like fiber boards, insulation panels for walls, floors and roofs, and paper [Collins et al., 2019]. Crops like cattail, miscanthus and reed have good insolation characteristics due to air cavities in the leaves and branches, high durability and strength. The time of harvesting is important in the biomass quality, for building materials it normally occurs in winter or early spring where the moisture content is low [Bestman et al., 2019].

Figure 9.3.: Insulation board made of cattail. Source: NAPORO

**Horticultural substrates** Paludicrops can be used as peat alternatives in sustainable growing media in horticulture. Currently, there is a high demand of new and more sustainable alternatives to peat in horticulture due to excessive CO2 emission from drained peatlands [Duursen et al., 2016]. Peat moss is the most fitting one thanks to its similar chemical and physical characteristics compared to peat. Miscanthus, reed and soft rush can also be suitable after some optimization treatments [Vandecasteele et al., 2018, 2021].

Figure 9.4.: Horticultural substrates trials with miscanthus and other fibers in the project I-Love-T. Source: Miscanthus als biomassagewas

**Animal feed and bedding** Wet crops can be a good source of nutrients for animal feed. When harvesting before the flowering period, the green leaves contain adequate levels of protein and are easily digestible. Normally cattail and willow can be used as supplementary or complementary food for ruminants [Bestman et al., 2019]. Dry straws from some paludicrops (e.g. cattail, miscanthus) harvested in winter or early spring are also very suitable for animal bedding. They have a good water absorption capacity and do not promote bacterial growth and skin lesions, important for the general comfort of the animals [Bestman et al., 2019, Van Weyenberg et al., 2016].

Figure 9.5.: Dry reed used for animal bedding [Bestman et al., 2019]

**Energy production** Bio-energy for heat and electricity production is considered one of the most profitable uses for some paludicrops like miscanthus and reed. Currently, the limited fossil fuel available is highly expensive, and there is a trend for switching to more climate-friendly alternatives [Waegebaert and Mey, 2019, Köbbing et al., 2013]. Winter-harvested biomass is used for this purpose, because the moisture content is low and the leaves have already fallen. Leaves contain potassium and chloride, which corrode the equipment, and produce more ashes during combustion [Bestman et al., 2019, Köbbing et al., 2013].

Figure 9.6.: Miscanthus pellets for biofuel [Waegebaert and Mey, 2019]

### Environmental services

**Water purification and water storage** Paludicrops can potentially be used to extract excess nutrients from agricultural lands or nutrient-rich ditch water. Nutrients like nitrogen and phosphates are absorbed by the roots and used for biomass production. In summer, most of these nutrients are stored in the above ground biomass, while in winter the nutrients are placed in the roots. Crops like cattail and reed can absorb large amounts of nitrogen, phosphorus and potassium, leading to a high nutrient biomass. Wet crops can allow to store the surplus water during precipitation events ( e.g. cattail). For water storage possibilities, the selection of suitable crops is critical, as no all paludicrops can withstand flooded conditions [Bestman et al., 2019].

Figure 9.7.: Cattail in ditch sides in a dairy farm to absorb the nutrient-rich run-off [Bestman et al., 2019]

**Carbon sequestration and peat conservation** One of the main purposes of paludicrops is the reduction of greenhouse gas emissions for drained peatlands by rewetting them, creating anaerobic conditions and thus reducing $CO_2$ and $N_2O$ emissions. $CH_4$ emissions can increase under wet conditions, but paludiculture crops also ensure that methane emissions remain lower in some cases. Wet crops are able to capture carbon and storage it in the roots and biomass. In building materials, the carbon remains fixed during the life of the material, while in applications such as animal feed some of it will re-enter the atmosphere after decomposition. Some crops like reed and peat moss can help to also increase the peat layer [Collins et al., 2019, Bestman et al., 2019].

**Nature conservation and biodiversity** Establishing the optimal water tables makes a shift from a terrestrial ecosystem to an aquatic ecosystem. By allowing wet plant species to spontaneously develop, help to restore a variety of habitats for endangered species like the Aquatic Warbler (Figure 9.8) and Greater Spotted Eagle [Greifswald Mire Center, 2015]. In protected areas, some regulations for nature conservation have to be respected, to avoid a conflict between biomass production, water purification and nature conservation. Very dense vegetation is desired for maximum absorption of nutrients but this can hinder the mobility of aquatic animals. Furthermore, mowing has to be done outside of the breeding seasons [Belle, 2021].

According to LIFE Multi Peat, wet crops can also serve as a buffer between agricultural areas and nature conservation areas. In this way, high water levels from wetlands are less influential in agricultural lands, and nature is more protected against the negative effects of nearby agriculture (e.g. leaching).

Figure 9.8.: The globally endangered Aquatic Warbler breeds in the ground of aquatic meadows [Greifswald Mire Center, 2015]

## 9.3. Paludiculture exploration in Flanders

Table 9.2 summarizes some of the projects regarding paludiculture in Flanders and their main results. In Flanders, most of the research has been focused on Miscanthus (Miscanthus x giganteus) and their potential as bulk material for sustainable growing media [Vandecasteele et al., 2018]. Soft rush (Juncus effusus) has also been studied as an alternative horticultural substrate [Vandecasteele et al., 2021]. Other explored possibilities for miscanthus included their use as bio-based raw materials for biofuel, paper production, packaging, or as a natural weed killer, and a complete guide exists for their cultivation [Waegebaert and Mey, 2019]. Additional studied uses are alternatives for bedding material for dairy cows Van Weyenberg et al. [2016], and sustainable biomass for energy production [Hulle et al., 2012].

When comparing with other perennial crops such us reed canary grass, switchgrass and willow; Miscanthus (Miscanthus x giganteus) seems to be more productive and persistent under Belgian conditions [Hulle et al., 2012], although the energy use efficiency is lower due to rhizome preparation [Muylle et al., 2015]. To solve this problem and to find other high yielding and stress-tolerant varieties of Miscanthus, around 100 miscanthus genotypes were tested under abiotic stresses (cold, drought and salinity) for biomass optimization [Lewandowski et al., 2016]. Several new genotypes were identified that can adapt to specific conditions, but the currently commercial genotype Miscanthus x giganteus is still a feasible option for many locations and conditions.

Other projects briefly analyzed the option of paludiculture but it remained only in possibilities or was not suitable. In the rewetting project in the valley of the Zwarte Beek in Limburg, the largest peat bog complex in Flanders, results indicated that under iron and phosphorus-rich wet soils, the predominant vegetation consisted on different species of sedges, and peat moss in the more acidic places [Emsens et al., 2019]. Although, paludiculture was not evaluated here, sedge (Carex sp.) has high potential for biofuel production and possibilities for carbon credits (Table 9.1). In the ongoing project LIFE Multi Peat, in the valley of the Grote Beek also in Limburg, paludiculture with willows is intended to be implemented as a measure for peatland restoration. Willows are planned to be used as a buffer between wet nature and agricultural lands, and maybe also for biomass, cattle food, stable litter or isolation. Finally, reed, cattail and duckweed were part of the business models proposed to face the water problems in the Livestock farm Hoeve De Waterkant, within the Productive Landscape Pilot Projects. However, paludiculture seemed to be unsuitable in this case due to large investment costs for the farmer, the lack of compensation for blue services and the absence of sufficient market opportunities.

Table 9.2.: Overview of main paludiculture projects in Flanders and their outcomes.

| Project/research | Scope | Paludicrops | Results |
|---|---|---|---|
| Carbon Connects (CCONNECTS) | Reduce the high carbon footprint of peatland soils in Northwest Europe by introducing new bio-based business models developed for sustainable land management practices. Two pilot projects in West Flanders. | Willow<br>Pitrus<br>Reed | Intended applications of paludiculture involves the use of biomass for on-farm composting and their subsequent use in arable lands, and animal bedding. |
| I-LOVE-T | Produce an innovative peat replacement with disease and/or pest suppressing properties, based on locally available plant fibers. | Miscanthus<br>Reed | +++<br>Defibrated plant fibers<br>showed low N fixation and were easily colonized by biocontrol fungi. |

| | | | |
|---|---|---|---|
| Bi-o-ptimal@work | Maximize the potential of heath management residues and/or their micro-organisms in the production of bio-active substrates and disease-suppressing additives for open field, forest greenery and acid-loving crops. | Soft rush | ++<br>After acidification, chopped soft rush was more stable (i.e. low oxygen uptake rate, CO2 flux and water extractable C) indicating their high potential for substrate blends. |
| Growing a Green Future | Contribute to a bio-based economy by growing raw materials that can also be processed locally into an end product. | Miscanthus | +++<br>Miscanthus resulted attractive because it has several use possibilities (biofuel, construction materials), high biomass yield and low investment costs. |
| Yield and energy balance of annual and perennial lignocellulosic crops for bio-refinery use | Compare yield potential and energetic balance for bio-refinery | Miscanthus<br>Reed<br>Reed canary grass<br>Willow | ++<br>Miscanthus is high yielding but willow is more energy use efficient. |

| | | | |
|---|---|---|---|
| OPTIMISTIC | Optimize the production and use of Miscanthus biomass, and to develop new high-value applications. | Miscanthus | ++<br>Other varieties like M.sinensis × M. sacchariflorus hybrids appeared to perform better than the commercially known variety Miscanthus x giganteous in certain locations. Although this is on average very suitable for all locations. |
| Productive Landscape Pilot Projects | Combine innovative business operations with a qualitative interaction with the landscape and society. | Reed<br>Cattail<br>Duckweed | -<br>Paludiculture not feasible due to large investment costs, the lack of compensation for blue services and the absence of sufficient market opportunities. |
| LIFE Multi Peat (European LIFE Climate Change Mitigation project) | Focus on climate impact of nature reserves by restoring peatlands and monitoring their greenhouse gasses emission/uptake.<br>Part of the project involves the restoration of the valley of the Grote Beek in Limburg by stablishing paludiculture. | Willow | It is expected that willows can serve as a barrier between wet nature and agricultural lands. Other environmental services could be water purification and pollination. |

## 9.4. Paludicrops with potential for cultivation in Flanders

Paludiculture is poorly known in Belgium and the research is still in its infancy. Other countries like The Netherlands and Germany have been intensively researching new sustainable and profitable agricultural activities in the peat meadow areas that minimize land subsidence, reduce greenhouse gas emissions from peatlands and improve water quality in the areas nearby agricultural polders [Bestman et al., 2019, Duursen et al., 2016, IPV, 2022, Wichmann, 2018]. Cattail, azolla and peat moss seem to be the most promising crops because they have multiple uses and offer several market opportunities [Duursen et al., 2016]. Cattail and reed are the most interesting crops in dairy farming according to Bestman et al. [2019], because they have the capacity to absorb significant amount of nutrients, so they can become high nutritional crops for animal feed. Although, the crop is converted back into $CO_2$ and $CH_4$ when using as animal feed [IPV, 2022]; therefore, other uses like building and isolation materials are preferred from the climate change perspective. Miscanthus has potential for being used in horticultural substrates and bioenergy, and some experience is already available in Flanders [Waegebaert and Mey, 2019]. Willow has been also explored in Flanders within Agroforestry [Bracke et al., 2020] and is just being researched in the project LIFE Multi Peat focused on environmental services.

On the other hand, final conclusions of pilot projects point out that there is still a long way to go in paludiculture due to insufficient and variable crop production to meet demands, lack of cultivation knowledge, and inconsistencies between regulations and wet cultivation implementation in the European agricultural system [IPV, 2022]. Paludiculture market is still small and it is unclear which revenue models are more efficient, especially in Flanders where studies are not available. Profitability would be possible if several uses are combined and if paludiculture is eligible for wetland agricultural payments within the Common Agricultural Policy (CAP) [IPV, 2022]. Nonetheless, there is a growing ideology towards more sustainable practices and bio-based alternatives, in the construction, bioenergy and animal sectors. The EU missions have ambitious goals to reduce net GHG emissions by 55 % by 2030; therefore, conservation of soil organic carbon stocks involving among others peatland restoration and paludiculture, is part of the innovative actions to meet this target. Simultaneously, the necessary policies, regulations and promotion will also be developed to facilitate and encourage the societal uptake of the new solutions and approaches. This certainly offers high opportunities for paludicrops in the future.

Although there is certainly potential in these ‘new’ crops, currently there is insufficient research on the Flemish market potential, the value-chain and its robustness. Valuable and positive experience gained in neighboring countries can be used as inspiration for continuing research and creating market opportunities in Flanders. Some areas can have similar conditions to the peat meadow areas in The Netherlands, but fragmentation of the agricultural area can be a limiting factor for industrial applications to become profitable. According to a discussion open in the Vlaamse Parlement [Talpe and Crevits, 2021], revenue models based on local cultivation and processing can be more suitable in the Flemish context.

Below, the main characteristics, potential uses and limitations are presented for cattail, miscanthus, peat moss, reed and willow.

### Cattail (Typha sp.)

Cattail (Typha spp.) is a perennial crop from the bulrush family (Typhaceae) that grow naturally in wetlands, nutrient-rich banks, on peat soils and shallow pools, from 1.5

Figure 9.9.: Cattail with its typical “cigar” [Duursen et al., 2016]

to 3 meters high [Duursen et al., 2016]. The most common variety is typha latifolia or large bulrush. Cattail multiplies by seed and rhizome and can form dense vegetation under favorable conditions [Morton, 1975]. This plant has a distinctive “cigar” or flower that contain the seeds; once they are ripe, the “cigar” disintegrates to disperse the seeds. The leaves are flat and similar to grass [Morton, 1975, Duursen and al., 2016]. Cattail thrives better in high water levels (+20 cm), biomass is smaller in winter than in summer due to dehydration and dry leaf drop. The dry matter yield ranges from 4 to 20 ton ha$^{-1}$, which can be enhanced by addition of nitrogen [Bestman et al., 2019]. Harvesting depends on the foreseen application, it is done in spring before flowering if used as roughage, or after flowering for structured feed, pollen production or insulation material. For building materials or bedding, harvesting is done in winter [Bestman et al., 2019].

### Potential uses

Cattail has some characteristics that make it excellent for insulation and construction materials and it is the most interesting use nowadays. It has a long-tear resistant fiber and around 85 % of spongy fiber, the insulation capacity is as good as typical insulation materials due its low thermal conductivity coefficient. Cattail is also fire-resistant and light weight, which is an advantage in the construction of ceilings and roofs. The high polyphenols content in bulrush protect the materials from fungi or insects and therefore little additives are required in the building materials. Carbon content in the plant remains fixed in the whole production process and in the building materials, important from the carbon footprint and for avoiding emissions of harmful substances as it happens in some synthetic materials Duursen and al. [2016].

Cattail can be used as supplementary animal feed, both fresh or in silage. For using as roughage, harvesting during the growing season and before the flowering period allow to conserve at maximum the nutritional levels of the plant and to have acceptable protein content and moderate fiber. The digestibility of the organic matter is around 70 % and the protein content is 120 g kg$^{-1}$ DM, compared with 79 % and 183 g kg$^{-1}$ DM in fresh grass [Bestman et al., 2019]. Some nutritional benefits include high selenium content, which is normally low in common grass, and high manganese content. Cattail is however poor in phosphorous, magnesium and zinc [Bestman et al., 2019]. When used as animal feed, carbon is converted back into $CO_2$ and $CH_4$ [IPV, 2022]. Cattail can be also used as animal bedding, since it has a comparatively high water absorption of around 3.2 ml $g^{-1}$ bedding material, compared to 4 - 4.5 ml $g^{-1}$ in usual bedding materials [Bestman et al., 2019].

Cattail is very productive and can absorb significant amounts of carbon, nitrogen, phosphorus and potassium and dispose them at harvest [Belle, 2021]. Cultivation of cattail for high biomass production combined with other environmental services like water purification and storage, nutrient removal and peat preservation is possible and can be profitable [Geurts et al., 2020]. According to Geurts et al. [2020], based on a biomass production of at least 10 ton DM $ha^{-1}$, carbon sequestration ranges between 4 - 14 ton C $ha^{-1}$, and nutrient removal between 100-500 kg N $ha^{-1}$, 20-80 Kg P $ha^{-1}$ and 100-450 kg K $ha^{-1}$. Since cattail prefers flooded conditions, methane emissions may increase, which lower its potential for climate change mitigation [IPV, 2022]. However, Vroom et al. [2018] found that cattail strongly reduced $CH_4$ emissions in rewetted peatlands compared to conditions without vegetation. The reduction of $CO_2$ emissions in rewetted peatlands ( -21.6 ton CO2-eq $ha^{-1}$) normally offset $CH_4$ emissions and make cattail cultivation (and other wet crops ) still very attractive [de Jong et al., 2021].

Other possible uses, less explored but with high-quality applications include pollen production for predatory mites [Samaras et al., 2019] or for medicinal purposes, and cattail cultivation for bioenergy [Bestman et al., 2019].

### Limitations

Cultivation of cattail is still difficult because of lack of knowledge and experience; for example, pests can sometimes decrease significantly the expected yield [IPV, 2022]. Currently, the demand is higher than the available production, which prevents the market to expand. This is mainly due to high investments costs, low revenue models and the lack of carbon credits, which also makes cattail not competitive with dairy farming [de Jong et al., 2021]. Potential uses can sometimes impossible to be combined; for example, biomass production for construction materials can not be used together with animal feeding or pollen production, which decreases the profitability. Also, there is a trade-off between yield and methane emissions. $CH_4$ emission can decrease significantly in lower water levels at expense of a smaller yield. Finally, current pollen extracts markets are dominated by Chinese companies, with low prices although poor quality. Western companies cannot compete with these prices and further research is still needed. The production of pollen for medicinal applications is also not feasible because it is not registered as official medicine in Europe [Duursen et al., 2016].

### Examples

- Naporo Klima Dämmstoff GmbH (Austria): utilizes cattail for the production of ecological climate active insulation materials [Duursen et al., 2016].
- EcoScala (The Netherlands): construction materials made with cattail.
- Typha Technik (Germany): insulating materials with cattail [Duursen et al., 2016]

### Elephant grass (Miscanthus giganteus)

Figure 9.10.: Miscanthus. Source: Ghent University

Miscanthus (commonly known as Elephant Grass) is a high yielding perennial crop that grows over 3 meters tall. A dense and extensive root system is formed during the first 2-3 years after planting; in this period, the yield is rather low and therefore not harvested. Propagation of miscanthus is mainly through rhizomes (subterranean stems from where roots and shoots come out) that grow in the first 25 cm of the top soil [Waegebaert and Mey, 2019]. Planting is done during spring with 1 or two rhizomes/m$^2$. Planting is a sensitive period and therefore tillage, moisture content, and weed control are important in this phase [Waegebaert and Mey, 2019]. After three years of establishment, harvesting can be done once a year in autumn or spring. The yield varies from 20 to 50 ton ha$^{-1}$ yr$^{-1}$ for early harvest, and from 10 to 30 ton ha$^{-1}$ yr$^{-1}$ for late harvest [Ben Fradj et al., 2020]. In Flanders, the expected dry matter yield is 20 ton ha$^{-1}$ [Waegebaert and Mey, 2019].

Miscanthus has low soil nutrients and pesticides requirements, and can be grown in marginal lands [Waegebaert and Mey, 2019, Lewandowski et al., 2000], but it is sensitive to compacted soils and flooding. The crop performs better at water levels lower than 20 cm below the soil surface [Bestman et al., 2019]. Overall, the rapid growth and high biomass yield after establishment, the low maintenance and the ease of cultivation of Miscanthus make it a good choice as a biofuel, outperforming maize and other bioenergy crops [Waegebaert and Mey, 2019, SEIL, 2012].

### Potential uses

Currently, the most profitable use for miscanthus is their use as biofuel for heat and electricity production. The limited fossil fuel availability and high energy prices open new opportunities for energy crops like miscanthus [Waegebaert and Mey, 2019, Muylle et al., 2015, Ben Fradj et al., 2020]. Under Flemish conditions, miscanthus can be more productive than other wet crops like reed and willow, for bio-ethanol production [Hulle et al., 2012]. Miscanthus has a high energy balance compared to other crops like sugar beet or rapeseed. The thick stems can be converted in woody material and used for burning. 1 ton can provide 500 l of heating oil, with low $CO_2$ emissions. After combustion, the ashes can serve as soil fertilizer [Waegebaert and Mey, 2019]. For this purpose, harvesting of the thick stems is done in winter or early spring, when the amount of potassium and chloride present in the leaves is low and the moisture content is between 15 to 20 %, avoiding further drying steps [Waegebaert and Mey, 2019]. Currently, farmers in Flanders are advised to plant Miscanthus whenever is possible in very wet or poor soils, where other arable crops like maize are not suitable. An example is the farm Hog Ter Vrijlegem in Flemish Brabant, which has around 1.2 ha of Miscanthus for heat production and subsequent use in the farm. Production of energy even at local scale can be advantageous taking into account that all the oil and natural gas supply in Belgium is imported, and that a strong emphasis is put in Belgium to accelerate its clean energy transition [IEA, 2022].

Another potential use is construction material for insulation purposes, fiber boards, paper and cardboard, due to its fiber strength and insulating properties [Waegebaert and Mey, 2019]. Lime-miscanthus mixtures can be used in the construction of walls, floors and roofs for heating purposes. Miscanthus chips can be also used instead of sand and gravel in new porous-concrete type materials ( e.g. “xiriton”). This new material benefits from the lightness of the fibers and the temperature and sound insulation characteristics [Waegebaert and Mey, 2019].

The thick and dry stems (chips) of Miscanthus are good for using in mulching, chicken stables or bedding materials for dairy cows or poultry. Miscanthus chips have high absorption capacity, they dry fast and do not stick together, also can absorb nitrogen which reduces bad odors from ammonia [Waegebaert and Mey, 2019]. Compared to straw, Miscanthus chips have no differences regarding bacterial growth or animal comfort [Van Weyenberg et al., 2016]. In the case of mulching, miscanthus chips are also a good option, for controlling weed growth and absorbing excess moisture.

There is a growing interest of obtaining more sustainable horticultural substrates (e.g. Horti-BlueC), where peat can be eliminated or at least replaced. Miscanthus fibers can be used to partially replace peat in growing media after different physical and chemical treatments. Processed plant fibers present low nitrogen fixation and become easily colonized by fungal biocontrol strains, which reduce the need for chemical crop protection [Vandecasteele et al., 2018].

Miscanthus can also provide environmental services like carbon sequestration and low greenhouse emissions [Waegebaert and Mey, 2019, Ben Fradj et al., 2020]. Since the crop requires water levels below the soil surface, there is no risk of methane emissions like in cattail cultivation. When the crop is used as a construction material, the carbon remains fixed during the lifetime of the material, which offer possibilities for carbon sequestration [Bestman et al., 2019]. Finally, miscanthus has an efficient nutrient uptake due to its perennial rhizome system, which contains most of the plant nutrients, and in general does not need nitrogen fertilization [Waegebaert and Mey, 2019].

### Limitations

There is only 20000 ha of Miscanthus in the EU grown for commercial purposes, half of this is in the UK [Lewandowski et al., 2016]. In Belgium, there were about 268 ha declared in Belgium by 2018 [Waegebaert and Mey, 2019]. The high investments requirements and the lack of available markets make farmers hesitant to cultivate this crop and just local use is possible. Compared to other common crops, miscanthus is very labour intensive, and also biomass processing for energy production requires more management and follow-up than ordinary fuel or oil boilers [Waegebaert and Mey, 2019].

**Examples**

- Promis©Belux (Belgium): supply miscanthus rhizomes and offer full guidance during cultivation and purchase of production.
- Miscanthus Nursery Limited (MNL) (UK): 36 farmer grower shareholders grow fresh rhizome for propagation, harvest and trade. They negotiate themselves end use contracts as well as give advise on all aspects of growing and marketing Miscanthus.

### Peat moss (sphagnum sp.)

Figure 9.11.: Sphagnum field trial in the project PROSUGA at the University of Greifswald [Greifswald Mire Center, 2020]

Sphagnum moss is commonly found in swampy areas, it has a great capacity to hold water of up to 16-26 times its own dry weight [Duursen et al., 2016]. After hundred of years, the slowly humified old peat moss formed the sphagnum peat. Sphagnum farming is the cultivation of this peat moss, for renewable biomass production, peat conservation and reduction of greenhouse gases emissions [Greifswald Mire Center, 2020]. Peat moss can potentially be cultivated in degraded bog sites which currently are used for grassland, and can provide a sustainable and climate-friendly land use on these bogs, while producing a substitute for peat in horticultural growing media [Gaudig et al., 2017]. Yield is around 3.5 ton DM $ha^{-1}$ $yr^{-1}$ according to sphagnum farming sites in Germany [Greifswald Mire Center, 2015]. Peat moss grows at water levels of about 10 cm below ground surface and permanent and stable wet conditions are fundamental for optimal productivity. Unlike other paludicrops, nutrient-poor soils and acid conditions are preferred to avoid competition with algae or weeds, also low PH [Collins et al., 2019]. Nutrients are extracted from the water, creating an acidic environment which reduce competition with other plants but also the breakdown of the organic matter, which is the main source of GHG in peatlands [Holtuis et al., 2021]. Brackish conditions are not suitable for peat moss cultivation [IPV, 2022]. Propagation of sphagnum is done via fragments or micropropagated plants [Collins et al., 2019, Gaudig et al., 2017]. Harvesting normally can be done all the year around, as long as there are not nature conservation regulations or high water levels [Collins et al., 2019].

### Potential uses

Sphagnum is used and researched primarily for horticultural substrates and potting soils thanks to its similar properties to peat. These properties include structural stability, water retention capacity, airiness, acidity and nutrient and organic matter content. Peat moss is not very well-known but it is already been used in the orchid substrate market [Duursen et al., 2016]. Producers of agricultural and horticultural substrates are looking for peat alternatives to reduce their carbon footprint [CANAPE, 2020]. Currently this market is highly competitive because specific product specifications have to be fulfilled, which varies with sphagnum varieties [Duursen et al., 2016].

Sphagnum can also be used as decorative material in the short term in flower arrangements and other applications. There is a small but growing market in this area since production quantities, knowledge and investments requirements are clear [Duursen et al., 2016]. For this purpose, water retention and greenery are fundamental. Other uses include wastewater filtering, biodegradable adsorbent of hydrocarbons, and lining of terrariums [CANAPE, 2020].

### Limitations

As the other paludicrops, sphagnum cultivation limitations relies in the small market opportunities, lack of awareness of producers and consumers, and the fact that further research is needed to find optimal varieties and cultivation methods for different applications. Starting material is currently expensive and higher initial investments are required [Duursen et al., 2016] There are just limited pilot/research projects, mostly in Germany (Sphagnum Farm Barver, Ramsloh site), which are still ongoing. Also, the specific growing conditions (i.e. poor-nutrient soils, acidic conditions) does not allow the cultivation of other wet crops, which can be a limiting factor under nature protection laws.

### Examples

- Bio-Kultura: according to Duursen et al. [2016], this company uses around 20% sphagnum in their substrates.

## Reed (Phragmites australis)

Reed is the most common wetland plant worldwide, it can be found in Europe, Middle East and America. In Europe, reed is planted mainly in South Sweden, Austria and

Figure 9.12.: Common reed growing spontaneously on the banks of the canal "Vaart Leuven-Mechelen".

Estonia [Köbbing et al., 2013]. This crop has been used for centuries, either as fodder when harvested in summer, or for building material in thatching, paper production or insulation if harvested in winter [Köbbing et al., 2013]. Reed is a tall and thin grass that can reach 3 to 4 m high, the roots can grow very deep in the soil which makes the crop highly resistant to drought or water level fluctuations [Bestman et al., 2019]. The yield depends on climate, water supply, soil and nutrients and can reach up to 30 ton ha$^{-1}$ yr$^{-1}$ [Köbbing et al., 2013], although yields of around 10 ton ha$^{-1}$ yr$^{-1}$ are more realistic [Bestman et al., 2019]. In winter, nutrients are stored in the roots, allowing more stable yields during winter. In summer, nutrients distribute to above-ground biomass. Reed performs better at high (+20 cm) or relatively lower water levels (-20 cm) [Bestman et al., 2019]. During the establishment phase, reed can be vulnerable to weeds and aquatic herbivores [Geurts and Fritz, 2018].

### Potential uses

According to Köbbing et al. [2013], potential uses for reed can be divided into industrial, energy, agricultural and environmental uses. Within industrial uses, thatching is probably the most traditional use of reed thanks to their durability, flexibility and sturdiness. For this purpose, moisture content has to be lower than 18 % and therefore harvesting is done in winter where the plant is already dry. Reed used to last from 50 to 100 years, but currently this has drop to maximum 30 years as result of pollution. Another industrial use is insulation materials for walls and roofs, and panels. Here, also the leaves and leftovers from thatching can be employed since the quality required is lower. Reed has a low thermal conductivity of ($\lambda$) of 0.055 W m$^{-1}$K$^{-1}$, which is not much inferior to traditional insulation materials, and provide a high volume-to weight ratio [Bestman et al., 2019, Köbbing et al., 2013], excellent to provide an appropriate interior climate. Further, reed pulp can be used for paper production thanks to the cellulose and hemicellulose present in reed biomass. However, this application is no longer explored in Europe due to insufficient reed supply and environmental reasons [Köbbing et al., 2013].

In terms of energy uses, reed biomass can be used for combustion, biogas and biofuel production [Köbbing et al., 2013]. Winter-harvested reed with low moisture content is used for combustion and biofuel, while summer-harvested reed with high moisture is used for biogas. In winter, the nutrient and ash content in above-ground biomass is low, which is favorable against corrosion of equipment and emissions after combustion. The caloric value or energy present in reed biomass is around 14-17 MJ kg$^{-1}$ [Bestman et al., 2019, Köbbing et al., 2013], similar to wood pellets. Reed biomass occupies large volume due to its low density, therefore, compressing into pellets or briquettes is important for easy transportation and less storage requirement. A processing at local scale is also preferred. For biogas (i.e. methane) production, fresh summer reed with high nutrient content is required, since the process involves anaerobic digestion by bacteria. The methane then serves for heat and electricity production. In biofuel production, glucose is extracted from reed cellulose after pre-treatments. This use is still in research [Köbbing et al., 2013].

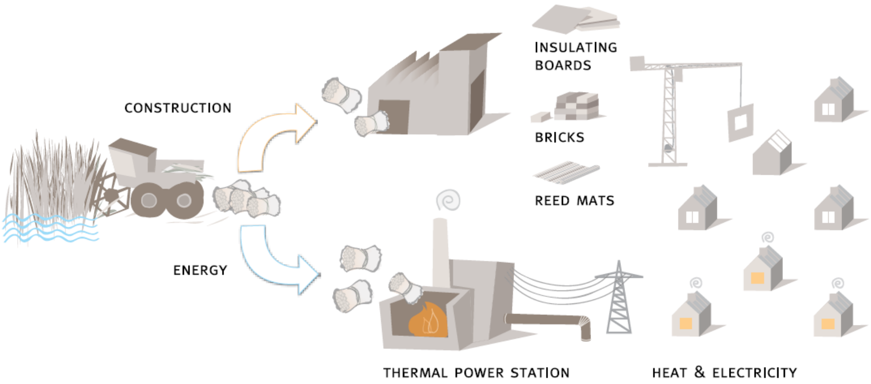

Figure 9.13.: Energy cycle from cultivation to end-product for reed [Greifswald Mire Center, 2015]

Agricultural uses include fodder and fertilizers. Reed harvested in summer has a moderate crude protein content of around 60-115 g kg$^{-1}$ DM [Bestman et al., 2019], and high nitrogen, potassium and manganese content, which make reed a highly nutritious fodder for livestock [Köbbing et al., 2013]. Alternatively, winter-reed can be used as animal bedding. For using as fertilizer, reed is first chopped and composted together with garden waste to increase nitrogen content. Also, the remains from biogas production is ready available for plants [Köbbing et al., 2013].

Reed can also offer environmental services such as water purification, water storage and peat conservation. These services can be easily combined with other productive uses. Reed production for fodder or biogas can also serve for purifying nutrient-polluted waters. For a yield of minimum 10 ton DM ha$^{-1}$, carbon sequestration can be 4-14 ton C, and nutrient removal 150–600 kg N ha$^{-1}$, 10–60 kg P ha$^{-1}$, and 50–350 kg K ha$^{-1}$ [Geurts et al., 2020]. Reed can promote peat formation and conservation when it grows over it. Since reed is highly resistant to flooded conditions, it can be also used along with water storage projects [Bestman et al., 2019].

### Limitations

Reed cultivation faces similar limitations as other paludicrops. Further research is still needed to optimize cultivation and nutrient dynamics for a long-term perspective of paludiculture. Additionally, some potential uses like paper production have been forgotten and cannot be explored again due to low supply. Some conflicts can also appear between nature conservation and energy production [Becker et al., 2020].

### Examples

- Biomass heating plant Malchin (Germany): Since 2014, reed and sedges from the rewetted meadows at lake Kummerow, Mecklenburg-Vorpommern, is used for heat production, which is used in the Malchin city.

## Willow (Salix sp.)

Figure 9.14.: Willow tree. Source: Natuurpunt

Willow trees or shrubs are widespread in Flanders in the borders between land and water. There are many varieties and species, gradually more tolerant to diseases and with higher yields [Natuurpunt, 2022, Larsen et al., 2016]. They can grow typically at flood zones along rivers or in nutrient-poor and moist areas. Willow can grow in water levels ranging from -40 to 20 cm, but lower water levels are preferred [Collins et al., 2019]. They can withstand short periods of flooding (less than 10 weeks), followed by dry period in which recovery can take place [Bestman et al., 2019]. The typical specie is white willow (salix alba), this can grow up to 20 m high [Natuurpunt, 2022]. Propagation is done with twigs cuttings of 20-30 cm and planting with a density of 16000 plant ha$^{-1}$. Yields are on average 4.3 ton DM ha$^{-1}$, which depends on the tree age, and can decrease if water levels are too high [Bestman et al., 2019]. Willow can be more advantageous than other wet crops since they can grow in poor soils [Larsen et al., 2016].

### Potential uses

More feasible uses for willow include agroforestry and other profitable uses like animal feed and water storage purposes. Twigs, young branches and green leaves can be used as food for cows, goats and sheep as they contain a crude protein content up to 190 g $kg^{-1}$ DM, high selenium and zinc levels, which make willow good for roughage [Bestman et al., 2019]. Willow can also serve as shelter for free-range chickens to protect them against wind, rain, bright sunlight or predators [Bracke et al., 2020]. This is also beneficial for improving meat and egg quality and physical health of chickens. Other uses include wood fiber for energy production, due their high caloric value of 18 MJ $kg^{-1}$ [Bestman et al., 2019].

Willow can be grown in temporary water storage areas (i.e. in winter), as long as flooding periods are followed with dry periods [Bestman et al., 2019]. According to LIFE Peat Restore, willow can also serve as a buffer for wet nature and agricultural lands, to prevent negative effect from both sides, and also provide flowers for many pollinators such as solitary bees, honeybees and hoverflies. These environmental uses can be easily combined with productive uses.

### Limitations

The major limitations are the lack of regulations, work complexity and lack of knowledge about managing the trees. Areas with willow trees can be identified as forest instead of agricultural land, which can devaluate its price. Also, weed control is required during establishment of willow, which increases initial investment costs [Luske, 2014].

### Examples

- AGFORWARD WP5 (The Netherlands): Willow for cattle and goats
- LEGCOMBIO (Belgium): Willow for chicken shelter

## 9.5. Business models

Table 9.3 describe some possible business models for Flanders involving paludiculture in rewetted areas, which are in research of already implemented in other countries. Further research is certainly needed.

Table 9.3.: Possible business models in Flanders

| Business model | Description | Pros/Cons | Source |
|---|---|---|---|

| | | | |
|---|---|---|---|
| Cattle in wet meadows | Cattle adapted to wet conditions (i.e. water buffalo) for meat and milk production can be combined with paludiculture (e.g. reed) for animal feed or biofuel. | + Good for cattle farmers, who already have experience. Low investments in machinery.<br>- Scientific support for monitoring water levels | [Collins et al., 2019]<br>[Greifswald Mire Center, 2015]<br>[Ziegler et al., 2021] |
| Multi-purpose use of rewetted grasslands | Paludiculture and natural grassland can be used for compost, animal feed and building materials, combined with environmental services. | + Just minor changes in biomass harvesting. Biomass can serve for different applications according to the farmers' choice.<br>-Transport cost to compost plants are high. | [Collins et al., 2019]<br>[Compeer and Mattheij, 2019] |
| Growing horticultural substrates | Suitable for raised bogs where sphagnum can be grown | + High demand for growing substrates and peat alternatives in the market.<br>- High costs for adapted machinery or hydrological infrastructure.<br>- Farmers should do market profitability research. | [Collins et al., 2019] |
| Nature conservation | Paludiculture can be used in buffer zones or nature areas for CO2 emissions reduction and biodiversity recovery. | + Several and important environmental services<br>- Biomass cannot be harvested at any time, except for sphagnum. | [Collins et al., 2019] |

| | | | |
|---|---|---|---|
| Biomass for energy production | Paludicrops like cattail, miscanthus or reed can be used for combustion. | + Useful for low-quality biomass.<br>- Heating plant has to be close to the farms.<br>- Adaptation in machinery is required. | [Collins et al., 2019]<br>[Greifswald Mire Center, 2015] |
| Agroforestry | Trees like willow adapted to wet conditions can provide food and shelter for animals. | + Several productive and environmental services that can be marketed to generate extra income and/or diversification.<br>- Land price devaluation due to lack of regulations. | [Bracke et al., 2020]<br>[Luske, 2014] |

## 9.6. Further research

The follow recommendations for further research in Flanders are based largely on Ziegler et al. [2021] and results of several pilot projects already exposed in The Netherlands and Germany.

- Look for collaboration with other companies and organizations who may be interested in testing and further developing paludiculture.
- Establish long-term pilots or demonstrations projects to explore the unique properties of wet crops and prove their viability in Flanders. These tests can also serve to calibrate crop models for these wet crops.
- Adopt the stakeholder participation approach in research projects and new initiatives from the beginning, in order to include their needs and knowledge, to rise awareness about climate change, and to create a new culture of sustainable farming.
- Use the business models implemented of other countries as an example to create adapted revenue models for Flanders. Explore also other business models suitable for rewetted lands like the use of grass in wet conditions for energy production or compost.
- Make an economical study of the most fitting paludicrops, from cultivation to the end-use product, for directing interested parties on a transition to “wet agriculture”, and encouraging them to make that transition.

- Develop incentives and policies to stimulate paludiculture investments and more diverse applications, which in turn will increase revenues. Subsidies and payments for ecosystem services (e.g. carbon credits) and services related to wetlands should be implemented.

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# 10. Conclusions

The main objective of the study was to evaluate the effect of rising groundwater levels on agricultural production in Flanders and to provide a modeling tool that policymakers and researchers can easily use to predict those effects. We conducted an extensive literature review on the impact of too-wet conditions on agriculture and nutrient mobilization, and on the opportunities and obstacles for wet agriculture (paludiculture) in Flanders. We applied the SWAP-WOFOST model to the entire Flemish agricultural area for five conventional crops: grass, fodder maize, potato, winter wheat, and sugar beet, using public data layers. We used the agricultural area around De Zegge-Mosselgoren as an example of how the model can also be used locally to estimate the impact of groundwater management on agriculture. The model and corresponding documentation are freely available in the PEILIMPACT github repository.

Based on this study, the following main conclusions can be drawn:

## Literature review

- Too shallow groundwater levels cause yield reduction since most of the arable crops are sensitive to oxygen stress, and wet conditions may lead to weed, disease, and pest proliferation. It also affects agricultural practices involving the use of machinery, because wet soils have less carrying capacity.

  For example, the land can be too wet for plowing or harvesting, leading to delays in sowing or harvesting.

- Soil texture largely determines how much water can be stored in the soil and how much of it is available to plants. It also determines how roots develop and thus to what extent plants gain access to soil water.

- Too wet conditions lead to insufficient oxygen in the soil, which drastically changes its physical and electrochemical characteristics. In these new conditions, adsorbed phosphorus and organic carbon substances are more mobile and can be diffused to surface waters or groundwater.

- Wet farming or “Paludiculture” can be an alternative to conventional agriculture in areas where rewetting projects are foreseen, with several economic and ecological benefits. The small-scale agricultural areas in Flanders can be a limiting factor for paludiculture to become profitable at industrial levels. However, it could be more suitable on a local scale. Research/pilot projects would aid in determining if paludiculture in all can offer a sufficiently robust and profitable revenue model in the Flemish conditions.

## Regional analysis & Plausibility check

- Regionally, droughts cause higher yield reduction in crops than wet conditions, and among crops, potato, silage maize, and sugar beet are more sensitive to water stress compared to grass and winter wheat. The high variability of weather conditions, soil and groundwater levels mostly determine the temporal and spatial yield variability. Yields are normally higher in areas with sandy loam and loamy soils than in clayey soils due to fewer root growth restrictions by the soil.
- Average groundwater levels less than 1 m below the soil surface generally have a negative effect on yield in wet years, but benefit in dry years. The optimal groundwater level is on average 1 m in normal and dry years, and 1.5 m in wet years. These thresholds can widely change due to variability introduced by crops, soils, groundwater dynamics and weather. It is therefore advisable to take this complexity into account and not to rely on these general guidelines in concrete cases.
- The plausibility check of the model showed that it is able to describe general multi-annual trends in average crop yield, despite many limitations in the input data and model simplifications. However, the model tends to underestimate the crop yield, except for grass. The underestimation was large for sugar beet. This can be attributed to the use of outdated crop parameters, missing site-specific field management information (e.g. irrigation), a limited yield data set for validation, and the uncertain difference between harvest results from test plots compared to farmer's fields.

## Case study "De Zegge-Mosselgoren"

The model was applied to the study case De Zegge, for grass and silage maize, where the nature reserves De Zegge and Mosselgoren are situated and surrounded by agricultural lands.

- Shallow groundwater levels in the study area benefit crop production in dry years, but cause oxygen stress in crops in wet and slightly wet years. The total yield reduction caused by too dry or too wet conditions, and by indirect effects (e.g. less workability, harvest delays) is normally no higher than 30 % for the two crops in consideration, for the current climate and water management in the area.
- Currently, field management and groundwater level control in the area are optimal for the cultivation of grass and silage maize, especially in dry years. Detailed conclusions of the impact of rising groundwater levels due to rewetting strategies on agriculture in the study area could not be drawn from this study, since groundwater level scenarios from the ecohydrological study in the area were not available up to the conclusion of this project.

# 11. Recommendations

The current model framework is freely available and can therefore in principle be used by anyone for new policy questions or impact studies. However, it is still necessary to have basic knowledge of programming in order to easily use the tools available on Github. Some knowledge of soil-plant interactions and crop modeling is also needed to correctly assess the current shortcomings. In order to give governments or farmers the opportunity to work with this tool themselves, a translation is still needed to the needs and background of these end users. Before this translation can take place, it is advisable to work on a number of shortcomings in the model itself and its input in the short term.

The model framework with SWAP-WOFOST and open data layers for Flanders was demonstrated to be good enough to simulate crop yield even with limited input data and model simplifications. However, there is certainly room for improvement, especially with regard to sugar beet simulations.

The yield database contains valuable but limited data, mostly from variety trials located in West- and East-Flanders. Usually, no data is available on groundwater levels. It is necessary to include **existing yield data from trials throughout Flanders** in the database, preferably through structured collaboration with all trial centers. In addition, **targeted field experiments under different known hydrological conditions** would be welcome. Measurements of soil and crop growth would have to take place there, with special attention to drought and oxygen stress for the most important crops in Flanders. In this way, the crop parameters can be updated to recent varieties under Flemish conditions, and site-specific management data and environmental factors can be used for model validation, where significant improvements in the simulations can be expected.

Models are only a representation of reality, and input data and parameters also inherently have uncertainty. Only old soil properties derived from the Aardewerk database and the Belgian soil map were available at the regional scale. The maximum rooting depth allowed by the soil was approximated based on clay content and calculated bulk density. In reality, soil compaction might affect rooting depth in agricultural fields. **It would be appropriate to revise the rooting depth for each soil type and include soil compaction when available.** A project is currently being financed by the Environment Department of the Flemish government, namely ”Inschatting van de vochtretentiecapaciteit van bodems op basis van bodem- en landgebruikskenmerken”, which was awarded to Antea Belgium, Ghent University and the Soil Service of Belgium, which will be ready in February 2025. The aim of this project is to determine current pedotransfer functions for soil moisture characteristics for Flanders through easily measurable soil parameters. This information will be very valuable to improve the current soil parameters in the model.

The characterization of the seasonal groundwater level fluctuations was based on a simple sinus function and maps of the average highest groundwater level (GHG) and average lowest groundwater level (GLG). These fluctuations can be also estimated from the drainage classes presented on the Belgian soil map, but they are already outdated and therefore less reliable. A project is currently underway, financed by the Environment Department of the Flemish government and carried out by, among others, Antea group, namely "Update drainageklassen van de bodemkaart". This project should provide an **updated map of groundwater tables and drainage classes** that can also be used as input for the model in this project. In addition, there is a need for a **regional groundwater model that describes phreatic groundwater dynamics**, which is crucial to predict its impact on the growth of arable crops. The ongoing research project TURQUOISE, financed by FWO SBO, may be able to take its first steps here.

Increasing the resilience to the effects of climate change through restoration/remediation of drained wetlands to promote infiltration and water storage is a major goal in Flanders. Farmers and policy-makers would need to adapt to the impacts of excessive soil water in agricultural areas close to restored wetlands, so nature reserves and (adapted) agriculture can coexist. The case study at De Zegge-Mosselgoren is a good example of how these two land uses influence each other and how conflicts can arise. The developed model instruments can now be used with local data and by including all relevant factors (agricultural practices, specific water management, ...). Future research in these types of areas can then estimate the consequences of specific rewetting scenarios for agricultural plots. However, it would also be good to conduct a number of **pilot studies in which the impact is also monitored in reality**, so that the model can be further validated and systematically improved.

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