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Paludiculture pilots and experiments with focus on cattail and reed in the Netherlands

Technical report

CINDERELLA project

FACCE-JPI ERA-NET Plus on Climate Smart Agriculture

Radboud University Nijmegen
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Summary

In 2015 the international, transdisciplinary research project CINDERELLA, funded by ERA-NET FACCE-JPI, was started to investigate the productive use of rewetted peatlands and the simultaneous restoration of ecosystem services, including reduction of greenhouse gas (GHG) emissions and land subsidence, water and nutrient retention, and water purification. The main objective was to extend the scientific base for a sustainable, productive land use of wet peatlands and making alternative uses accessible to farmers and land authorities. “Paludiculture” is a form of productive land use that allows rewetted peatlands to produce food, fiber and energy. Typical crops grown in paludicultures (“paludicrops”) are perennial crops that thrive on waterlogged or flooded soils, for example *Sphagnum* (peat moss), *Phragmites* (reed), *Typha* (cattail), *Salix* (willow) and *Zizania* (wild rice).

In this report, an overview of existing and future paludiculture pilots is given, with the main focus on Dutch pilots with *Typha* and *Phragmites*. The most important experiences and results from these pilots are presented and information is given about the experimental setting, species and plant parts used, planting density and method, soil type, soil removal, scale, water level range, water source, and plant performance. Success factors and failures are discussed in the light of existing knowledge found in the international literature.

Water management should maintain waterlogged conditions during germination and facilitate prolonged surface flooding of 5-30 cm depending on plant height. Drying of the soil surface including water levels < 10 cm below the soil surface should be avoided to prevent drought damage to young plants and seedlings, and to prevent shading stress from grass-like weeds. Well established *Typha* cultures can probably cope with water levels of 30 cm below the soil surface when lasting for a few weeks only, whereas *Phragmites* stands can tolerate more surface drying and drought.

Before the establishment of paludicrops the remaining grass and/or grass sod (upper 5 cm) should be removed or left to decompose after low mowing/milling. Topsoil recycling can be beneficial to build infrastructure like small dikes and elevated tracks, further improvement of the GHG balance or raising surface levels of neighboring fields. Removing the topsoil can also reduce the availability of phosphorus, and partly nitrogen and potassium, which in turn can lead to nutrient deficiency in highly productive paludicultures and therefore influence green biomass use in summer. However, top soil removal is certainly not required for the planting of paludicrops.

The establishment of *Typha* is successful when planting (commercially grown) young plants of 25-50 cm length or field collected shoot bases with growing buds at densities of 5'000-10'000 plants per ha, provided that waterlogged conditions and shallow flooding (0-20 cm) can be maintained. Establishing *Typha* cultures from seeds is technically feasible, but only cost-effective when water levels can be managed very accurate (0-5 cm) in the first weeks of cultivation. Seeding to establish *Phragmites* requires an even narrower hydro-regime, so this seems more suitable for low-cost paludiculture fields where species richness is amongst the main goals. The establishment of *Phragmites* is most successful when rhizomes are planted. *Typha* and *Phragmites* plants and rhizomes can be planted both by hand and by machines, depending on the scale. A density of up to 1 plant per m² (*Typha*) or up to 4 rhizomes per m² (*Phragmites*) is sufficient under optimal site conditions.

Typha and *Phragmites* can grow under a wide range of abiotic conditions and nutrient levels, but highest productivity is reached under nutrient-rich conditions, especially when nutrients are in balance. In wet conditions, nitrogen becomes the most limiting factor for growth. A pH below 4 to

4.5 can significantly reduce productivity of *Typha* and *Phragmites*. *Phragmites* is also sensitive to accumulation of anaerobic toxins like sulfide, ammonium, and organic acids.

Typha and *Phragmites* are most prone to weeds and aquatic herbivores in the establishment phase. High water levels will prevent weed growth, whereas temporary water level drawdowns and fences may protect paludicrops against grazing. Insect herbivory seems to have less impact in most cases.

Paludicrops can be harvested in different seasons, depending on the wide range of biomass applications. It is a trade-off between moisture content, yield, and optimal, sustainable nutrient removal from surface water and soil. Sustainable yields of 10-25 ton dm ha⁻¹ a⁻¹ are possible, and *Typha* biomass can even be harvested twice a year under ideal circumstances. Several harvesting machines for harvesting biomass from wet soils are already available.

The establishment costs of paludiculture depend on site conditions, scale, lifetime, available (water) infrastructure, and the purpose of paludiculture in each specific case. There is an urgent need for policy facilitation, further market development, and well-documented, large-scale, and long-term pilots. Codes of good agricultural practice need to be defined for peat soils, including higher water tables and the accounting for provided ecosystem services, to achieve implementation of climate smart agriculture on organic soils.

1 Introduction

1.1 Paludiculture

CHRISTIAN FRITZ & JEROEN GEURTS (RADBOD UNIVERSITY NIJMEGEN)

What is paludiculture and what are paludicrops?

Paludiculture (lat. *palus* - swamp) is a form of productive land use that allows rewetted peatlands to produce food, fiber and energy (Wichtmann & Joosten 2007; Wichtmann et al. 2010, Giannini et al. 2015). On rewetted peat, paludiculture facilitates the transition to flood adapted crop species (reed, cattail, reed canary grass, sedges, peat moss and others), harvesting machinery and biomass utilisation options (Wichtmann et al. 2016). Annual groundwater levels close to or above the surface (+/- 20 cm) conserve soil productivity by replacing drainage-based conventional peatland use, which leads to large emissions of greenhouse gases, nutrients to the surface water and abandonment of peatlands after years of peat soil degradation (Zak et al. 2010; Biancalani & Avagyan 2014; Tiemeyer et al. 2016). Research has shown that paludiculture allows the re-establishment and maintenance of ecosystem services of wet peatlands such as carbon sequestration and storage, water and nutrient retention, as well as local climate cooling and habitat provision for rare species (Biancalani & Avagyan 2014; Joosten et al. 2016; Wichtmann et al. 2016, Gaudig et al. 2017; Günther et al. 2015, 2017; Temmink et al 2017; Zak et al. 2017).

Wichtmann et al. (2016) argue that paludiculture implies an agricultural paradigm shift. Instead of draining them, peatlands are used under peat-conserving permanent wet conditions. Deeply drained and highly degraded peatlands have the greatest need for action from an environmental point of view, and provide the largest land potential. The implementation of paludiculture is the best choice for degraded peatlands.

Paludiculture is a worldwide applicable land management system to continue land use on rewetted degraded peatlands. Various plants can be cultivated profitable under wet conditions. Globally, paludiculture may also be a land use alternative for natural peatlands particular for regions where the increasing demand for productive land drives the drainage. Because of their vulnerable ecosystem services, pristine peatlands should be protected entirely. If land use on pristine mires is unavoidable, paludiculture should always be given preference over drainage-based land use (Joosten et al. 2012). The World Food Programme (WFP) regards paludiculture on rewetted peatlands as a high potential form of climate smart agriculture on productive peatlands (Biancalani & Avagyan 2014). For Central and Western Europe the implementation of paludiculture is likely to focus on rewetted peatlands to restore ecosystem services and to form a wet/rewetted buffer zone adjacent to restored and semi-natural mires.

Typical crops grown in paludicultures (“paludicrops”) are perennial crops that thrive on waterlogged soils (e.g. *Sphagnum* – peat moss (see Box 1), *Phragmites* – reed, *Carex* - sedge) and some of them may even benefit from prolonged flooding, e.g. cattail (*Typha*) and wild rice (*Zizania*). Obligatory paludicrops such as *Sphagnum* and *Typha* suffer production losses from drainage and soil moisture deficits (Gaudig 2017; Li et al. 2004). Flood adapted crops and plants that prefer drained conditions (water levels 50 to 20 cm below the surface) but can stand periods of flooding (e.g. *Phalaris*, *Vaccinum*, *Salix*, *Miscanthus*, *Arundo*, most grasses from *Poacea*-family) can be either used in paludiculture fields or drained mineral soils and peat soils (Abel et al. 2013, Wichtmann et al. 2016).

Annual wet grains (e.g. *Oryza*, *Zizania*) require intensive tillage and pesticide use (Oelke et al. 1997; Crepeau & Kuivila 2000; Mikha & Rice 2004; Singh et al. 2009). Similarly, slow growing plants (e.g. *Vaccinium*) are often outcompeted by invasive grasses and require pesticides and intensive mechanical weed control for viable crop production. Both tillage and pesticides conflict with the provision of ecosystem services such as carbon storage, water purification and water storage on paludiculture fields. Therefore, this report concentrates on perennial paludicrops with preference for high water tables.

Limits of drainage-based land use on peatlands

Conventional agriculture and forestry on drained peatlands cause peat degradation, subsidence (up to 2 cm annually), enormous greenhouse gas (GHG) emissions (20-40 t CO₂ per ha and year annually) and eventually often loss of productive land (Joosten 2015; Leifeld & Menichetti 2018). Subsidence and erosion of the peat soil provoke insufficient drainage, ponding water following soil compaction and drought prone top soils due to the hydrophobic nature of degraded peat (Zeitz & Veltz 2002; Kechavarzi et al. 2010; Joosten et al. 2012; Wallor & Zeitz 2016; Joosten et al. 2017). These adverse soil conditions raise costs of water management including a higher water demand for irrigation (Regional Water Authority Hunze en Aa's 2018; STOWA Delta factsheet 2018).

Drained peatlands lose – depending on the climate and intensity of use – some millimeters up to several centimeters of height per year through peat oxidation (Berglund & Berglund 2010). These losses are accelerated by ploughing and by addition of lime and fertilizers (which increase peat oxidation) and by wind and water erosion (by which bare peat is blown or washed away). The resulting lowering of the surface necessitates – in case of continued conventional exploitation – a continuous deepening of the drainage ditches. This again enhances peat oxidation, surface lowering, ditch deepening, etc. in what is known as ‘the vicious circle of peatland utilization’. The continuously lowering surface makes gravity drainage increasingly difficult and necessitates more and more complex and expensive hydrological management to keep the areas drained and conventional agriculture possible. In coastal peatlands subsidence increases the risk of floods and salt water intrusion, which is especially relevant in the light of climate change induced sea-level rise (Joosten et al. 2012; Hooijer et al. 2012).

Critical in the light of climate change adaptation is also the loss of water storage and hydrological buffering capacity at the landscape scale (Joosten et al. 2016). In drier summers and/or more continental climates, peat shrinkage and swelling as a result of frequent water level fluctuations cause the formation of blocks and fissures in the drained peat. This fissuring impedes capillary water flow and leads to even more frequent and deeper drying out of the soil. Activity of soil organisms then develop a loose, fine-grained topsoil that in the end may become totally hydrophobic, so that a few decades after initial drainage agriculture becomes impossible on the remaining black deserts (Joosten et al. 2012). Peatland drainage also leads to poorer water quality, as nutrient sinks (water purification by nutrient filtering, sedimentation and denitrification) change to nutrient sources (Verhagen et al. 2009; Zak et al. 2010). Also biodiversity suffers severely from peatland drainage, both at the species and at the ecosystem and landscape level (Joosten 2015). Rewetting reduces these effects and simultaneously restores other ecosystem services including water and nutrient retention, water purification, flood control and mesoclimatic cooling.

1.2 Greenhouse gas emissions from paludicultures compared to drained peatlands

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Peatlands soils consist of the largest carbon stocks per hectare (Gorham 1991; Joosten et al. 2012, Yu 2012; Leifeld 2013; Arets et al. 2018). Drainage, fire and peat excavation (fossil substrate production) convert peat carbon stocks into carbon dioxide (CO₂). Substantial emissions of nitrous oxide (N₂O) further impact the climate on fertilized drained peat soils and augmented methane (CH₄) emissions are related to drainage ditches, which can cover up to 20% of peatlands used for agriculture (Schrier-Uijl et al. 2014). In contrast, intact peatlands with water levels close or above the surface sequester CO₂ (peat formation) at rates that equal natural methane emissions resulting in climate neutral conservation of the largest terrestrial carbon stores (Joosten et al. 2012; Van den Berg et al 2016; Wilson et al. 2016; Leifeld & Menchetti 2018).

To estimate the climate mitigation potential of paludicultures total greenhouse gas (GHG) emissions of a reference (e.g. drained grassland, 4/5-cuts and fertilized which is typical for the Netherlands and N-Germany) are subtracted from GHG emissions found for vegetation that is dominated by paludicrops.

Greenhouse gas emissions from the reference, drained peatlands, are high (Schrier-Uijl et al. 2014; Wilson et al. 2016). Well-drained and well-fertilized (intensively managed) grasslands emit substantial amounts of CO₂ emissions (typical range 25-30 t CO₂-eq. ha⁻¹ a⁻¹) and variable amounts of N₂O (typical range 1.5-7 t CO₂-eq. ha⁻¹ a⁻¹ from nitrogen inputs (Schrier-Uijl et al. 2014; Wilson et al. 2016; Vonk et al. 2018). Drained peatlands with moderate to low management intensity (e.g. low livestock density, fertilization rate, no topsoil milling) seem to have 5-6 t CO₂-eq. ha⁻¹ a⁻¹ lower greenhouse gas emissions compared to intensively managed grasslands (Wilson et al. 2016). Shallow peatlands and organic soils (Dutch: moerige gronden) show in several cases substantially higher CO₂ emissions than intensively managed grasslands on peat soils (> 40 cm thick) suggesting that high soil density and mineral-rich silt (Dutch: lutum) may even increase carbon mineralization rates on a hectare scale in shallow peatlands (Eickenscheidt et al. 2015; Pohl et al. 2015; Van den Berg et al. 2018).

Rewetting of peatlands results in a net reduction of the cumulative global warming potential of (CO₂, CH₄, N₂O), the main 3 greenhouse gases in the agricultural sector (Hiraishi 2014, Schrier-Uijl et al. 2014; Wilson et al. 2016). Water levels close to the surface reduce CO₂ emissions and N₂O emissions to a larger extent than CH₄ emissions are increased by anoxic conditions (Couwenberg et al. 2011; Wilson et al. 2016; Leifeld & Menchetti 2018). High to very high CH₄ emissions are reported from agricultural fields that became flooded where standing crop (i.e. easily degradable biomass) and carbon/nutrient rich surface water stimulate algae growth and thereby methane production (Augustin & Meerbach 2008; Gelbrecht et al. 2008; Couwenberg et al. *subm.*; Vroom et al. *in prep.*). Interestingly, a number of plants adapted to wet soils (e.g. paludiculture crops, cushion plants) can substantially reduce CH₄ production in the soil by creating zones with an increased redox potential, which can outweigh the increase in soil methane ventilation (‘shunt’-effect) by vascular plants (Fritz et al. 2011; Couwenberg & Fritz 2012; Bhullar et al. 2014). Further research needs to quantify the net effect of paludicrops under management (e.g. *Phragmites*, *Typha*, *Salix*, *Phalaris*, *Sphagnum*) on methane production and transport compared to flooded fields with little vegetation or easily degradable dryland/wetland plants (e.g. grasses, algae).

Phragmites and *Typha* stands emit methane at similar rates (typical range CH₄ emissions 6-14 t (t CO₂-eq. ha⁻¹ a⁻¹) as shown by field studies (Wild et al. 2001; Günther et al. 2015; van den Berg et al. 2016; Wilson et al. 2016). Higher rates are found where lateral carbon import through floating biomass, soil erosion or DOC rich surface water increases CH₄ emissions (Augustin & Meerbach 2008, Van Huissteden unpubl. data). Topsoil removal largely reduces methane production potential of rewetted soils (Harpenslager et al. 2015; Zak et al. 2018; Fritz et al. in prep.). Harvesting may potentially even reduce CH₄ emissions because harvest removes degradable litter that can largely contribute to soil methane production (Segers 1998; Karki et al 2015;). However there have been no results published on long-term effects of biomass harvesting on methane emission (Jurasinski et al. 2016).

In case of *Phragmites* high CO₂ sequestration rates (CO₂ emissions < -5 t CO₂-eq. ha⁻¹ a⁻¹, negative emission means sequestration) seem to compensate the methane release (van den Berg 2016 et al.; Jurasinski et al. 2016; Couwenberg et al. subm.). Like *Sphagnum* also *Phragmites* can sequester CO₂ by peat formation. GHG emission measurements at a *Sphagnum* farm in N-Germany (see Box 1) revealed that *Sphagnum* production fields emit close to zero CH₄ emission and sequester CO₂ in litter and standing crop (amounts depend on harvesting cycles) while surrounding ditches emit substantial amounts of methane and carbon dioxide (Günther et al. 2017). Adjacent grassland/machinery tracks on elevated/draind peat levees is expected to increase CO₂ emissions by 6 t CO₂-eq. ha⁻¹ a⁻¹ (per ha *Sphagnum* farm with 40% grassland tracks). Weighing all land use types on the *Sphagnum* farm a climate neutral production of *Sphagnum* fibers for renewable horticulture substrates seems feasible (Günther et al. 2017).

N₂O emissions are negligible at water levels close to the surface (Van Beek et al. 2011; Günther et al. 2014; Wilson et al. 2016; Günther et al. 2017)

In conclusion, converting well-drained and fertilized grasslands into paludiculture fields may lower emissions from 25-31 t CO₂-eq. ha⁻¹ a⁻¹ (mainly CO₂) to 4-12 CO₂-eq. ha⁻¹ a⁻¹ (mainly CH₄) resulting in a net reduction of some 20 t CO₂-eq. ha⁻¹ a⁻¹.

1.3 Processes that drive successful establishment of a paludiculture

CHRISTIAN FRITZ & JEROEN GEURTS (RADBOD UNIVERSITY NIJMEGEN)

Which abiotic factors can conflict with establishment of paludicultures with *Phragmites* and *Typha*?

Both *Phragmites* and *Typha* are wetland helophytes that can form highly productive stands with water levels close to the surface. Helophytes root in the soil, their basal parts are submerged most of the time and their leaves and flowers grow above the water surface (Den Hartog & Segal 1964). In general, prolonged drought hampers the productivity of helophytes. However, the response to drought may differ depending on crop system (White et al. 2007; Driver et al. 2011). Both paludicrop species differ in their root system architecture that may have consequences for water uptake rates in drained, non-flooded soils. *Phragmites* forms an extensive belowground network, reaching down to 2 m depth, consisting of rhizomes, thick and fine roots developing from primordial buds located on the nodes of the rhizomes (Richert et al. 2000; Windham 2001; Asada et al. 2005). Even in riparian areas

of (semi-)desert ecosystem *Phragmites* is able to take up water from aquifers several meters below the desert soil (Yu et al. 2016). Photosynthetic activity of *Phragmites* is also quite constant within a broad water level range (Saltmarsh et al. 2006) compared to other wetland species.

In contrast, *Typha* species seem to allocate most belowground organs in the upper 15-30 cm and are generally vulnerable to top soil drying (Li et al. 2004; Wu et al. 2012). As *Typha*'s rhizomes are soft and roots are filled with aerenchyma, root growth functionally decreases as physical stress in drying soils (e.g. suction pressure, shear stress, compaction following shrinkage) increases. As a consequence, the productivity of *Typha* benefits from water levels above the surface especially during the first year of establishment: research in North America has pointed out that stabilized water levels promote *Typha* growth (Boers 2008). Similar results have been found in reedlands on the organic lake shore sediments of the Lesser Prespa Lake in Greece (Maliaka & Fritz, unpublished data). Especially seeds of *Typha* need a well-watered and muddy substrate to germinate and develop into young plants (Dubbe et al. 1988; Heinz, 2012). In contrast to young plants and early season drought, mid to late season water shortage may have little effect on *Typha* productivity as shown by studies in climates with warm summers and substantial water level drawdown (Goulden et al. 2007, Grosshans 2014, Günther et al. 2015).

Growth of young plants of *Typha* and *Phragmites* is stimulated by increased concentrations of nutrients in surface waters (Garver et al. 1988; Brix 1994; Sorrel et al. 2013). Young *Typha* plants in general benefit from N-loads that can exceed 250 kg N/ha/y (data from several experiments within Cinderella project; Box 2), which are commonly found in constructed wetlands cleaning nutrient emissions on the landscape scale (Land et al. 2016). Little research has been conducted on limitation of phosphorus and potassium (e.g. after top soil removal) at high nitrogen loads as polluted surface waters are often rich in P & K. Seeds of *Typha* and *Phragmites* also benefit from increased nutrient availability after germination (Stewart et al. 1997).

However, an excess of nutrients can have detrimental effects on seedlings and young plants. Increased external nutrient loads and internal eutrophication provoke algae growth, which causes shading and potential dieback of seedlings (Lamers et al. 2002; Lucassen et al. 2017). Accumulation of ammonium and other reduced redox-couples can reach toxic concentration for *Phragmites* (Armstrong et al. 1996; Sorrell et al. 1997; Armstrong et al. 1999; Tylova et al. 2008). Toxic effects of sulfur, iron and manganese species may play a small role for both crop species because of oxygenation of the rhizosphere as young plants already develop functional aerenchyma in their root network (Brix et al. 1992; Sorrel & Armstrong 1994).

Cold snaps and freezing temperatures can cause damage to seedlings and young plants (Brix 2003; Pratt et al. 1988). *Typha* and *Phragmites* species are more commonly found in temperate and warmer climates. Cold winters on the other hand do not limit the cultivation and growth of both crops (Brix 2003, Grace & Harrison 1986). Next to adverse climatic conditions, compacted soil layers may have adverse effects on root growth, especially for soft rhizomes of *Typha* and therefore limit the access to soil moisture and soil nutrients.

Which biotic factors can hamper paludiculture?

Herbivory can play an important negative role in the development and growth of helophytes, such as *Typha* and *Phragmites* (Lucassen et al. 2017). Geese, ducks, swans, coots, muskrats and even grass carp can significantly hamper the establishment of riparian plant species and lower their

productivity in a wide range of abiotic conditions (Veen et al. 2013; Sarneel et al. 2014). Grazed helophytes also show much higher methane emissions (Dingemans et al. 2011). Insects seem to have a minor impact on *Typha* and *Phragmites* in most cases (see paragraph 3.6).

Dense algae growth in nutrient-rich, shallow water layers can inhibit seedling growth after germination (Armstrong et al. 1999). On the other hand, full-grown *Typha* and *Phragmites* plants can produce phytotoxins that control algal growth by allelopathy (Aliotta et al. 1990; Li & Hu 2005). Bourgeois et al. (2012) found that increasing moss cover inhibited *Typha* seed germination, because of competition for light and space. Shading by weeds or trees also puts pressure on young (small) helophytes (Haslam 1971; Brix 2003). A combination of *Typha* and *Phragmites* with trees (agro-forestry paludiculture) would therefore need testing.

1.4 The CINDERELLA Project

CINDERELLA CONSORTIUM (EDITED BY CHRISTIAN FRITZ & JEROEN GEURTS)

Background information

In 2015 the international, transdisciplinary research project CINDERELLA (funded by ERA-NET FACCE-JPI) was started to investigate the productive use of rewetted peatlands and the simultaneous restoration of ecosystem services, including reduction of greenhouse gas (GHG) emissions and land subsidence, water and nutrient retention, and water purification. The reason for this was that conventional agriculture on drained peatlands causes peat degradation, subsidence and high GHG emissions. For this new concept, called paludiculture, knowledge and experience has to be gained about adapted wet crop species (e.g. *Phragmites*, *Typha*, *Sphagnum*, *Salix*), adapted planting and harvesting machinery, and innovative biomass applications.

The goals of the CINDERELLA project include maximizing biomass production in paludiculture, minimizing GHG emissions and nutrient release, incorporating ecosystem services, developing management strategies and implement them in the field, disseminating this innovative concept over Europe. The main objective is to extend the scientific base for a sustainable use of wetlands and making alternative uses accessible to farmers and land authorities.

The research approach builds on the experience and expertise of the involved partners. The University of Greifswald (Germany) is responsible for the coordination, economic analysis of land use concepts, socio-economic aspects, and biomass utilization. Aarhus University (Denmark) focusses on applied genetics of *Phragmites*, the selection of varieties of *P. australis*, *Typha* and *Arundo* (Giant Reed) for different applications, and the interaction with nutrients. Halmstad University (Sweden) investigates nutrient fluxes and nutrient retention in constructed wetlands, next to biomass utilization options (mainly biogas). The Radboud University is coordinator of the joint fieldwork campaigns and is specialized in crop-soil-water interactions (biogeochemistry), GHG emission measurements, and management support systems.

The project links information on soil-water-crops interactions as a basis for biomass productivity with genetics related to the productivity of genotypes under changing climatic conditions. The role of nutrient removal, retention and supply is taken into account to improve productivity and to address other ecosystem services.

Micro-economic studies of site management, harvest and bioenergy use potentials in various European regions are combined with Life Cycle Assessments to assess sustainability capability and the provision of ecosystem services. A review of political and legal boundary conditions shows current opportunities and constraints for large scale implementation of paludiculture and allows recommendations on how to support paludiculture.

The project involves close communication with and dissemination of project results to stakeholders (farmers, scientist, practitioners, authorities, consultants) from participating countries by demonstrating various aspects of wet peatland use at pilot sites. Also other European regions are taken into consideration to introduce wet peatland use.

Agriculture on organic soils under wet conditions is innovative. The project aim was to develop and strengthen farming techniques and economic tools to make it work as a basis for large scale implementation. With a strong science based transdisciplinary approach the project facilitates this innovative strategy to adapt to climate change – with sustainable peatland utilization becoming part of resilient agricultural regions.

Relevant work packages

In this report several work packages from the CINDERELLA project are addressed. First of all, soil conditions, nutrient loads and water levels are linked to biomass yields and nutrient content of different paludicrops on wet peat soils in several pilots and field experiments (WP 4.2). In all these cases the first focus was on bottlenecks at young plant stages and the development of growth protocols (WP 4.3). As young plants are more susceptible to stress factors than mature plants, optimization of the planting stage is crucial to avoid premature loss. Early development was investigated to compare the performance of young plants derived either from seeds, pre-cultivated seedlings, or rhizomes with growing buds. The influence of several soil treatments (incl. milling or top soil removal) on the development of young plants and the productivity of full-grown plants was also tested.

Water level management is also an important subject in this report (WP 4.4). In some field experiments water levels were manipulated and the effects of water level and water level fluctuations on nutrient availability, plant growth and productivity could be identified. In other pilots the effect of drying periods could be investigated. The results were used to determine critical water levels and fluctuations for paludicrops, which were also reported to water boards and other stakeholders on dissemination events.

Part of the pilot sites and experiments in this report were also used as core site for collaborative field work, data collection (to fill the joint database), and discussion of management options with farmers, stakeholders, and authorities (WP 5.1 and 5.2). On these sites biomass, water and soil were sampled according to protocols developed by the Radboud University. Samples were also exchanged between project partners for specific analyses. Questions about water sources, land use history, recent management, site accessibility and nutrient supply were addressed, as well as the perspectives of farmers, biomass use, and the practicable solutions for the implementation of climate smart agriculture on a larger scale. Field data that was generated by the abovementioned work packages was used to derive critical levels of water table, plant density, and soil conditions for an optimal balance between paludiculture productivity, nutrient removal and reduction of GHG emissions (WP 5.3). This is the basis for a decision support system and management guide for farmers and other stakeholders that want to start with paludiculture.

Box 1. *Sphagnum* (peat moss) projects

Sphagnum farming in Germany

RALPH TEMMINK (RADBOD UNIVERSITY)

Sphagnum farming is the cultivation of peat moss (*Sphagnum*) aiming for the production and harvest of peat moss biomass. *Sphagnum* is cultivated to obtain renewable raw material for the production of horticultural growing media. To investigate this, several projects have started in Germany since 2004: TORFMOOS, MOOSFARM, MOOSGRÜN, MOOSWEIT and MOOSzucht. Partners involved are the University of Greifswald, University of Rostock, University of Oldenburg, Torfwerk Moorkultur Ramsloh, University of Freiburg, Radboud University, Karlsruhe Institute of Technology (KIT) and the enterprise Niedersächsische Rasenkulturen (NIRA).



Pictures by Ralph Temmink, G. Block and lensescape.org.

On a former bog, near Rastede, North-Western Germany a 14 ha *Sphagnum* farm was established (4 ha in 2011 and 10 ha in 2016). The top layer of degraded peat was removed to expose the underlying hardly decomposed peat with high water holding capacity and hydrological conductivity. Two *Sphagnum* species were introduced, namely, *Sphagnum palustre* and *S. papillosum*. The water level was actively managed to obtain high and stable water levels required for high *Sphagnum* growth. During the growing seasons vascular plants were mown twice a month without removing the biomass. Biomass was harvested using a crane with long arms, which removes the moss biomass by scraping the mosses from the old peatmoss surface. A yield of 6.5 t DW ha⁻¹ y⁻¹ (from May

2013 to May 2014) can be obtained (Temmink et al. 2017), provided that pH is low, alkalinity is low, vascular plants are mown regularly, water level is high and stable, and that nutrients are available in optimal amounts (not too much nitrogen, which can impede *Sphagnum* growth). *Sphagnum* biomass can be used as a growing media in horticulture. Vascular plants like *Drosera intermedia* and *D. rotundifolia* can be used for medicinal purposes.

AddMireNL/Omhoog met het Veen: Sphagnum farming as tool for nature restoration

BAS VAN DE RIET (B-WARE RESEARCH CENTRE), NIELS HOGEWEG (PWN), EVA VAN DEN ELZEN & LEON LAMERS (RADBOD UNIVERSITY)

In the Ilperveld Nature Reserve (5 km north of Amsterdam) we applied the technique of *Sphagnum* farming for restoring ecosystem functions of drained peatlands. The project location is a small polder (8 ha) that has been in agricultural use for decades. The meadows were used for cattle grazing, groundwater tables in summer were as low as 80 cm below the surface and the grass was regularly mowed. The main aim of the project was to develop a peat-forming *Sphagnum* vegetation on former agriculturally used peat soil and concomitantly restore peatland ecosystem functions. Partners involved are Radboud University, B-WARE Research Centre and Landschap Noord-Holland. The project was financed by Provincie Noord-Holland.

During site construction the grass vegetation and top 10 cm of the peat soil was removed. As surface water in the Ilperveld is nutrient-rich and alkaline, a 2.5 ha water buffer was constructed to buffer rain water. This was applied to the *Sphagnum* fields during time of high evaporation. The water level was raised and kept stable to a few centimeters below surface level. In September we collected *Sphagnum* from a nearby donor site, chopped it into fragments and applied it on the recently sod cut fields.

Project results

1. During 4 growing seasons the vegetation development was monitored (Figure B-1). Over time the vegetation shows a fast establishment of *Sphagnum* of 90% within the first two year. Fen species, like *Drosera rotundifolia*, *Dactylorhiza majalis*, *Hydrocotyle vulgaris*, *Carex canescens* and *Peucedanum palustre*, show a steady increase over time and grassland and pioneer species disappear from the vegetation. Soft rush (*Juncus effusus*) germinated mostly from seeds that were present in the *Sphagnum* cuttings. It is abundantly present, but not dominant. Regular mowing (2(-3)x per year) seems adequate to decrease its cover.
2. After 3.5 years the *Sphagnum* vegetation created a thick layer (8-12 cm) of recently formed 'white peat', consisting of largely undecomposed light brown peat mosses (Figure B-2). It covers the former agricultural soil (nutrient-rich fossil peat), restores the hydrological properties and thereby it supports the establishment of typical fen species.
3. The greenhouse gas emissions are strongly reduced compared to a drained peat grassland nearby. The change in land use reduced the net emissions from 300-620 g CO₂-equivalents m⁻² y⁻¹ (drained reference) into -86 (net sequestration) to 94 g CO₂-equivalents m⁻² y⁻¹. After rewetting methane emissions remained very low, making CO₂ rather than methane dominant on the greenhouse gas balance.

Conclusions

The project shows that the technique of *Sphagnum* farming is suitable for restoration of a *Sphagnum*-dominated vegetation on former agriculturally peatlands.

The development of *Sphagnum* cover from plant fragments (cuttings) is fast (< 1 year) and supports several ecosystem functions: it harbours characteristic fen plants and fungal species, it restores peatland hydrology by acting as a sponge and it sequesters carbon.

Key factor for *Sphagnum* establishment and growth is water management: *Sphagnum* depends on moist conditions. The surface water in the Ilperveld Nature Reserve is alkaline (3.5 meq l⁻¹) and not suitable for

inundating the *Sphagnum* fields. For its water supply the *Sphagnum* vegetation strongly depends on precipitation.

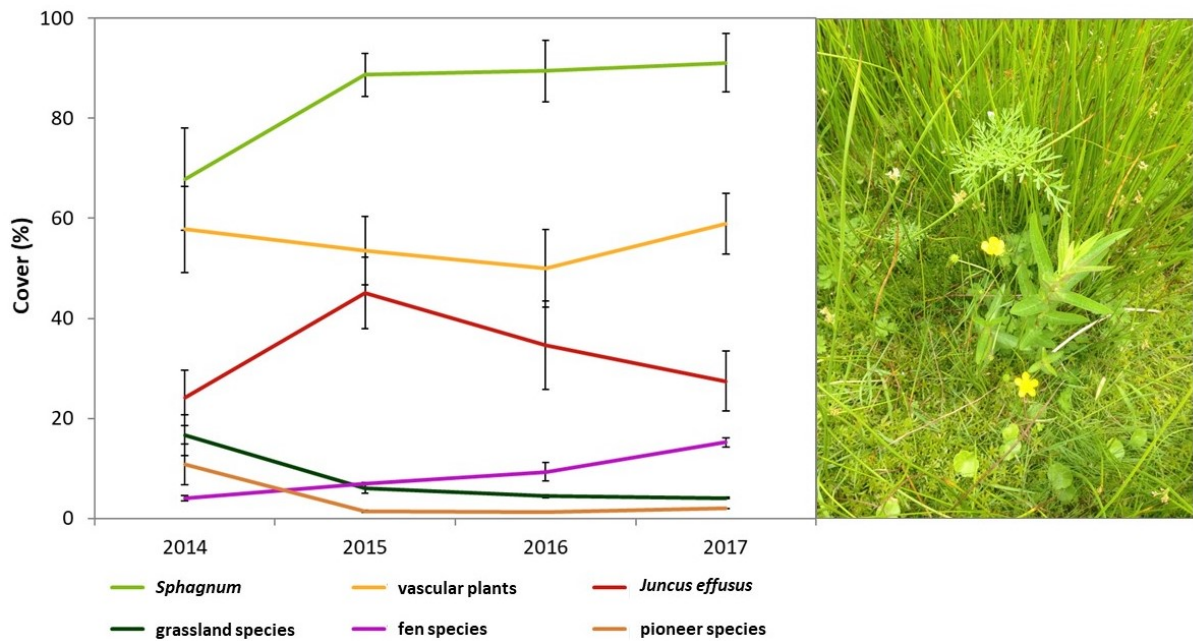


Figure B-1. Vegetation development in Omhoog met het Veen/AddMireNL.



Figure B-2: After 3.5 years the *Sphagnum* vegetation created a thick layer (8-12 cm) of recently formed 'white peat', consisting of largely undecomposed light brown peat mosses. It covers the former agricultural soil (nutrient-rich fossil peat), restores the hydrological properties and supports the establishment of typical fen species. Pictures by Bas van de Riet.

Sphagnum is able to develop on nutrient-rich, decomposed peat soil. In contrast to our expectations, we did not find negative effects of nutrients mobilized due to rewetting. Adequate management (mowing) is important as it seems it makes *Sphagnum* able to outcompete *Juncus effusus* after a few years.

Rewetting former agriculturally used peat meadows strongly reduces the emission of greenhouse gasses. We expect that after a few years the overall net carbon sequestration, as peat oxidation is strongly hampered and a peat forming vegetation has developed.

Sphagnum introduction to stimulate acrotelm development in Dutch raised bog remnants

HILDE TOMASSEN (B-WARE RESEARCH CENTRE) AND GERT-JAN VAN DUINEN (BARGERVEEN FOUNDATION)

In the Netherlands a research project has been started in 2017 to restore raised bog remnants by introduction of specific peat mosses. The project is carried out by B-WARE Research Centre, Wageningen University & Research, KWR Watercycle Research Institute, and the Bargerveen Foundation. The research is funded by the province of North Brabant and the Knowledge Network for Restoration and Management of Nature in The Netherlands (OBN).

For the restoration of raised bog remnants, it is important that a new functional acrotelm (top layer of the peat including the living peat mosses) is formed. An acrotelm will only develop when specific species of peat mosses are dominant. The aim is to accelerate the development of the acrotelm by introducing these peat mosses. In three Dutch raised bog remnant (Deurnsche Peel & Mariapeel, Haaksbergerveen and Bargerveen) experimental introductions of hummock forming peat mosses (*Sphagnum papillosum* and *Sphagnum magellanicum*) were carried out under three different conditions:

1. Introduction in a floating vegetation dominated by *Sphagnum cuspidatum* (only Deurnsche Peel & Mariapeel);
2. Introduction in a floating vegetation dominated by *Sphagnum fallax* (all three locations);
3. Introduction on bare, strongly humified peat (with and without regulation of the water table; all three locations).



Overview of the experiment in a floating *S. cuspidatum* vegetation in the Deurnsche Peel (left) and a detail of introduced *S. magellanicum*. Pictures by Hilde Tomassen.

In the winter of 2017/2018, *S. papillosum* (all three locations), *S. magellanicum* (only Deurnsche Peel & Mariapeel), and *S. palustre* (only Deurnsche Peel & Mariapeel) were introduced in plots of 50 x 50 cm. During two growing seasons (Haaksbergerveen and Bargerveen) or 5 growing seasons (Deurnsche Peel & Mariapeel) the development of the peat mosses and the pore water quality will be monitored. In the spring of 2018

(March and April) the experiments on bare, strongly humified peat started. Locations with strongly humified peat (black peat) were selected where the water table was relatively stable, but with no development of peat mosses. The existing vegetation was removed and *S. papillosum* (all three locations), *S. magellanicum* (only Deurnsche Peel & Mariapeel) and *S. cuspidatum* (only Deurnsche Peel & Mariapeel) were introduced. The peat mosses were introduced as complete mosses (only Deurnsche Peel & Mariapeel) or as fragments of 1 cm (diaspores; all three locations). Three treatments were applied to protect the peat mosses from desiccation: control, protection by *Eriophorum vaginatum* and protection by straw. All treatments are carried out under natural and controlled hydrological conditions. Under the controlled hydrological conditions water shortage is prevented by using a pump on solar energy to compensate for water losses. During 2 growing seasons (Haaksbergerveen and Bargerveen) or 5 growing seasons (Deurnsche Peel & Mariapeel) the development of the peat mosses and the pore water quality will be followed.



Photo of the experiment on bare peat in the Deurnsche Peel, where a solar pump is used to compensate for water losses. Picture by Hilde Tomassen.

2 Pilots

In this chapter, an overview of existing and future paludiculture pilots and further upscaling is given. Table 1 gives a summary of the differences and similarities between the pilots with respect to experimental setting, species and plant parts used, soil removal, planting density and method, total area, and water source.

location	year(s)	experimental setting (WL = water level)	species	soil removed?	plant type	machine-planted?	start density plants/m ²	total area m ²	planting month	water supply
Bargerveen	2016-2017	WL drawdowns	T.latifolia	no	old plants		4	10	jun	groundwater/lake
Bargerveen	2016-2017	WL drawdowns	P.australis	no	rhizomes		4	10	jun	groundwater/lake
Bargerveen	2016-2017	WL drawdowns	T.angustifolia	no	young plants		4	10	jun	groundwater/lake
Bargerveen	2016-2017	WL drawdowns	S. alba	no	branches		4	10	jun	groundwater/lake
Butefjild	2016	WL drawdowns	T.latifolia	no	old plants		6.5	40	may	ditch
Butefjild	2017	stable high WL planting method	T.spec	20	seeds		N.A.	450	apr	ditch
Butefjild	2017	stable high WL planting method	T.latifolia	20	old plants		4	450	mar	ditch
Butefjild	2017	stable high WL planting method	T.angustifolia	20	old plants		4	450	mar	ditch
Ilperveld	2017	stable high WL brackish water	T.latifolia	20	old plants		4	20	sep	ditch
Ilperveld	2017	stable high WL	T.latifolia	20	old plants		4	5	sep	ditch
Ilperveld	2017	WL drawdowns	T.latifolia	5	old plants		4	20	sep	ditch
Ilperveld	2017	stable high WL brackish water	T.angustifolia	20	old plants		4	40	sep	ditch
Ilperveld	2017	stable high WL	T.angustifolia	20	old plants		4	25	sep	ditch
Ilperveld	2017	WL drawdowns	T.angustifolia	5	old plants		4	30	sep	ditch
Krimpenerwaard	2017	stable high WL soil preparation	T.latifolia	no	young plants		6	49	jul	ditch
Krimpenerwaard	2017	stable high WL soil preparation	T.latifolia	7.5	young plants		6	49	jul	ditch
Krimpenerwaard	2017	stable high WL	P.australis	7.5	rhizomes		12	49	jul	ditch
Krimpenerwaard	2017	stable high WL	Sagittaria	7.5	young plants		5	49	jul	ditch
Krimpenerwaard	2017	stable high WL	S. alba	7.5	branches		1.8	49	jul	ditch
Peel (Nb)	2017	WL drawdowns	T.latifolia	no	old plants		1.4	7000	aug	groundwater/ditch
Peel (Lb)	2017	WL drawdowns	T.latifolia	no	old plants		1	2500	aug	groundwater/ditch
Rochow (D)	2016-2017	WL gradient	T.latifolia	20-90	young plants		1	90	jun	groundwater/lake
Rochow (D)	2016-2017	WL gradient	T.angustifolia	20-90	young plants		1	90	jun	groundwater/lake
Zegveld	2015	drying out	T.latifolia	7.5	young plants		7.7	384	jun	ditch
Zegveld	2015	drying out	P.australis	7.5	rhizomes		6.7	384	jun	ditch
Zegveld	2015	drying out	S. alba	7.5	branches		3	384	jun	ditch
Zegveld	2015	drying out	M. giganteus	7.5	rhizomes		4	384	jun	ditch
Zegveld	2015-2017	stable high WL high density	T.latifolia	7.5	young plants		15	48	jun	ditch
Zegveld	2015-2017	stable high WL high density	P.australis	7.5	young plants		10	48	jul	ditch
Zegveld	2016-2017	stable high WL	T.latifolia	12.5	young plants		4	48	may	ditch
Zegveld	2016-2017	stable high WL	P.australis	12.5	rhizomes		15	48	apr	ditch
Zegveld	2016-2017	stable high WL	S. alba	12.5	branches		1.5	48	apr	ditch
Zegveld	2016-2017	stable high WL	M. giganteus	12.5	old plants		1.5	48	apr	ditch
Zegveld	2016-2017	WL drawdowns	T.angustifolia	15	young plants		4	48	jul	ditch
Zegveld	2016-2017	WL drawdowns	T.latifolia	12.5	young plants		4	48	may	ditch
Zegveld	2016-2017	WL drawdowns	P.australis	12.5	rhizomes		15	48	apr	ditch
Zegveld	2016-2017	stable high WL	T.latifolia	10	young plants	✓	3.5	4000	jul	ditch
Zegveld	2017	soil preparation planting method	T.latifolia	no	seeds		N.A.	48	may	ditch
Zegveld	2017	soil preparation planting method	T.latifolia	no	seeds		N.A.	16	may	ditch
Zegveld	2017	soil preparation planting method	T.latifolia	no	young plants		4	48	may	ditch
Zegveld	2017	soil preparation planting method	T.latifolia	no	young plants		4	16	may	ditch
Zuiderveen	2017-2018	planting method	T.latifolia	yes	rhizomes	✓	6	3000	may	ditch
Zuiderveen	2017-2018	planting method	T.latifolia	yes	young plants	✓	6	3000	may	ditch
Zuiderveen	2017-2018	planting method	T.latifolia	yes	seeds	✓	N.A.	3000	may	ditch
Zuiderveen	2017-2018	planting method	T.angustifolia	yes	rhizomes	✓	6	2750	may	ditch
Zuiderveen	2017-2018	planting method	T.angustifolia	yes	young plants	✓	6	2750	may	ditch
Zuiderveen	2017-2018	planting method	T.angustifolia	yes	seeds	✓	N.A.	2750	may	ditch
Zuiderveen	2017-2018	field scale	A. filiculoides	yes	plants		N.A.	8000	?	ditch
Zuiderveen	2017-2018	field scale	L. minor	yes	plants		N.A.	6000	?	ditch

2.1 Zegveld: experimental paludiculture plots with high and low water tables

RENSKE VROOM, JEROEN GEURTS (RADBOD UNIVERSITY NIJMEGEN)

Establishment of paludiculture plots in combination with drying periods

In 2015 experimental paludiculture plots were established on the experimental farm of the Veenweide Innovatiecentrum (VIC) in Zegveld (Province of Utrecht). First 5-10 cm of the topsoil of the peat meadow were removed to build little dikes around two basins of 10x120m. On the 12th of June 30-40cm tall, very young cattail plants (*Typha latifolia*; 8 plants/m²) were planted by hand in 8 random plots of 48 m². In other plots, reed (*Phragmites australis*; 7 rhizomes/m²), willow (*Salix alba*; 3 branches/m²), and *Miscanthus giganteus* (silvergrass; 4 plants/m²) were planted. Water was supplied from the adjacent ditch by a pump (Portmann Solar). In the first 3 months of the pilot the farmer/site manager intended to irrigate with a pump attached to a tractor without sufficient water input to achieve wet conditions. The solar pump was working from late august onwards. Due to these problems in combination with hot and dry weather conditions, plots were regularly drying out in summer to more than 40 cm below the surface (Figure 1). In August water levels fluctuated between 0 and +20 cm and from October onwards, water levels were definitely raised to 20 cm above the surface.



Figure 1. Left: plots drying out in July 2015 (groundwater level > 30-40 cm below the surface). Right: stable high water level in July 2016 (20 cm above the surface). Pictures by Jeroen Geurts.

Because of the drying periods and subsequent weed development, only 20% of the *Typha* plants survived the first month, whereas more than 75% of the *Phragmites* and *Salix* survived (Figure 2).

Weed development at the end of the growing season was highest in the plots with *Phragmites* and *Miscanthus* (95% cover), followed by the *Typha* plots (66%) and *Salix* plots (12.5%; biodegradable foil was used).

Experimental paludiculture plots with high and low water levels

In spring 2016 all experimental paludiculture plots, except for the high density plots, were reestablished with new, more vital *Typha* plants and *Phragmites* rhizomes, and reused *Salix* and *Miscanthus* plants from the old experiment. First, an extra soil layer of 5 cm was removed and new dikes were made around three basins of 9x40m. On the 12th of May, 50 cm tall cattail plants (*T. latifolia*; 4 plants/m²) were planted by hand in 8 random plots of 12 m² divided over the northern and middle basins. In the other plots, *Phragmites* (15 rhizomes/m²), *Salix* (1.5 branches/m², without foil this time), and *Miscanthus* (1.5 plants/m²) were planted in April. In July, *T. angustifolia* was planted (4 plant/m²) in 4 plots in the northern basin only. The southern basin only contained demonstration plots. Water was supplied from the adjacent ditch to the middle basin by a pump (Solar Portmann) and the other two basins were connected by pipes. Water levels were continuously monitored by automatic water level data-loggers (type ElliTrack-D, Leiderdorp Instruments).

Water levels in 2016 (first year of replanted plots) were maintained at +20 cm in all basins (Figure 1). In October 2016 the water level in the northern basin was lowered to 20 cm below the surface ('drought treatment') and the connection pipe was closed. The reason for choosing lower water levels was the poor performance of *Salix* (little height increase and yellow leaves) and the very poor performance of *Miscanthus* at water levels of + 20 cm. In spring 2017, water levels regularly dropped to 30-40 cm below surface in the 'drought treatment' and therefore water was pumped in again in June to raise the water level above the surface for two weeks. After that, water levels were maintained at -20 cm again.

All species except for *Salix* grew better at higher water levels compared to the dry conditions in 2015, with average plant heights of about 160 cm in 2016 (Figure 3). Survival rates were also higher, especially for *Typha* and *Miscanthus*, although *Miscanthus* density still decreased and its biomass production was very low. Plant density of *T. angustifolia* increased to more than 50 plants/m², whereas *T. latifolia* even produced 80-100 new shoots per m² (Figure 2). The number of *Phragmites* shoots increased more than 10 times in the first growing season.

Due to the higher water levels, weed development was much lower than in 2015: only 2% cover in the *Typha* and *Salix* plots, 4% in the *Miscanthus* plots, and 13% in the *Phragmites* plots. Instead of weeds, floating algae beds developed in the plots with low vegetation cover (*Miscanthus* and *Salix*). *T. latifolia* had the highest winter biomass in the first year (2.8 ton dm/ha), followed by *Phragmites* (1.9 ton dm/ha) and *T. angustifolia* (1.0 ton dm/ha; Figure 3). *Miscanthus* biomass was very low (45 kg dm/ha) and therefore not suitable to grow under permanent wet conditions.

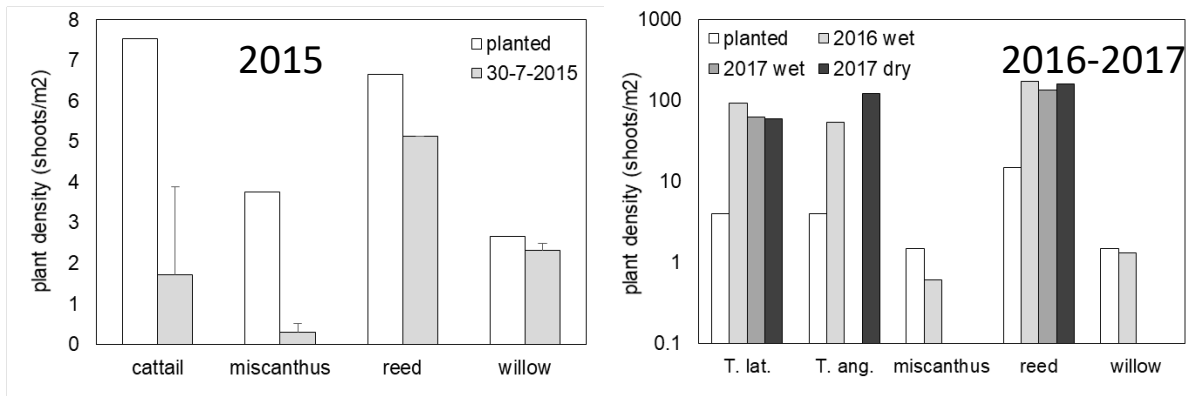


Figure 2. Left: Plant density development under very dry conditions in 2015. Right: Plant density development in 2016 (water level +20 cm) and 2017 (water level +20 cm and -20 cm).

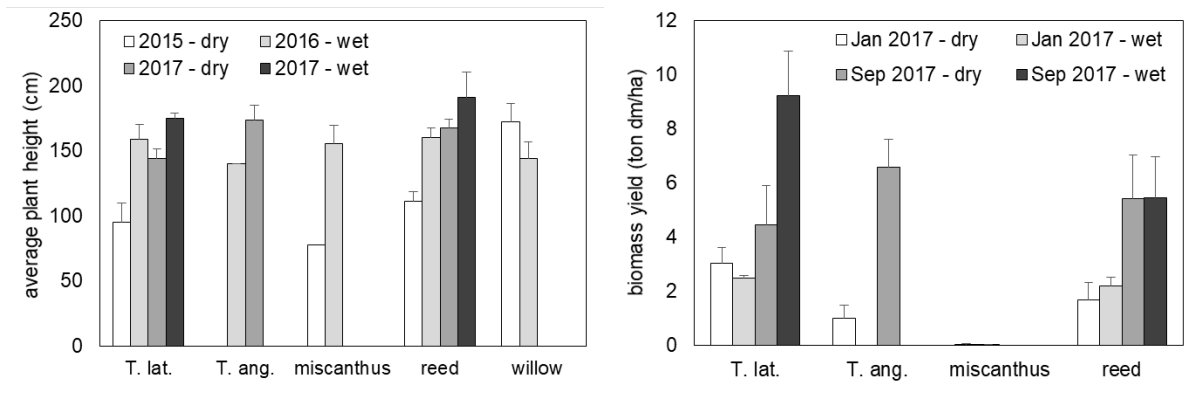


Figure 3. Left: Average plant heights¹ in September 2015 (dry conditions), 2016 (water level +20 cm) and 2017 (water level +20 cm and -20 cm). Right: Dry biomass yield² in January and September 2017 (water level +20 cm and -20 cm). ¹no data for *Salix* and *Miscanthus* in 2017; ²no data for *Miscanthus* in September.

For that reason only *Typha* and *Phragmites* plots were monitored in the growing season of 2017. There were big differences between plots in the high and low water level basin (Figure 3). *T. latifolia* biomass was two times higher at high water levels (9.2 ton dm/ha) than at low water levels (4.4 ton dm/ha). Moreover, plants were on average 30 cm taller (Figure 3) and produced almost two times more flowers (19 vs 11 per m²). Plant density did not differ, but was 25-40% lower than in the first growing season (2016). In contrast, *T. angustifolia* more than doubled the number of shoots to 121 per m² in 2017. Biomass production was also higher than in the dry *T. latifolia* plots (6.6 ton dm/ha), whereas the number of flowers was lower (5 per m²).

Phragmites produced 5.5 ton dm/ha and did not differ between the dry and wet plots. However, plants were more than 20 cm taller under wet conditions, whereas plant density was almost 20% higher under dry conditions.

Harvest time and frequency in high density *Typha* plots

In June and July 2015 two extra demonstration plots of 48 m² were planted with a higher *Typha* and *Phragmites* density (respectively 15 and 10 young plants per m²). Because of the higher density and better plant material, almost all plants survived the drying periods in 2015. The number of *Typha* shoots increased 5 times and number of *Phragmites* shoots even 10 times. However, the *Phragmites* plants did not grow very well. They suffered more from drought and weed growth than the *Typha* plants, probably because they were grown from seeds.

The high density *Typha* plot was used in 2016 to gain insight into the most suitable harvest time and frequency. Subplots of 50x50 cm were harvested in May, July, August, September, October and January. In October, the earlier harvested plots were harvested again to see the regrowth of the biomass.

Results show that an early harvest in May is possible for *Typha*, after which an equivalent amount of biomass can be harvested at the end of the growing season. Multiple harvests are also possible, but the total cumulative biomass production of 10 ton dry matter per hectare was not dependent on the time of the first harvest (Figure 4). Biomass yield decreased 30-40% when plants were first harvested in October or January, due to senescence and physical damage after storms. The average number of shoots was 73 plants/m² in 2016 and did not increase in comparison with 2015. The average plant height was 180 cm, which is 50 cm higher than the year before.

However, the fodder value and nutrient composition was different at each harvest time, which is important for choosing the most suitable biomass application. Fodder value and nutrient content was highest in spring, with a raw protein content of 127 g/kg dm and a digestion coefficient (VCOS) of 63 % (Pijlman et al. *subm.*). At the end of the growing season a large part of the nutrients was stored in the rhizomes already and the aboveground biomass contained more fibers and less moisture (40-60%, depending on the weather). Therefore, biomass from a winter harvest is better suitable for e.g. isolation material or bedding.

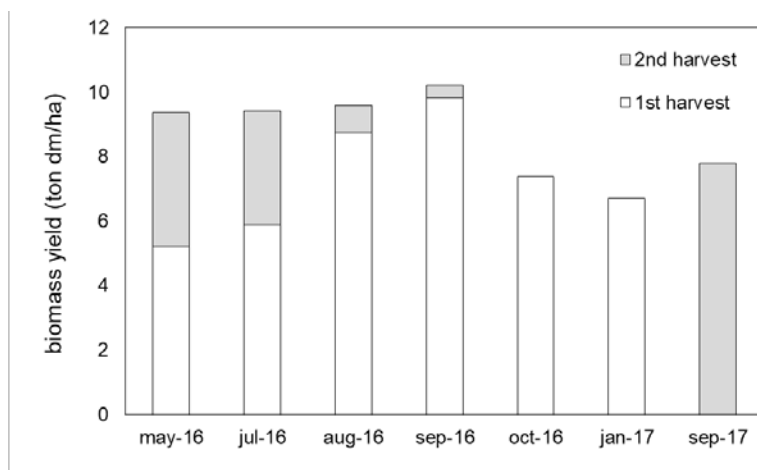


Figure 4. Biomass yield in case of multiple harvests of *T. latifolia* (dry weight). First harvest in the respective months. Second harvest in October of the same year. For September 2017, yield of the harvested side of the plot is shown.

In January 2017 half of each high density plot was harvested to see the effect of a winter harvest on biomass regrowth in the next growing season. The harvested side of the *Typha* plot developed much

faster in spring and it was the only side that produced flowers (17 per m²). This may imply that a winter harvest stimulates flower development. The newly formed biomass in September 2017 was also higher than on the unharvested side (7.8 vs 5.8 ton dm/ha), but lower than in 2016, probably due to nutrient limitation (Figure 4). Plant density (48 vs 43 plants/m²) and average plant height (175 vs 160 cm) were higher on the unharvested side of the plot.

Biomass production in the *Phragmites* plot was low (2.8 ton dm/ha) and did not differ between the harvested and unharvested side of the plot. However, plant density was higher on the harvested side (165 shoots/m²) than on the unharvested side (148 shoots/m²). The most likely reason for the low biomass production compared to the other *Phragmites* plots is that these plants were originally grown from seeds and not from rhizomes.

2.2 Zegveld: establishment of 0.4 ha cattail (*Typha latifolia*) for fodder

MONIQUE BESTMAN, JEROEN PIJLMAN (LOUIS BOLK INSTITUTE)
JEROEN GEURTS (RADBOD UNIVERSITY NIJMEGEN)

In July 2016, a 0.4 ha parcel (ca. 25x160 m) of cattail (*Typha latifolia*) was established at the Veenweiden Innovatiecentrum in Zegveld. The purpose of this parcel is to grow enough biomass for feeding experiments with dairy cows, and to get more experience with weed control, fertilization, harvesting moment versus biomass production and nutritional values, and harvesting techniques on larger parcels (other than the 12 m² experimental plots that have been planted in 2016). The grassland paddock on peat soil was prepared by mowing the grass at a very short stubble height (2-3 cm) and consequently removing the top soil layer (± 10 cm). The removed soil was used for making a small dike surrounding the parcel. By doing so, the soil surface for planting *Typha* became below the surface of the surrounding grasslands and the dike slightly above, making it possible to maintain a water level of 20-30 cm above soil surface permanently inundating the *Typha*.

Young *Typha* plants were obtained from a professional grower. Plants were reared using seed from *Typha* obtained from nature in a greenhouse. After germination, seedlings were planted in pots (4.8 x 4.5 x 11.0 cm) filled with potting soil and kept in the greenhouse until May. In July at planting, plants were 30-60 cm high. Right after removing the top soil layer, the surface was dry, which made it possible to use a small tractor for pulling an adapted vegetable planting machine followed by a light trailer (Figure 5). The planting machine drilled holes in the soil and on the plateau of the trailer planting material and three workers were carried. These workers put the plants in the plant holes at a density of 3.5 plant/m². Right after planting the parcel was inundated, to ensure a good start for the plants and repress the growth and development of weeds. During the season a water level of on average 20 cm was realized using a solar-powered water pump (Solar Portmann) equipped with a water level sensor.



Figure 5. Planting the *Typha* plants and view on the parcel on the 2nd of September 2016 (Pictures: Monique Bestman).

The plants grew well: in September (only 2 months after planting) 9-16 new shoots per m² were counted with plant heights up to 80 cm (Figure 5). At 8 and 30 November the amount of grown biomass at $\pm 5-10$ cm above water level was estimated at 371 kg ha⁻¹ on both moments. The plants did not flower in the year of planting. In 2016 the plants were not fertilized nor weed control was necessary; the water level and clean soil at establishment created good conditions against possible weeds.

At the 18th of January 2017, during a period of frost, all *Typha* plants were mowed at ± 5 -10 cm above water level with a brush cutter, while walking over the ice. The cut biomass was removed, but biomass yields were not determined.

In May 2017, the field was fertilized with 150 kg N and 150 kg K in the form of coated urea and potassium nitrate, and in July and August the field was fertilized three times with each time 20 kg N in form of coated urea. In June 2017, the *Typha* plants flowered and their pollen were harvested by a company that grows predatory mites for application in greenhouses. After that, *Typha* was harvested twice (June and September) to make silage for feed experiments, by mowing around 10 cm above water level with a long-armed crane (June) or a two wheeled reaper-binder (September).

At 23 June, shoot density was 28-42 per m², flower density 12-18 per m², plant height 1.5-2 m and biomass yield was 6.81 ton dry matter ha⁻¹. At 19 September, shoot density was around 33 per m², plant height 1.2-1.6 m, and biomass yield was only 1.94 ton dry matter ha⁻¹ (Figure 6). Therefore the total yield in 2017 was 8.75 ton dry matter ha⁻¹. After the first harvest in June, it was observed that regrowth was mainly from new shoots.



Figure 6. *Typha* harvest using a two wheeled reaper-binder at the 19th of September 2017 (Picture: Monique Bestman).

2.3 Zegveld: *Typha* planting and seeding trials without topsoil removal

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JEROEN PIJLMAN, MONIQUE BESTMAN, NICK VAN EKEREN (Louis Bolk Institute)

KAREL VAN HOUWELINGEN, FRANK LENSINCK (Veenweide Innovatiecentrum Zegveld)

The costs and chance of success of establishing a *Typha* paludiculture field is very important for the implementation. Therefore different *Typha* planting and seeding methods were tested at the Veenweiden Innovatiecentrum in Zegveld. In all treatments, the topsoil of the peat meadow was not removed, because this is cheaper and better for optimal peat preservation. The following treatments were applied on the original sod:

- 1) spraying herbicide, milling the sod in bands;
- 2) mowing the grass very short, milling the sod in bands;
- 3) milling the whole sod;
- 4) spreading 10 cm of sludge on top of the sod

On the 31st of May, half of each treatment area (16 m²) has been sown with *Typha* seeds (ca. 5 ml/m²), the other half has been planted with young, 50 cm tall plants (*T. latifolia*; 4 per m²). After planting, water levels were raised to 20 cm above the surface. After sowing, water levels were raised to 5 cm above the surface. The sludge was kept waterlogged.

Planting is most successful

Typha plants developed well in the 3 months after planting. The highest biomass yield (6 ton dm/ha) was reached when planting in the sludge or after spraying herbicide (Figure 7). This can easily increase to 15 tons in the second year and 20 tons in the third year, if nutrient availability is high enough. However, planting 4 plants per m² will be too expensive if it is scaled up to several hectares. Plant density already increased 10 times in the first 3 months (Figure 7), being highest after milling the whole sod (46 per m²) and lowest after mowing (37 per m²). Milling stimulates the development of new shoots, at the expense of biomass yield in the first year. Furthermore, plants were taller in the nutrient-rich sludge (2 m on average) than in the other treatments (1.6 m on average).

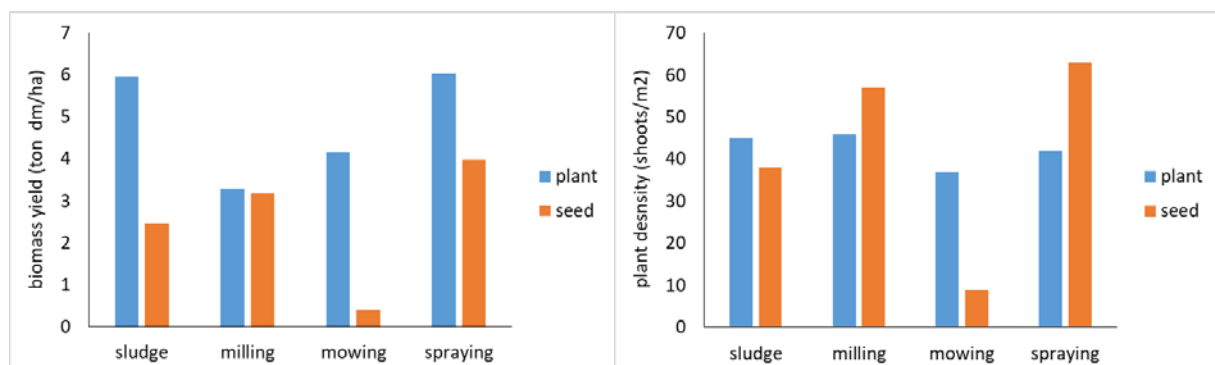


Figure 7. Biomass yield (left) and plant density (right) 3 months after application of different seeding and planting methods.

Sowing is most cost-efficient in the long term

Sowing was also very successful in most cases. The highest plant cover (73%), plant density (60 per m²), and plant height (1.3 m) was reached after milling the whole sod or after spraying herbicide (Figure 7). The biomass yield of 3-4 ton dry matter per hectare after just 3 months is certainly optimal after sowing. The yield after milling the whole sod was just as high after sowing as after planting. Moreover, plant density in the most successful sowing treatments was higher than after planting, which means that also higher yields may be expected in the second growing season.

If the grass was only mown very short, the germinating *Typha* plants suffered from the competition with grass, which led to a lower yield, plant cover (13%), plant density (9 per m²), and plant height (1 m). In the sludge layer, plants developed on an average level in terms of plant cover (43%) and plant density (38 per m²). The type of seed, with or without fluff, did not influence germination and development. The seeds without fluff were only easier to sow.

Although biomass yields were significantly lower after sowing than after planting (Figure 8), sowing is a much cheaper method. Furthermore, the expectation is that yields will be equal or higher in the second year. This means that sowing will be the most cost-efficient method in the long term, provided that the water level can be maintained just above the surface (0-5 cm) during germination and early development of the *Typha* plants. Frequent irrigation will therefore be necessary on the driest parts of the field.



Figure 8. Experimental plots with different planting and seeding methods after 3 months. The left side is planted, the right side is sown (Picture: Jeroen Geurts).

Conclusions

- For establishing a *Typha* paludiculture field it is sufficient to remove the sod by milling or to suppress the grass growth.
- Planting of young *Typha* plants gives the highest biomass yield in the short-term, but is much more expensive than sowing.
- The success of sowing is dependent on stable water levels by regular irrigation (0-5 cm above the surface).

2.4 Bargerveen: paludiculture field experiment in the buffer zone

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JEROEN GEURTS (RADBOD UNIVERSITY NIJMEGEN)

On the 23rd of June 2016, a paludiculture field experiment was established in a 70 ha buffer zone surrounding the Bargerveen bog reserve (Province of Drenthe). The aim of the buffer zone is to improve the hydrological situation in the peat bog itself and to increase biodiversity, while still having the opportunity for economically profitable land use.

On a bare spot on the shore of a rain-fed shallow lake, 4 fenced plots of 10 m² were created and planted by hand with 30 cm tall *Typha* plants (both *T. latifolia* and *T. angustifolia*; 4 plants/m²), *Phragmites* rhizomes (4 per m²) and *Salix* branches (4 per m²). At that time, water levels were just above the soil surface, but due to drying periods in summer water levels dropped to almost 50 cm below surface in October 2016 and again to 40 cm below surface in September 2017 (Figure 9). Unfortunately, water levels could not be controlled in this area. The soil is nutrient-poor, has a low pH (<5), and consists of 15 cm decomposed peat, 35 cm intact peat, 10 cm transition layer, and then brown, organic sand.

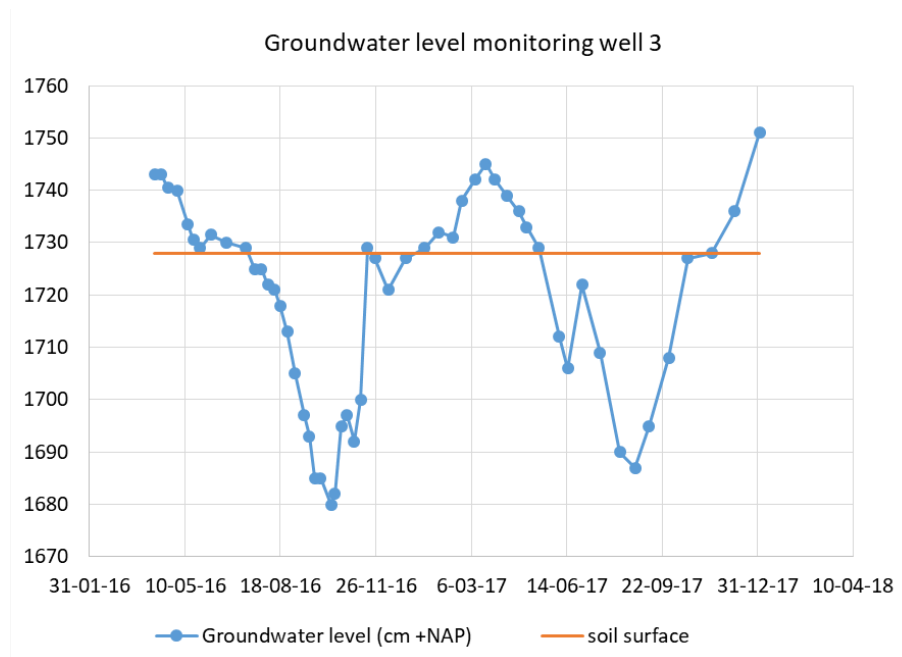


Figure 9. Groundwater levels in 2016 and 2017 (in cm relative to NAP). The orange line indicates the soil surface.

In the first year, the density of *Typha* and *Phragmites* did not increase, but in the second year shoot density was 2-3 times higher on the wetter side of the plots (Figure 10), where the water level dropped less fast in summer. Plant heights (up to 1 m) and biomass yields (up to 1.6 ton dm/ha) of these three species were also higher at the lakeside of the plots (zone 3), but still rather low as a result of the drying periods. Besides that, it was striking that only *T. latifolia* developed flowers, whereas *T. angustifolia* and *Phragmites* barely did (Figure 11). The *Salix* branches did not grow very well, and were not measured at all.

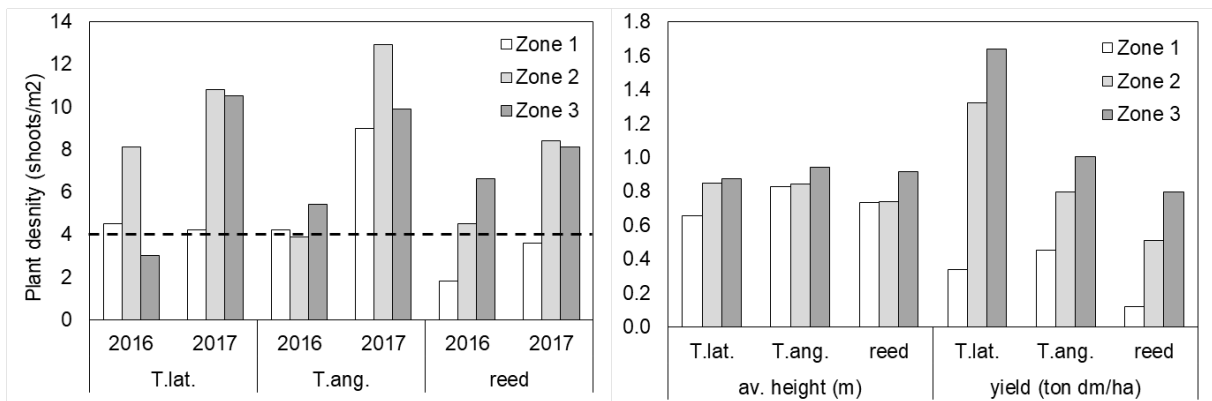


Figure 10. Left: plant density at the end of each growing season. Right: biomass yield and plant height in September 2017. Zone 1 is the drier side of the plot, zone 3 is the wetter side of the plot. The dashed line indicates the plant density at the start.



Figure 11. Left: Field experiment just after planting in June 2016 (Picture: J. Geurts). Right: *T. latifolia* plot in September 2017 (Picture: Arnold Lassche).

2.5 Bûtefjild: *Typha* field experiments under dry and wet conditions

IVAN METTROP, SJOERD POSTMA (ALTENBURG & WYMENGA ECOLOGICAL CONSULTANTS)

JASPER VAN BELLE (VAN HALL LARENSTEIN UNIVERSITY OF APPLIED SCIENCES)

Typha experiment under dry conditions

In the peat meadow area of Bûtefjild (Province of Friesland), *Typha* field experiments were started in 2016 within the Better Wetter project. On the first location, broadleaf cattail plants (*T. latifolia*) from a nearby natural stand were planted in spring on a 40 m² area (4 or 9 per m²) and cut at 20 cm above the soil surface. The original vegetation was mown beforehand, but the sod was not removed. Water level could not get higher than 20 cm below the surface, because of the agricultural nature management (SNL) on this location, which does not allow higher water tables and wet agriculture. This is an important obstacle for paludiculture (by farmers) on this kind of locations.

Despite the low water table, *Typha* plants developed quit well and 70% survived, but in the end they suffered from competition with soft rush (*Juncus effusus*; Figure 12). The plants also hardly produced any flowers (only 1%). Therefore, the experiment was considered to be unsuccessful and a new location had to be found the next year. Unfortunately plant height and density was not determined.



Figure 12. *Typha* development in Bûtefjild under dry conditions in 2016 (Picture: Ivan Mettrop).

Typha experiment under wet conditions

In 2017 a bigger field experiment was established on a different peat meadow location in Bûtefjild. Two basins of 450 m² each were created by removing the top soil (20 cm). On the 27th of March, one basin was planted by hand with mature *Typha* plants (a mix of *T. latifolia* and *T. angustifolia*) from a nearby natural stand (4 per m²; cut off at 20 cm). On the 18th of April, *Typha* seeds from nearby populations were sown in a grid in the second basin. In both basins, the water level was maintained at 15-20 cm above the surface until August. Water was supplied from a nearby ditch to the first basin by using the natural incline. The first basin is connected to the second basin with a pipe. After that,

water levels in both basins fluctuated between 20 and 30 cm. Water levels were continuously monitored by automatic water level data-loggers (type ElliTrack-D, Leiderdorp Instruments).

Two weeks after planting, new shoots started to develop, but growth rates really increased in May when average daytime temperatures started to rise (Figure 13). At the end of the month, plants even grew 3 cm per day on average. After that, growth rates of 1.5 cm per day were measured until the end of August. In the course of the growing season both *Typha* species could be distinguished better and differences in development could be determined. Both species continued to grow until the end of August. Figure 13 shows that *T. angustifolia* plants were growing a little bit faster in early summer than *T. latifolia* plants. Final average heights were 1.5 m and 1.3 meter respectively.

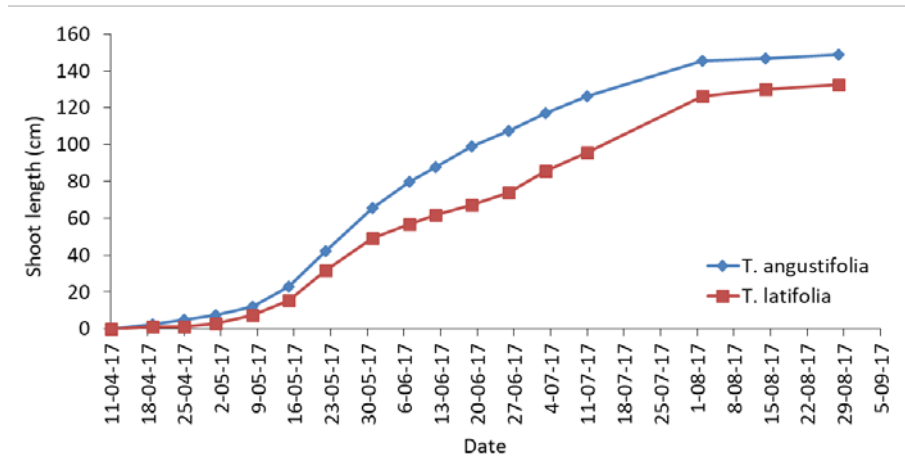


Figure 13. Length of the newly formed shoots of *T. angustifolia* and *T. latifolia* after planting.

No less than 96% of the planted mature *Typha* plants developed new shoots. In the first weeks, every *T. angustifolia* plant developed 1.5 new shoots, whereas every *T. latifolia* plant developed 1.25 new shoots (Figure 14). However, in the end of June there was a remarkable 2.5 time increase in the number of shoots for both species. Finally, *T. angustifolia* developed more than 4 shoots per planted *Typha*, whereas *T. latifolia* developed 3 shoots per planted *Typha*. About 5% of the plants produced flowers.

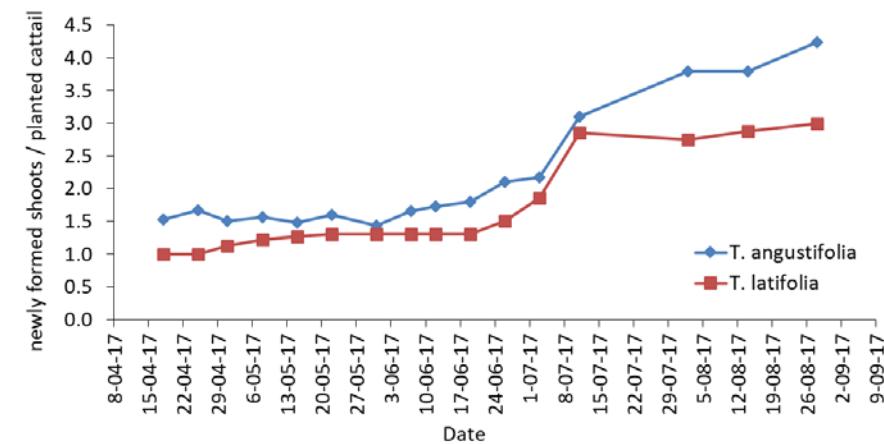


Figure 14. Number of newly formed shoots of *T. angustifolia* and *T. latifolia* per planted *Typha* plant.

This means that when *Typha* plants with rhizomes are planted in spring, a significant aboveground yield can already be expected in the same year (Figure 15). However, total yield in the first basin at

the end of the growing season was only 1.6 ton dm/ha, estimated by cutting 3 plots of 1 m² (sum of both species). The main reasons for this are the relative low plant densities and low nutrient availability. Single plants were also cut in the beginning of June to investigate the regrowth after a harvest. This regrowth was very fast, about 5 cm per day, whereby the harvested plants reached the same height as the non-harvested plants after 4 weeks already. In that way, a first harvest in early summer could result in an extra high total yield when the biomass is harvested again in September.



Figure 15. *Typha* development in Bûtefjild after planting under wet conditions in 2017 (Picture: Ivan Mettrop).

The sowing experiment in the second basin was less successful. Seeds were sown in April, but the first plants germinated in June, probably because of the low temperatures in spring, the early sowing time and continuous flooding. The germinated plants also did not grow very fast. They only emerged above the water surface at the end of June, because of competition with water mannagrass (*Glyceria fluitans*) and *Phragmites*. The seedlings were growing faster in July, but final average heights were only 60-70 cm, which is more than 2 times lower than after planting.

2.6 Krimpenerwaard: paludiculture pilot with and without topsoil removal

ANNA KOORNNEEF (VEENWEIDEN INNOVATIECENTRUM ZEGVELD)

JEROEN GEURTS (RADBOD UNIVERSITY NIJMEGEN)

In 2017 a small-scale paludiculture pilot was started in the polder Krimpenerwaard (Province of Zuid-Holland), commissioned by the municipality of Krimpenerwaard, the province of Zuid-Holland and Programmabureau Veenweiden Krimpenerwaard. The aim of this pilot is to introduce the cultivation of wet crops to dairy farmers with peat meadows, mainly to provide insight into the application possibilities of paludiculture crops in their own environment and possibly on their farm.

First, the top layer of the soil (5-10 cm) was removed and used to build 50 cm high dikes around 4 demonstration plots of 49 m². These plots were then milled and planted by hand with young, 40 cm tall *Typha* plants (*T. latifolia*; 6 plants/m²), *Phragmites* (12 rhizomes/m²), *Salix* (1.8 branches/m²), and 3 different species of duck potato (*Sagittaria*; 5 plants/m²) in July 2017. For *Salix*, biodegradable foil was used to counteract weed growth. For duck potato, 1/3 was planted with *Sagittaria sagittifolia*, 1/3 with *Sagittaria japonica*, and 1/3 with *Sagittaria latifolia*.

For *Typha* a second demonstration plot was created where the top soil was not removed. Before planting the *Typha* plants, the grass was mown very short, treated with acetic acid and then holes were drilled in the sod. All 5 demonstration plots were connected to each other with PVC tubes that can be closed individually to control the water supply per plot. An automatic pump on solar power is used to supply water from the ditch to the plot without top soil removal, and from there to the other plots (Figure 16). Water levels were gradually increased with plant growth until 20 cm above the soil surface, except for the *Salix* plot, where water levels were kept just above the soil surface (0-5 cm).

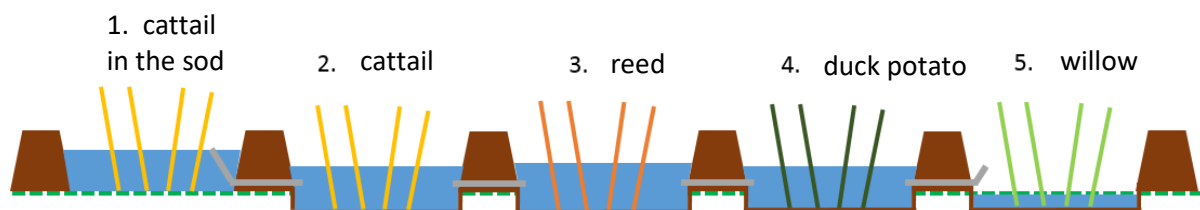


Figure 16. Schematic view of the demonstration plots (cross section by Anna Koornneef).

Typha plants developed faster in the plot with top soil than in the plot where the nutrient-rich top soil was removed (Figure 17). At the end of the growing season, average plant heights were also different: 135 cm and 104 cm respectively. The *Typha* plants that were planted in the sod also remained green for a much longer time in autumn.

In August, insects (lice and flies) were observed on the *Typha* and *Sagittaria* plants. These insects strongly decreased on the *Typha* plants in the following weeks. A lot of *Sagittaria* plants were damaged or extracted from the soil at the end of August, probably by ducks or geese that were eating the tubers (Figure 18).



Figure 17. The two Typha demonstration plots in polder Krimpenerwaard on the 20th of September. In the front, top soil was removed before planting. In the back, Typha was planted in the sod (Picture: Anna Koornneef).



Figure 18. Top left: Salix plot. Top right: duck potato plot. Bottom left: cattail pies. Bottom right: Phragmites plot. Pictures by Anna Koornneef and Jeroen Geurts on the 20st of September.

2.7 Deurnese Peel: *Typha* and *Salix* paludiculture in the buffer zone

JEROEN GEURTS, CHRISTIAN FRITZ (RADBOD UNIVERSITY NIJMEGEN)

GERT-JAN VAN DUINEN (STICHTING BARGERVEEN)

In the buffer areas that surround the bog reserve Deurnese Peel (province of Noord-Brabant) two paludiculture pilots were started in 2017, one with *Typha* and one with *Salix*. The main aim of the State Forestry Service (SBB) is to use these wet buffer zones as hydrological support for the restoration and conservation of the peat bog, but other goals are CO₂ emission reduction, water retention, development of habitat types, recreation, and the production of sustainable products. Paludiculture could also be a temporal measure here to extract nutrients from the nutrient-rich peat soil in the buffer zone until nutrient levels are low enough for certain habitat types.



Figure 19. The drier 0.7 ha *Typha* field (top) and the wetter 0.25 *Typha* field just after planting on the 30th of August (Pictures: Jeroen Geurts).

On the 30th of August 2017, 10,000 mature *Typha* plants with shoot base (*T. latifolia*) were planted by hand in rows on a milled field of 0.7 ha (Figure 19), where a peat layer of 60-100 cm was present. Because of extreme, persistent drought in this area, groundwater levels were far below the soil surface (50 - 70 cm) at that time. Therefore, the field was watered two times with local, acid surface

water to keep the soil moist, and a weir was installed in the adjacent ditch to retain the water. It was not possible to use the nearby canal water, due to the quality of this water (buffered and nitrate-rich) and the presence of peat mosses (*Sphagnum*) in the area. On another field of 0.25 ha with a higher groundwater table (between -20 cm and +10 cm), 2,500 *Typha* plants were planted by hand (Figure 19). On both fields, there was already some spontaneous development of *Typha* before the pilot started.

The *Typha* plants had a difficult start as a result of the low groundwater levels (Figure 20). Only 12% of the plants developed a new shoot after 7 weeks, with a maximum length of ± 30 cm. There was also a lot of weed development. In October groundwater levels were still low and the moisture content in the top soil (0-20 cm) was 40-50% of field capacity. Only at the end of October groundwater levels started to rise and in November water levels fluctuated between 0 and 20 cm below the soil surface (Figure 21). In the *Typha* field with higher groundwater levels, 73% of the plants survived in the wetter parts and 38% survived in the drier parts (Figure 20). Plants also became much taller (50-70 cm).



Figure 20. The drier 0.7 ha field (top) and the wetter 0.25 ha field (bottom) after 7 weeks, at the 19th of October 2017 (Pictures: Jeroen Geurts).

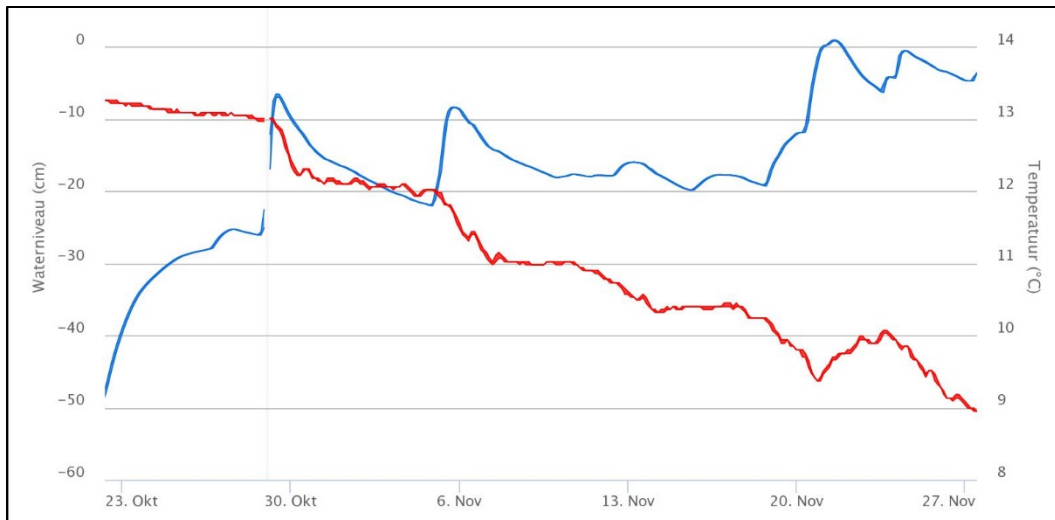


Figure 21. Groundwater levels (blue) and groundwater temperature (red) in the 0.7 ha *Typha* field between the end of October and the end of November.

In December 2017, 14,500 *Salix* branches (variety Linea) were planted by hand in rows on a 1.5 ha milled field, where a peat layer of 60-80 cm was present (Figure 22). Distance between rows was 120 cm and distance between plants was 75 cm. The field was divided in three parts by shallow trenches. At the time of planting, the field was very wet, although the water level in the adjacent ditch was still low. Shortly after planting, some of the planted branches were pulled out the soil by geese. In the first months of 2018, groundwater levels were 10-20 cm below the soil surface.



Figure 22. The 1.5 ha *Salix* field 1 month after planting (Picture: Jeroen Geurts).

2.8 IJperveld: *Typha* field experiments with different water, soil and salt levels

VICTOR DUIJKERS, JELLE ABMA (LANDSCHAP NOORD-HOLLAND)

EVA VAN DEN ELZEN, JEROEN GEURTS (RADBOD UNIVERSITY NIJMEGEN)

In an experimental setting in nature area IJperveld (province of Noord-Holland), 28 existing plots of 5 m² were used to investigate the development of *Typha* under different abiotic conditions. The main aim of this project is to use paludiculture with *Typha* to stop soil subsidence.

In 18 of the plots, 20 cm top soil was removed and average water levels were 3 (0-6) cm below the soil surface. Because of earlier Sphagnum experiments, 12 plots still turned out to be mildly brackish (EC = 3.4-3.9 mS/cm; green in Figure 23), while 6 plots were not brackish (blue in Figure 23). In 10 other plots, only 5 cm top soil was removed and average water levels were 14 (11-15) cm below the soil surface (red in Figure 23).

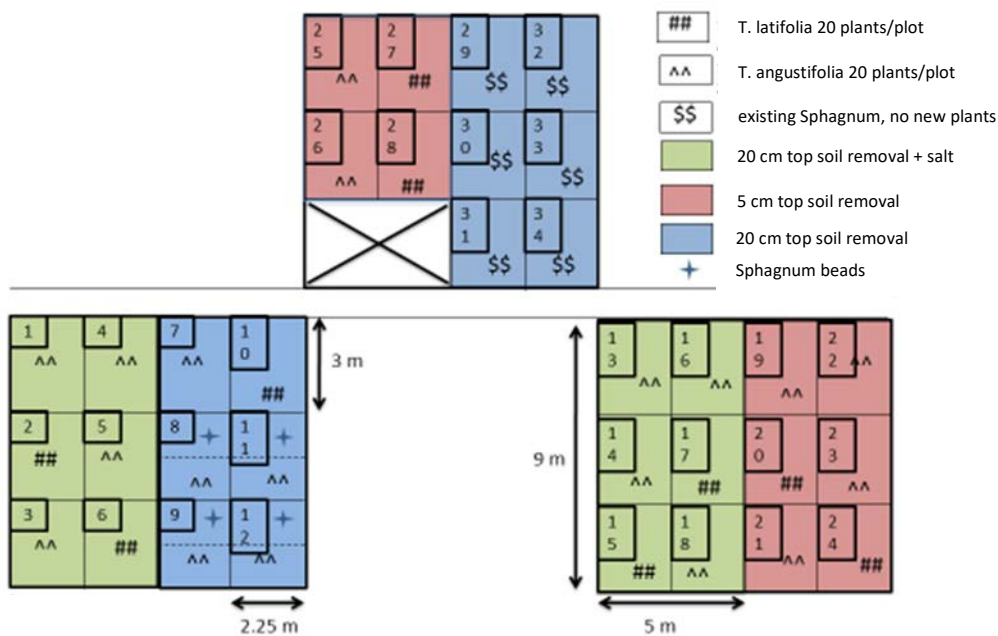


Figure 23. Overview of the plots where *Typha* was planted.

On the 21st of September 2017, mature *Typha* plants were planted in the plots by hand (4 per m²) and cut off at 30 cm (Figure 24). *T. latifolia* was planted in 4 green plots, 1 blue plot, and 4 red plots. *T. angustifolia* was planted in 8 green plots, 5 blue plots, and 6 red plots.



Figure 24. Left: overview of the plots just after planting on the 21st of September. Right: shoot development after 1.5 months. Pictures by Victor Duijkers.

After 1.5 month, on the 6th of November 2017, all newly formed *Typha* biomass was harvested and newly formed shoots were counted (Figure 25). *T. angustifolia* developed much more shoots than *T. latifolia* in the wet plots (fresh and brackish), which means that this species is more sensitive to water level drawdowns. However, *T. latifolia* generally produced more biomass, especially in the dry plots (red) and wet brackish plots (green), so this species seems less sensitive to changing water levels. Surprisingly, both species had a higher biomass production and shoot development under mildly brackish conditions.

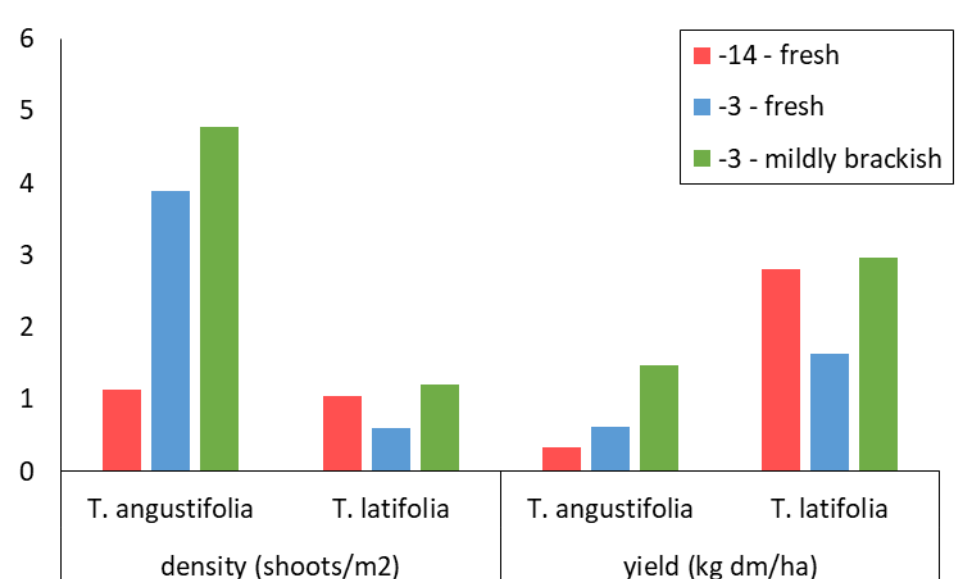


Figure 25. Density of newly formed shoots and biomass yield in the different treatments 1.5 months after planting.

2.9 Zuiderveen: 12 ha paludiculture pilot on former peat meadows

MARTIJN KORTHORST (LANDSCHAP NOORD-HOLLAND)

JEROEN GEURTS (RADBOD UNIVERSITY NIJMEGEN)

In the winter of 2017/2018, the preparations for a big paludiculture pilot of 12 ha were started in polder Zuiderveen (province of Noord-Holland; Figure 26). This pilot is part of the Peat Innovation Program (IPV), commissioned by the Province of Noord-Holland, Gebiedscommissie Laag-Holland, and water authority HHNK. Four promising paludiculture crops will be grown from 2018 until 2021: two species of cattail (*Typha*), waterfern (*Azolla*), and duckweed (*Lemna*). Peat moss (*Sphagnum*) as paludiculture crop is less suitable on this location because of the high alkalinity and cation content of the peat soil, and the bicarbonate/nutrient-rich surface water.



Figure 26. Start of the establishment of the paludiculture pilot in polder Zuiderveen (Pictures by IPV).

First, 28 basins with different sizes were created by excavating the top soil. *T. latifolia* will be planted and sown in 6 basins of 0.3 ha, and *T. angustifolia* in 6 other basins of 0.25-0.3 ha. A comparison will be made between planting rhizomes (in April), planting young plants (in May), and sowing (in June) with respect to practical advantages, plant development, and yields. Plant density will be 1 to 6 plants/m² and harvest frequency will be 1 or 2 times per year.

Azolla will be grown in 4 basins of 0.2 ha, and duckweed in 3 other basins of 0.2 ha. A comparison will be made between high and low water levels. The effect of fertilization and harvest method will also be investigated.

Small scale experiments with paludiculture crops will be done in 5 basins of 0.1 ha. The last 4 basins of 0.25-0.3 ha will probably be filled with sludge from a nearby lake to investigate the possible spontaneous development of *Typha*.

Water levels are adjustable up to 40 cm above the soil surface in all basins by using the natural incline. Accurate water level management will prevent drying periods and development of weeds.

2.10 Rochow (D): experimental *Typha* plots in a water level gradient

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JEROEN GEURTS (RADBOD UNIVERSITY NIJMEGEN)

In spring 2016, experimental *Typha* plots were established within an actively used grassland site in Rochow (State of Mecklenburg-Western Pomerania). The soil type is *Phragmites*-peat with a highly degraded top layer of about 20 cm. Two basins of 15x6 m were created by removing 40 cm of soil on one side and 110 cm of soil on the other side, leading to a water level gradient over the length of the basins. In order to simulate a rewetting of the original top soil, the degraded nutrient-rich top soil (20 cm) was put back into the basins. The intended water levels during summer were 0-70 cm above the soil surface along the gradient. Due to the unpredictable hydrological properties of the site, the actual water levels differed a little bit (2-67 cm) and the water level fluctuated about 15 cm over the whole vegetation period. Both basins were passively connected to a nearby lake and no water pumps were installed.

Young *Typha* plants (30-50 cm) were then planted into the soil with a density of 1 plant/m² (Figure 27). The plants were raised in a greenhouse and received no special treatments before or after planting. One basin was planted with *Typha latifolia*, the other one was planted with *Typha angustifolia*. In the following period of 4 months, the height of the plants, the number of plants per m², and the water level was monitored. No weed control was performed during the experiment.



Figure 27. Left: Field experiment shortly after planting in spring 2016. Right: *T. latifolia* basin in 2017, one year after planting. Pictures by Maximilian Wenzel.

Shallow water (5 to 15 cm) turned out to be much better for the shoot development of *T. angustifolia*, whereas *T. latifolia* seemed to prefer deeper water (40 cm). This is contradictory to their natural habitats (Grace & Wetzel, 1982). Because neither shoot development nor height increase alone indicate how well a stand is developing and biomass yield could not be determined, both factors (density and height) were multiplied (Figure 28). In that way, optimal water levels for *T. latifolia* appeared to be 10-30 cm, while *T. angustifolia* peaks at comparable water levels of 15-35 cm. This correlates with the distribution patterns of the two species in their natural habitats and also reflects the apparent growth patterns within the basins. There seemed to be no competition between the two species.

In conclusion, the optimal water levels for *Typha* cultivation are different for each species. In the first year, the water level could be optimized for shoot development since plants were not harvested. In

this way the plants have ideal conditions to spread rapidly over the desired area. After successful stand establishment, water level should be lowered by 10 cm for *T. latifolia*, and increased by 10 cm for *T. angustifolia*.

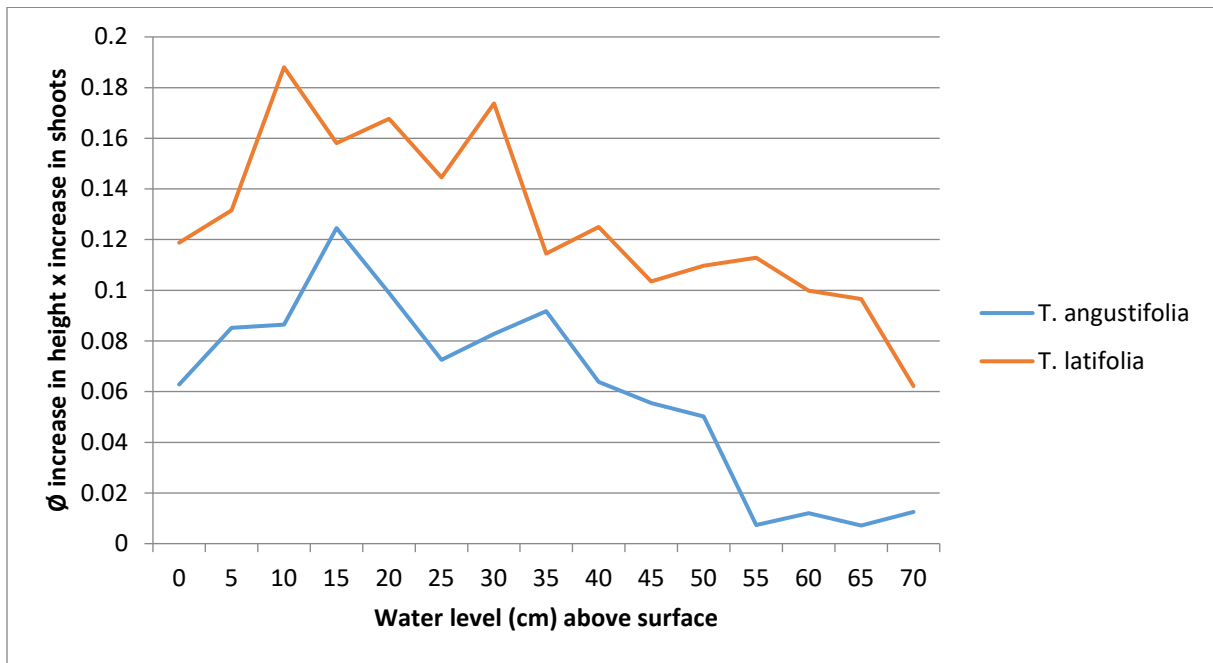


Figure 28. Increase in plant height per day multiplied by the increase in number of shoots per day, as a measure of plant performance.

2.11 Spontaneous growth of paludicrops in sludge deposits and flooded sites

JEROEN GEURTS, CHRISTIAN FRITZ (RADBOD UNIVERSITY NIJMEGEN)

Next to the pilots, an international field study was conducted using locations with spontaneous *Typha* and *Phragmites* growth on flooded sites and sludge deposits (Figure 29). There was a huge variation in peak biomass production and nutrient uptake (see paragraph 3.7). The sample locations could be divided in healthy and unhealthy locations, younger (<5 years) and older stands (>5 years), and soil type (see also paragraph 2.12).



Figure 29. Spontaneous growth of *Typha* and reeds in sludge deposits and flooded sites in Europe.

Former drained grasslands on peat along the rivers Hunze and Aa were excavated between 2000 and 2004 for nature development (Schollema et al. 2004; figure 29C). Because of the stable water levels *Typha latifolia* and *Phragmites australis* eventually established and increased in density. *Typha* plants growing into drier parts of the former grassland were smaller and seemed unhealthy. Colonization of deeply inundated areas is slow, which means that permanent high water levels during the establishment phase are undesired.

Several peat meadow sites that are used as sludge deposit (e.g. in Nieuwerbrug; figure 29A) or were abandoned due to high groundwater levels (e.g. in Voorschoten) spontaneously developed *Typha* stands, often mixed with other wetland plants. Especially sludge is a perfect substrate for *Typha*, as it contains a lot of nutrients and water, and often also *Typha* seeds and/or rhizomes. The *Typha* stand in Nieuwerbrug was also harvested and used for fodder trials at VIC Zegveld.

In Mecklenburg-Western Pomerania (Germany), large areas of drained, agricultural peatlands were flooded (e.g. in 2008/2009 in Kamp; figure 29B) and spontaneous development of mainly *Typha latifolia*, but also *T. angustifolia*, *P. australis*, and *Phalaris* occurred. A small part of these sites were also harvested in winter for the production of insulation material.

In Denmark, a drained peatland site right next to Lake Brabrand (Årslev Engsø) was rewetted in March 2003 and was rapidly colonized by *Phragmites*. Another site, Egå Engsø, was rewetted in October 2006 specifically in relation to the EU water framework and habitat framework directives. It was originally drained in the 1950s for agriculture and rewetting was achieved by simply turning off the pumps. In this case, the site was spontaneously colonized by *Typha latifolia*. In the peatland of Lille Vildmose, *Typha latifolia* developed after restoration of an excavated peat bog (Figure 29D).

In Italy, a 15 ha research area on rewetted peatland (close to Pisa) is used to compare the efficiency of a constructed wetland system (with *Typha* and *Phragmites*), a paludiculture system (with *Populus*, *Salix*, *Arundo donax*, *Miscanthus*, *Phragmites*), and a natural wetland system (Giannini et al. 2017; figure 29E). First results showed promising nutrient removal rates in the paludiculture system (>350 kg N and > 50 kg P per ha per year).

2.12 Paludicrops on mineral soils

JEROEN GEURTS, CHRISTIAN FRITZ (RADBOD UNIVERSITY NIJMEGEN)

Typha and *Phragmites* are used a lot in constructed wetlands, which often have a mineral soil. Both plant species also grow well on other substrates than peat. However, keep in mind that just the planting and biomass use of a wetland plant is not the aim of paludiculture, because the most important objective is peat rewetting and preservation. To compare the growth of *Typha* and *Phragmites* on organic soils (see 2.11) with growth on mineral soils samples were taken from constructed wetlands in Park Lingezegen, the Volgermeer polder and Halmstad (Sweden).

In Park Lingezegen, constructed wetlands with *Phragmites*, *Typha* and yellow iris were created on clay soil within the project Water Rich World (Figure 30). They have been mainly used for water purification and developed very well. In the longer term, biomass production of *Typha* was hampered by nutrient limitation.



Figure 30. Constructed wetlands with *Typha* (left) and yellow iris (right) in Park Lingezegen. Pictures by Christian Fritz and Tobias Dahms.

In het Peatcap project, the aim was to create a natural capping of the Volgermeer waste site by peat development, starting with bare sandy, organic or clay soils (Harpenslager et al. 2017; Figure 31). Water level drawdowns in the first year promoted a fast, spontaneous vegetation development from seeds of *T. latifolia*, *T. angustifolia* and *P. australis*, especially on the organic and clay soils.



Figure 31. Constructed wetlands on different substrates in the Volgermeer polder (left) and spontaneous biomass development after 2 years (right). Pictures by Sarah Faye Harpenslager.

In Halmstad (Sweden), 18 constructed wetlands were created on sandy soil in 2003, with an organic content of 2-8%. Halmstad University uses these wetlands to investigate N retention by different vegetation types and biogas tests with harvested biomass. Six wetlands were planted with emergent vegetation (*P. australis*, *Glyceria maxima* and *Phalaris arundinacea*), but on the long term all wetlands were colonized by emergent vegetation, including *T. latifolia* (Figure 32).



Figure 32. Constructed wetlands to investigate N retention by different vegetation types in Halmstad (Sweden). Pictures by Per Magnus Ehde.

2.13 Future projects and upscaling

JEROEN GEURTS, CHRISTIAN FRITZ (RADBOD UNIVERSITY NIJMEGEN)

Apart from the pilots and projects that are described in this report, several paludiculture and peatland rewetting projects have just started or will start in the near future. Many of them are listed by the National Knowledge Program Soil Subsidence (Nationaal Kennisprogramma Bodemdaling). Some examples of new projects and proposals with pilots, upscaling and/or further research are:

- Carbon Connects, an Interreg NWE project, by VHL University of Applied Sciences, water authorities AA & Maas and Dommel, State Forestry Service, Radboud University, The Rivers Trust (UK), Flemish Land Agency (Belgium), Chambres d'Agriculture (France), ILVO (Belgium), University of Marburg (Germany). Carbon Connects intends to reduce GHG emissions by running pilot studies, rewetting peatlands, implementing paludiculture in various North Western European countries, including the Netherlands, Belgium, France, the UK, and Ireland. The expectation is that CO₂ emissions will be reduced by 250-500 tons per year, in its pilot stage alone.
- PEATWISE (FACCE ERA-GAS), by the Norwegian Bioeconomy Research Institute, Swedish University of Agricultural Sciences, Radboud University, Aarhus University (Denmark), University of Eastern Finland, University of Oulu (Finland), University Of Waikato (New Zealand), and Leibniz Centre for Agricultural Landscape Research (Germany). PEATWISE will develop and refine sustainable soil and water management technologies for managed peatlands to reduce GHG emissions and maintain biomass production in different land use systems.
- Natte energieteelt behoud(t) veenlandschap (Wet energy cultivation preserves the peat landscape), by Smartland, Bureau Lantschap, KTC Zegveld, Radboud University and several water authorities. The aim of this project is to upscale the concept of paludiculture in landscape designs with a solid spatial motivation, create social support for changing land use practices, and contribute to the licensing process. The project will incorporate a concrete project plan from the province of Utrecht with paludiculture in polder Marickenland to counteract soil subsidence, realize a water retention area, and develop and restore nature areas.

3 Synthesis and discussion

In this chapter the most important experiences and results gathered from the pilots in chapter 2 are brought together and discussed in the light of existing knowledge found in the international literature. To start with, table 2 shows the water level range, experimental setting, used species and plant part, soil type, soil removal, plant performance, and success factors and failures for all pilots.

Table 2. Characteristics of the different pilots and field experiments, plant performance, success factors, and failures.

location	year(s)	experimental setting (WL = water level)	species	mean	min	max	soil removed?	plant type	performance	success factors	failures
<i>water level (cm)</i>											
Bargerveen	2016-2017	WL drawdowns	T.latifolia	-16	-48	16	no	old plants	poor	better on the wetter side	drying out, nutrients
Bargerveen	2016-2017	WL drawdowns	P.australis	-16	-48	16	no	rhizomes	poor	better on the wetter side	drying out, nutrients
Bargerveen	2016-2017	WL drawdowns	T.angustifolia	-16	-48	16	no	young plants	poor	better on the wetter side	drying out, nutrients
Bargerveen	2016-2017	WL drawdowns	S. alba	-16	-48	16	no	branches	poor		drying out, nutrients, plants
Butefjild	2016	WL drawdowns	T.latifolia	-20			no	old plants	moderate		drying out, weeds
Butefjild	2017	stable high WL planting method	T.spec	20	14	27	20	seeds	poor	no herbivory	high water level, sowing time, weeds
Butefjild	2017	stable high WL planting method	T.angustifolia	20	14	27	20	old plants	good	water level, plant quality	nutrients
Ilperveld	2017	brackish water	T.latifolia	-4	-6	-2	20	old plants	to early		planting time
Ilperveld	2017	stable high WL	T.latifolia	-1	-4	0	20	old plants	to early		planting time
Ilperveld	2017	WL drawdowns	T.latifolia	-14	-15	-11	5	old plants	to early		planting time
Ilperveld	2017	stable high WL brackish water	T.angustifolia	-4	-6	-2	20	old plants	to early	water level	planting time
Ilperveld	2017	stable high WL	T.angustifolia	-1	-4	0	20	old plants	to early	water level	planting time
Ilperveld	2017	WL drawdowns	T.angustifolia	-14	-15	-11	5	old plants	to early		planting time, low water level
Krimpenerwaard	2017	stable high WL soil preparation	T.latifolia	20	10	20	no	young plants	very good	water level, nutrients, plant quality	
Krimpenerwaard	2017	stable high WL soil preparation	T.latifolia	20	10	20	7.5	young plants	good	water level, plant quality	nutrients
Krimpenerwaard	2017	stable high WL	P.australis	20	10	20	7.5	rhizomes	good	water level, plant quality, density	nutrients
Krimpenerwaard	2017	stable high WL	Sagittaria	20	10	20	7.5	young plants	poor		herbivory
Krimpenerwaard	2017	stable high WL	S. alba	20	10	20	7.5	branches	moderate	plant quality	high water level
Peel (Nb)	2017	WL drawdowns	T.latifolia	-30	-48	-7	no	old plants	poor	water inlet, nutrients	drying out, planting time
Peel (Lb)	2017	WL drawdowns	T.latifolia	0	-30	10	no	old plants	moderate	water level gradient, plant quality	drying periods, planting time
Rochow (D)	2016-2017	WL gradient	T.latifolia T.angustifolia	35	0	70	20-90	young plants	very good	water level, plant quality, nutrients	water levels >50 cm

Table 2 (continued)

location	year(s)	experimental setting (WL = water level)	species	mean	min	max	soil type	soil removed?	plant type	performance	success factors	failures
<i>water level (cm)</i>												
Zegveld	2015	drying out	T.latifolia	0	-40	20	peat	7.5	young plants	poor		drying out, plant quality
Zegveld	2015	drying out	P.australis	0	-40	20	peat	7.5	rhizomes	moderate	plant quality	drying out
Zegveld	2015	drying out	S. alba	0	-40	20	peat	7.5	branches	good		drying out
Zegveld	2015	drying out	M. giganteus	0	-40	20	peat	7.5	rhizomes	very poor		drying out
Zegveld	2015-2017	stable high WL high density	T.latifolia	15	-40	25	peat	7.5	young plants	very good	plant quality, density, water inlet	drying out
Zegveld	2015-2017	stable high WL high density	P.australis	15	-40	25	peat	7.5	young plants	moderate	density, water inlet	drying out, plant quality
Zegveld	2016-2017	stable high WL	T.latifolia	20	10	30	peat	12.5	young plants	very good	water level, plant quality	
Zegveld	2016-2017	stable high WL	P.australis	20	10	30	peat	12.5	rhizomes	very good	water level, plant quality	
Zegveld	2016-2017	stable high WL	S. alba	20	10	30	peat	12.5	branches	poor		high water level
Zegveld	2016-2017	stable high WL	M. giganteus	20	10	30	peat	12.5	old plants	poor		high water level
Zegveld	2016-2017	WL drawdowns	T.angustifolia	-15	-30	15	peat	15	young plants	very good	plant quality, density, water inlet	drying periods
Zegveld	2016-2017	WL drawdowns	T.latifolia	-20	-35	10	peat	12.5	young plants	good	plant quality, density, water inlet	drying periods
Zegveld	2016-2017	WL drawdowns	P.australis	-20	-35	10	peat	12.5	rhizomes	good	plant quality, density, water inlet	drying periods
Zegveld	2016-2017	stable high WL machine-planted	T.latifolia	15	-5	35	peat	10	young plants	good	water level, plant quality	water level gradient, drying periods
Zegveld	2017	soil preparation planting method	T.latifolia	5	0	10	peat	no	seeds	good	water level, nutrients, no herbivory	sowing in the grass mown plot
Zegveld	2017	soil preparation planting method	T.latifolia	0	-10	10	sludge	no	seeds	good	water level, nutrients, no herbivory	slower development after sowing
Zegveld	2017	soil preparation planting method	T.latifolia	20	15	25	peat	no	young plants	very good	water level, nutrients, plant quality	
Zegveld	2017	soil preparation planting method	T.latifolia	0	-10	10	sludge	no	young plants	very good	water level, nutrients, plant quality	

3.1 Water level, drying periods, and water supply

JEROEN GEURTS, CHRISTIAN FRITZ (RADBOD UNIVERSITY NIJMEGEN)

Water management should maintain waterlogged conditions during germination and facilitate prolonged surface flooding of 5-30 cm depending on plant height (seedling age). Drying of the soil surface including water levels < 10 cm below the soil surface should be avoided to prevent drought damage to young plants and seedlings, and to prevent shading stress from grass-like weeds. Well established Typha cultures can probably cope with water levels of -30 cm below the soil surface when lasting for a few weeks only. Seeding to establish Phragmites requires a narrower hydro-regime than seeding Typha, but established Phragmites stands can tolerate more surface drying and drought than Typha.

Typha

In many *Typha* pilots farming pumps and active irrigation have been used to improve growing conditions and yields (Dubbe et al. 1988; Heinz, 2012; Wichtmann et al. 2016). In the first time after the establishment of a *Typha* paludiculture it is very important to raise and keep the (ground)water level above the soil surface. This will prevent drying out of seeds and young plants, and will hamper weeds from growing. Wet conditions will stimulate germination, but water levels should maximally be 5 cm above the soil surface for seedlings (i.e. moderate surface flooding; Münzer, 2001; Heinz,

2012). In case of young plants, water levels can be raised gradually with plant heights. Moreover, wet conditions will protect the peat against oxidation and will avoid CO₂ emission.

When plants are taller and the *Typha* vegetation has become denser, water level drawdowns below the soil surface and short drying periods with water levels of -20 to -30 cm may have negative effects on growth without detrimental effects for the standing crop. However, longer periods with groundwater levels of -20 cm and lower will certainly harm the *Typha* plants and reduce biomass production, even on the longer term.

In their wild range different genotypes of *Typha latifolia* and *Typha angustifolia* can be found in a wide range of water levels up to +100 cm (Grace & Wetzel 1981), where *T. angustifolia* shows a preference for deeper water levels. In the Donaumoos project in Bavaria (Southern Germany) both *Typha* species were grown under relatively high water levels (+40 cm) and performed equally well (Münzer, 2001; Heinz, 2012). Maintaining high to very high water levels (>60 cm) during May and June, in the case of early summer flooding or extreme water storage, may compromise photosynthetic rates, and eventually yields, as 25-50% of leaf biomass will remain shaded under water where humic substances largely attenuate light.

The easiest way of water supply is when a high water circuit is present (Dutch – onderbemaling) and the *Typha* field lies in a polder below the drainage base simply by gravitational pumps (Dutch – hevelpomp). In case that the water supply is below the soil surface (e.g. ditch, nearby lake) small dikes made of peaty topsoil can create a basin, and -solar powered pumps can be used to supply water from the ditch (e.g. Solar Portmann; investment costs ~6000 € per 5 ha). Storage of water surplus in winter and spring or retention of seepage (ground)water are efficient ways to provide a *Typha* cultivation with enough water and should even be compulsory to prevent water to be pumped out the area. In other cases, any kind of motor-driven pump can be used to supply water, provided that enough freshwater is available (normally not a problem in the Netherlands and NW-Germany). Drainage surrounding the *Typha* cultivation site should be reduced to a minimum by growing *Typha* on larger fields or clustering a number of narrow production fields (stripes in peat districts) to larger production units while maintaining the historic ditch pattern. Alternatively, drainage water from the surrounding could be pumped into a water storage reservoir to be maintained in the polder and be used again during summer in *Typha/Phragmites* cultivation and/or shallowly drained grassland. Interestingly, Goldman et al. (2009) showed surprisingly low evapotranspiration rates of *Typha* stands compared to potential evapotranspiration of open water and well-watered grasslands.

A regular water supply is not only important to maintain certain water levels, it is also important an important source of nutrients. If the retention time of the water is too high, purified water can also be discharged to make the inlet of new, nutrient-rich water possible (flow through system). Regular monitoring of the surface water quality can help to estimate nutrient uptake by the plants and thus nutrient depletion in the surface water. Especially nitrogen, but sometimes also potassium and/or phosphate, can become growth limiting (Brix 2003, Geurts et al., 2017a; Sorrell et al., in prep.).

Other species

The optimal soil moisture regime for planting *Miscanthus* seems narrow. Under dry conditions in June 2015 (water levels < -40 cm), *Miscanthus* failed to develop well from tubers without additional irrigation. Similarly, intact tussocks of *Miscanthus* did not expand in constantly flooded fields (+20 cm) and neither in fields with water table fluctuations (-40 cm to +20 cm), although some plants survived. Seeding to establish *Phragmites* also requires a narrow hydro-regime. Research suggests that *Phragmites* seeds germinate only on wet soil (after floating), but not underwater. After germination seedlings are prone to drying out and require constant water supply (mild irrigation, rain) while flooding should be avoided (Ter Heerdt 2016). In contrast, when established from

rhizomes *Phragmites australis* can tolerate surface drying and can tolerate drought in established cultures.

For the establishment of *Phragmites* and *Salix* from vegetative parts (rhizomes, twigs), drying periods are not a limiting factor given a soil water potential well above -0.5/-1 MPa (close to wilting point). *Salix* in particular benefits from fluctuating water levels. However, weeds will develop better under dry conditions, so higher water levels are still recommended. The water level management should also be optimized to avoid herbivory by geese and water fowl. For smaller wetland grasses and sedges, continuously high water levels or high water level fluctuations will be disastrous (Wilcox et al. 1984).

3.2 Removal, recycling or preparation of the top soil

JEROEN GEURTS, CHRISTIAN FRITZ (RADBOD UNIVERSITY NIJMEGEN)

Before the establishment of paludicrops the remaining grass and/or grass sod (upper 5 cm) should be removed or left to decompose after low mowing/milling. Topsoil recycling can be beneficial to build infrastructure like small dikes and elevated tracks, further improvement of the GHG balance or raising surface levels of neighboring fields. However, removing the topsoil can also reduce the availability of phosphorus, and partly nitrogen and potassium, which in turn can lead to nutrient deficiency in highly productive paludicultures and therefore influence green biomass use in summer. Moreover, top soil removal is certainly not required for the planting of paludicrops.

Removal of the topsoil before establishing a paludiculture field has both advantages and disadvantages. The advantages of top soil removal are that *Typha* is easier to plant, and grass and other weeds have difficulties to establish. The upper 5-10 cm (mostly root mat, clay/silt and humic substances) can lead to higher methane emission in the first years after rewetting when plant cover is sparse because of the high fraction of labile carbon. Removing this layer rich in reactive carbon may improve the GHG balance allowing for a net cooling effect of paludicultures (Harpenslager et al. 2015, Fritz et al. in prep.). However, methane emissions from rewetted top soils will be much higher when no paludiculture plants are present. The total GHG balance finally also depends on how the removed topsoil is used and what the aim of paludiculture is in each specific case. The removed topsoil can be recycled by building little dikes around the paludiculture field or to raise conventional agricultural meadows.

The disadvantage of top soil removal is that there will be an immediate “soil subsidence” (when dikes are not taken into account) and furthermore the subsurface may become less stable when a large part of the root layer (upper 15 cm) is removed. The removed top soil also contains a lot of nutrients that are not available anymore for plant growth. Moreover, research has shown that *Typha* can be planted in the grass sod (no top soil removal) very well, for example after milling in bands (Geurts et al. 2017b). Münzer (2001) also showed this in Germany, but found that plants grew a little better in loose, tilled topsoil (stem size, plant height and biomass 10-20% higher). Sowing or planting after milling the sod or after spreading a sludge layer on the sod also resulted in good plant development (Geurts et al. 2017b). An extra advantage of using ditch sludge (Dutch - bagger) is that it often contains *Typha* seeds or rhizomes already. Anaerobic sludge will be less favourable for *Phragmites*, as it may contain high concentrations of sulphide, ammonium and/or volatile monocarboxylic organic acids (e.g. acetic acid), which have phytotoxic effects on *Phragmites* (Armstrong & Armstrong 2001; see also paragraph 1.2 and 3.5).

3.3 Plant material and seeds

JEROEN GEURTS, CHRISTIAN FRITZ (RADBOD UNIVERSITY NIJMEGEN)

The establishment of *Typha* is successful when planting (commercially grown) young plants of 25-50 cm length or field collected shoot bases with growing buds at densities of 5'000-10'000 plants per ha, provided that waterlogged conditions and shallow flooding (0-20 cm) can be maintained. Establishing *Typha* cultures from seeds is technically feasible, but only cost-effective when water levels can be managed very accurate (0-5 cm) in the first weeks of cultivation. In contrast, *Phragmites* cultures from seeds seem more suitable for low-cost paludiculture fields where species richness is amongst the main goals. The establishment of *Phragmites* is most successful when rhizomes are planted.

Seeds

When *Typha* is sown, it is important to maintain stable, waterlogged conditions (0-5 cm above the soil surface) until the plants are large enough to raise the water level along with plant height. Seeds can be collected in winter or early spring. It is recommended to sow when temperatures increase (end of May), to achieve a faster and better germination. It is sufficient to sow between 20-100 seeds/m², which means that less than 1 kg/ha is needed. One female flower spike of *T. latifolia* contains about 350,000 seeds (Heinz, 2012) and weighs 15-30 g (dry weight). Flower spikes of *T. angustifolia* contain about 200,000 seeds. In the Donaumoos project, more than 150 plants/m² developed after sowing in the first year (Münzer, 2001), which is a lot compared to the 60 plants/m² in the seeding trials in Zegveld. Because of variation in water depth, there were also open spots in the *Typha* vegetation. This more structured biotope turned out to be an interesting ecological habitat for waterfowl and insects. Open spots might need to be sown again when water tables are lower in the following year or filled up with plants.

In the Netherlands, experience with sowing of *Typha* on larger scale is growing only slowly (Geurts et al., 2017b). The problem is that the fluffy seeds are difficult to spread, because they drift or blow away. In Germany methods have been developed to separate the fluff from the seed (estimated costs €100/ha) or to make loam granules with seeds inside (Münzer, 2001). Another option is to pre-germinate the seeds in water basins and then spread water with seedlings over the land using conventional machinery for organic fertilizers or irrigation. It is clear that research is still needed on the large-scale implementation of sowing *Typha* seeds.

Interestingly, on several locations in the Netherlands and Germany, *Typha* was able to germinate and establish spontaneously under beneficial conditions (wet without flooding), for example in Kamp (D), the Volgermeer polder (experiments from Radboud University, University of Amsterdam and Utrecht University), and park Lingezege (Figure 29). These conditions appear when the soil is waterlogged for a longer time, with sufficient rain and relatively stable, shallow water levels until late summer (August) when growth of seedlings and young plants is often frustrated by evaporative stress.

For *Phragmites* the use of seeds for establishing cultures is limited, because of seed dormancy, slow growth of seedlings, and young plants being largely susceptible to flooding, shallow drying, and competition with weeds (Brix 2003). The narrow range of optimal conditions for germination and growth of seedlings increases the potential of inhomogeneous cultures for *Phragmites*. Substrate for germination and water management need to be carefully chosen (Lenssen et al. 1999; Ter Heerd 2016). However, there are examples of successful large-scale establishment of *Phragmites* by

repeated seeding from the air (Van der Toorn et al. 1994; Ter Heerdt 2016). For low-cost paludiculture fields with high richness in species and vegetation structure large-scale seeding of *Phragmites* and spontaneous establishment of *Typha*, *Salix* and to a lesser extent *Phragmites* seem to be promising options (Lucassen et al. 2007; Van der Laan et al. 2018; Harpenslager et al. 2017; Figure 29).

Miscanthus × giganteus derived seeds are sterile, which is why propagation is only performed with rhizomes/buds. Establishing *Salix* plantations from seeds is inferior to growing *Salix* from freshly cut branches after leaf fall (Luske & Van Eekeren 2015; Börjesson & Berndes 2006).

Young plants

If hydrological conditions are suboptimal, it is better to use pre-cultivated *Typha* plants of good quality. Ideally plants are green, 25-50 cm tall and grown with a well-developed root system (at least 5 wide and 10 cm long). These can be ordered at specialized breeding companies (€0.30-0.85 per plant, depending on size). Smaller plants can also be pre-cultivated on-farm in small plastic trays using compost, self-collected seeds and tap/rain water. The HAS Den Bosch and the Radboud University can provide growing protocols based on trials to optimize cost-effectiveness of on-farm cultivation of *Typha* seedlings in 2016. During planting (best between April and July) it is recommended to lower the water level below the soil surface. Leafs of *Typha* can be trimmed before planting down to 20-40 cm to prevent evaporation when they start to grow, especially in warmer periods. After planting, water levels should be increased above the soil surface as soon as possible (max. 2 days during summer) to prevent desiccation stress and seed spreading from potential weeds. Depending on the plant height, water level can be increased to 20 cm above the soil surface, which prevents weed growth (e.g. grasses) and facilitates a good development of the *Typha* plants. When plants develop well and grow bigger and denser, they can also handle higher water levels, temporary water level drawdowns and drying periods (up to -20 cm). By nature, *T. latifolia* can better cope with water level drawdowns than *T. angustifolia*, whereas *T. angustifolia* may perform better when spring and summer water levels are high (up to 60 cm).

For establishing *Phragmites* cultures from pre-cultivated plants the abovementioned principles also apply (Wichtmann et al., 2016), although *Phragmites* seedlings are more vulnerable than *Typha* seedlings. As seed dormancy occurs in the genus of *Phragmites*, cultivation of seedlings should be done by specialized breeding companies. Another option is to grow young *Phragmites* plants from stem cuttings in the glasshouse or bending over established plants in the field (Brix 2003). Prices for young *Phragmites* plants can be higher than for *Typha* seedlings, which is probably one of the reasons why preference is given to establishing *Phragmites* from rhizomes (Van Duinen et al 2018).

Mature plants / rhizomes with shoot base

The use of mature *Typha* plants or rhizomes also works very well in several pilots. The advantage is that they can already be planted early in the season (March; see paragraph 2.5). It is very important that a shoot base with one or more buds is used, because otherwise no new shoots will be formed. The water level can be increased to just under the buds and after that gradually be increased with shoot length. This method is also used by landscaping companies. Mature plants / rhizomes are normally harvested from natural stands or sludge deposits (€0.30-€0.40 per plant).

Phragmites cultivations are commonly established by using rhizomes and landscaping companies apply this already on large scale (e.g. in Park Lingezege; Lucassen et al. 2017). Sowing seeds or planting young plants is not recommended for *Phragmites* if a fast and full coverage is desired, although large nature areas in the Netherlands (Oostvaardersplassen, Markerwadden) have been sown with airplanes or hovercrafts (Van der Toorn et al. 1994; Boskalis 2017; Van de Akker et al. in prep). In the Netherlands, good results are also achieved when *Phragmites* cultures are established by spreading milled topsoil from floating *Phragmites* stands (Dutch – rietkragge).

3.4 Density of plants and planting method

JEROEN GEURTS, CHRISTIAN FRITZ (RADBOD UNIVERSITY NIJMEGEN)

Typha and Phragmites plants and rhizomes can be planted both by hand and by machines, depending on the scale. A density of up to 1 plant per m² (Typha) or up to 4 rhizomes per m² (Phragmites) is sufficient under optimal site conditions.

A plant density up to 1 plant per m² is sufficient under optimal hydrological conditions without drying periods, because of the powerful clonal growth of *Typha*. The increase in number of shoots can be up to factor 10 in 2 months and factor 30 in a growing season (Wild et al. 2001; Münzer, 2001). In Germany there are even good experiences with planting 0.5 or 0.25 plants per m² or only sowing, where maximal yields (18-22 t dm/ha) and high plant densities (>100 plants/m²) were reached in the second year after planting in all cases (Heinz, 2012; Münzer, 2001). This is only valid under ideal water level conditions, which means that water levels can be controlled, no drying periods occur, and weed pressure is low. On the contrary, it makes no sense to plant a very high density if conditions are far from optimal and less than 20% of the plants survive (see for example paragraph 2.7). Planting in low densities can be combined with sowing to spread the risk and reduce the costs. Another option is to sow the field and fill open spots in the field with plants later. The ecological advantages of open spots would be that more structure is created in the *Typha* vegetation, which may attract several bird and insect species (Münzer, 2001).

Adapted planting machines for *Phragmites* rhizomes (Figure 33) have already been applied in several projects (Wichtmann et al. 2016; Gebr. Visscher, Hanze Wetlands pers. comm.). A density of 2-4 *Phragmites* rhizomes per m² is recommended (Brix 2003). Planting of *Typha* has been done by hand in most pilots and experiments, but in Zegveld some experience was gained with *Typha* planting machines (see paragraph 2.2). Mechanized planting of *Typha* will further be developed in the IPV project in Zuiderveen (see paragraph 2.9) in cooperation with Nautilus Eco-Solutions and the Veenweiden Innovatiecentrum (Figure 33). In the South of the Netherlands planting methods will be refined in the *Carbon Connects* project in cooperation with Hanze Wetlands, De Beijer Bladel and Staatsbosbeheer. Interestingly, for smaller areas (< 2 ha), planting by hand is probably still the cheapest method.



Figure 33. Planting machines developed for *Typha* (left; picture by Martijn Korthorst) and *Phragmites* rhizomes (right; picture by Gebr. Visscher).

3.5 Abiotic conditions: pH and nutrients

JEROEN GEURTS, CHRISTIAN FRITZ (RADBOD UNIVERSITY NIJMEGEN)

Typha and Phragmites can grow under a wide range of abiotic conditions and nutrient levels, but highest productivity is reached under nutrient-rich conditions, especially when nutrients are in balance. In wet conditions, nitrogen becomes the most limiting factor for growth. A pH below 4 to 4.5 can significantly reduce productivity of Typha and Phragmites. Phragmites is more sensitive to accumulation of anaerobic toxins (sulfide, ammonium, organic acids).

Typha can grow in a wide pH range (Brix et al. 2002), but like many grass-like plants *Typha* shows signs of deficiency in acid soils (pH <4) as nutrient uptake and cation supply (Mg, Mn, K) become frustrated (Box 2; Vroom et al. in prep.), which can result in growth depressions (Dyhr-Jensen & Brix 1996). However, in some cases *Typha* can grow in surface waters with a pH of 3.5 that receive acid mine drainage (Wieder et al. 1990), but they probably developed an avoidance strategy in that case modifying the pH in the rhizosphere. Some studies show that a low pH (4) has no influence on germination and seedling growth (Rivard & Woodard, 1989), whereas other studies found low germination rates on fibric peat with a pH of 3.7 (Bourgeois et al. 2012).

Under rewetted conditions N is the most limiting factor for *Typha* growth. However, if N availability is high, P and K can also be (co-)limiting. Compared to grasses *Typha* can convert nitrogen very efficiently into biomass (Pijlman et al. subm.). In drained peatlands intensive grasslands receive 230-330 kg N ha⁻¹ a⁻¹ from fertilization and additionally up to 180-450 kg N ha⁻¹ a⁻¹ from peat decomposition and N-mineralization (Deru et al. 2012, Tiemeyer et al. 2016) while maximum gross yields are limited to 11- 14 t dm ha⁻¹ a⁻¹. In contrast, *Typha* fields yields of ±20 t dm ha⁻¹ a⁻¹ where achieved with nitrogen loads of 300-350 kg N ha⁻¹ a⁻¹ (Wild et al. 2001; Geurts et al. 2017a).

In standing crops of *Typha* and *Phragmites* nitrogen loads should exceed 100 kg N ha⁻¹ a⁻¹ to produce economically viable yields. At the moment experiments with focus on K limitation are ongoing (Box 2). Growth stimulation by phosphorus in *Typha* cultures that are deprived in nitrogen deserve further attention as a mesocosm study shows high biomass yields at surprisingly low foliar N:P ratios (Xie & Vroom et al. subm.; Box 2).

Box 2. Greenhouse & climate room experiments

Within the CINDERELLA project, several experiments have been conducted in the greenhouse and climate rooms of the Radboud University to take a closer look at plant-soil interactions, nutrient dynamics, biogeochemical processes, and greenhouse gas (GHG) emissions. They will not be fully discussed in this report, but are shortly introduced here.

Typha and Phragmites in a nitrogen gradient on acid and neutral peat soil

In a mesocosm experiment in a water bath of the greenhouse, cores of two different peat soils with low and neutral pH were inundated. The peat cores were planted with *T. latifolia* and *P. australis*, and subjected to four different N loads during three months. Biomass production and nutrient uptake increased with increasing N load, but this was most apparent in *T. latifolia* and on the neutral peat soil.

Topsoil removal, greenhouse gas emissions, and nutrient mobilization

Cores of the same two peat soil types were sod-cut at different depths to simulate six degrees of topsoil removal. After that, soils were inundated in a dark climate room at 15°C for two years. Methane emissions and nutrient mobilization decreased rapidly after already 5-10 cm of topsoil removal. Long-term effects are still under investigation.

Water level experiment with different paludicrops

In the greenhouse, *T. angustifolia*, *Miscanthus*, and *Salix* were planted on peat soil in a mesocosm experiment with different water levels (+20, 0, -20 cm). All treatments received a realistic N load, except for the waterlogged treatment (0 cm) that also received a high N load. Differences between the paludicrops with respect to biomass production and nutrient uptake at different water and nitrogen levels reflected field observations.

Prevention of nutrient mobilization and GHG emissions by Typha at different N sources

Organic and mineral N forms were provided in different frequencies to 72 inundated peat soil mesocosms with *T. latifolia* and bare soil. The experiment was placed in a water bath in the greenhouse and lasted for 3 months. Clear differences between vegetated and unvegetated peat soils were found with respect to nutrient mobilization and methane emissions. Growing *Typha* in combination with *Azolla* did not increase biomass on the short-term.

Typha latifolia in a potassium gradient

Another mesocosm experiment in the greenhouse focused on the effect of potassium on the productivity and nutrient uptake of *T. latifolia*. Columns were planted and inundated as in earlier experiments, and gradually fertilized in a gradient of decreasing N:K ratios to investigate possible potassium limitation.

Topsoil removal, Typha productivity, and greenhouse gas emissions

Intact peat soil cores with three degrees of topsoil removal were inundated in a greenhouse experiment and half of them were planted with *T. latifolia*. Nutrient mobilization and methane emissions decreased with topsoil removal depth, but this was more striking in unvegetated columns as *Typha* lowered GHG emissions and nutrient leaching.

Brix et al. (2010) found that *Typha domingensis* can both grow at extremely high and extremely low P concentrations by adjusting P uptake kinetics and improving the allocation of P within the plant. Seed germination is also influenced by nutrient availability (Stewart et al. 1997), although *Typha* species can germinate in a wide range of nutrient levels. Differences between species exist, e.g. *T. latifolia* germinates faster at lower nutrient levels and *T. domingensis* germinates faster at higher nutrients levels.

Phragmites also thrives under nutrient-rich conditions (Ulrich & Burton 1985; Brix 1994; Brix 2003). Research has shown that vegetation dominated by *Phragmites* can take up more than 2000 kg of nitrogen and 150 kg phosphorus (Brix 2003) with a preference for nitrogen compared to *Typha*, which is also depicted in higher N:P ratios in foliar biomass than in *Typha* (Geurts et al. 2017a; Vroom et al. in prep). An accumulation of ammonium in the soil can lead to deprived growth in *Phragmites* cultures especially when ammonium levels are above 3 mM in low pH (<4.5) soils (Tylova et al. 2008). Also other toxins (like sulfide and organic acids) result in lower productivity at low pH (<4.5) when compared with buffered environments (pH 6) as shown by mesocosm experiments (Armstrong & Armstrong 2001)

3.6 Weed control, herbivory and plant diseases

JEROEN GEURTS, CHRISTIAN FRITZ (RADBOD UNIVERSITY NIJMEGEN)

Typha and Phragmites are most prone to weeds and herbivores in the establishment phase. High water levels will prevent weed growth, whereas temporary water level drawdowns and fences may protect paludicrops against grazing. Insect herbivory seems to have less impact in most cases.

To control the growth of weeds in a *Typha* field, it is necessary to maintain water levels above the soil surface, the higher the better. It is especially important to prevent water level fluctuations or drying periods in the establishment phase. If plants are full-grown and plant densities have become higher, plants are less sensitive to weed growth, there will be less space for weeds to grow and therefore water level fluctuations are allowed after the establishment phase.

Geese and water fowl may become a limiting factor in young cultures when plant density and plant height is low in *Typha* stands. *Phragmites* cultures, however, are often protected by lines and rabbit fences (Loeb et al. 2016; Lucassen et al. 2017). Another suggestion is to lower the water level for some weeks to 0 cm or 10 cm below soil surface in established stands as most water birds need water to eat plants. The disadvantage is that weed growth is promoted.

Penko & Pratt (1987) identified several phytophagous insect species that feed on *Typha* species in the US. They concluded that plants only showed minor damage in most cases and they did not expect that insect pests would influence *Typha* biomass yields. No effects of water level and plant nutrient content on herbivore pressure were found in this study, only geographical/climatological differences were recognized. Oertli & Lachavanne (1995) found that most macroinvertebrate species feed on senescent *Typha* shoots and only a few herbivore species feed on young shoots. Jordan et al. (1990) compared herbivory pressure between fertilized and unfertilized *T. angustifolia* stands and found more infestation by moth larvae in fertilized plots. This only becomes a problem in years with high infestation rates when an outbreak of insect larvae or caterpillars is combined with chronically high

nutrient levels. In such a case, 30-50% of the above-ground biomass could be destroyed (Jordan et al. 1990). *Typha* trials in S-Germany got infested by insects which largely impacted biomass production for one season (Wendelin Wichtmann pers. comm.). In the following year the *Typha* culture seemed to be recovered. In pilots in the Netherlands and N-Germany the authors observed minor biomass damage due to insect herbivory.

3.7 Harvesting and biomass applications

JEROEN GEURTS, CHRISTIAN FRITZ (RADBOD UNIVERSITY NIJMEGEN)

Typha and Phragmites can be harvested in different seasons, depending on the wide range of biomass applications. It is a trade-off between moisture content, yield, and optimal, sustainable nutrient removal from surface water and soil. Sustainable yields of 10-25 ton dm ha⁻¹ a⁻¹ are possible, and Typha biomass can even be harvested twice a year under ideal circumstances. Several harvesting machines for harvesting biomass from wet soils are already available.

Harvesting requirements

Sustainable yields of *Typha* and *Phragmites* require harvesting above the water table, because oxygen transport to the roots and rhizomes is necessary to keep plants healthy (Sale & Wetzel 1983). If plants are cut below water, oxygen in roots and rhizomes becomes depleted and anaerobic processes lead to the decay of the submersed plant parts. This will considerably reduce the regenerative capacity of the biomass compared to plants that are cut above the water table. Harvesting three times below the water table during the growing season will even kill the whole stand (Sale & Wetzel 1983; Brix 2003). We estimate that during winter several weeks of complete submergence (flooding) will have limited negative effects on regrowth as temperatures are typically low during that period. Only if dead shoots bend over or cut off close to the soil surface by storm, snow, or herbivores early in the dormant season, plant biomass will be lower in the next growing season (Jordan & Wigham 1988). Further research is needed to determine the number of days harvested stems (culms) of *Typha* can remain shallowly flooded during summer when regrowth is fast but also oxygen demand of roots and plants are high.

Nutrient removal and harvest period

To obtain maximum nutrient removal, the optimal harvest period of *Typha* is in summer (Svedarsky et al. 2016). P removal (up to 60-80 kg ha⁻¹) is stable between May and September, then steeply decreases in autumn (Figure 35; Grosshans 2014). N removal (up to 500 kg ha⁻¹) still increases in summer, although the N content and therefore protein content is highest in spring, before flowers start to develop in June (Geurts et al. 2017a; Pijlman et al. subm.). Spring biomass can also be ensilaged for storage very well (Figure 34). The mentioned N and P removal rates for *Typha* are on the high end of removal rates found in constructed wetlands in Sweden and the USA (Land et al. 2016).

If *Typha* is harvested in summer, it is possible to collect pollen from the flowers in June, which is used as food for predatory mites (biological control agents), and as medicinal tea in China (Figure 34). The subsequent summer harvest can be used in biogas installations (Dragoni et al. 2017) or as fiber-rich

fodder. If *Typha* is harvested in winter, preferably after a frost period, biomass can be used as insulation or construction material (Georgiev et al. 2014), growing substrate, or as a bioenergy feedstock (Figure 34; Grosshans 2014; Wichtmann et al. 2014; Giannini et al. 2016), because moisture content is lowest. *Typha* winter biomass only has to be air-dried for most applications and long-term storage. Moreover, damage to soil and plants will be lowest in winter (Svedarsky et al. 2016). However, a 30% biomass loss due to storms has to be taken into account. A winter harvest will still remove a significant amount of nutrients (5-10 kg P ha⁻¹), although most nutrients are stored in the rhizomes. The choice for a certain biomass application and harvest period seems to be a trade-off between moisture content, standing crop and optimal, sustainable nutrient removal from surface water and soil (Figure 35 & 36; Geurts et al. 2017a). *Phragmites* is typically harvested during winter as most biomass applications require biomass with a high dry matter content (Van der Sluis et al. 2013; Wichtmann et al. 2016).



Figure 34. Overview of different biomass applications of *Typha*. Pictures by AliExpress.com, typhatechnik.com, cosedicasa.com, Jeroen Pijlman and Jeroen Geurts.

Depending on the nutrient availability, a sustainable yield of 10-25 ton dm ha⁻¹ a⁻¹ is possible (Figure 36; Grosshans 2014), and biomass can even be harvested twice a year (Dubbe et al. 1988; Wichtmann et al. 2016; Geurts et al. 2017a). However, in a young *Typha* plantation (paragraph 2.2) it was noticed that harvesting green biomass three times in only 10 months had a detrimental effect on

the regrowth in spring 2018 (both density, height and biomass). After planting in June 2016 plants did not complete a single growing cycle without artificial cutting of green biomass. Because of that plants could not transfer enough carbon and nutrients to their rhizomes. Parts of the field that were only harvested in winter developed much better. Other factors that enhance this effect are herbivory by waterfowl, frost periods in March 2018 in combination with low water levels, and low nutrient availability in the soil after top soil removal.

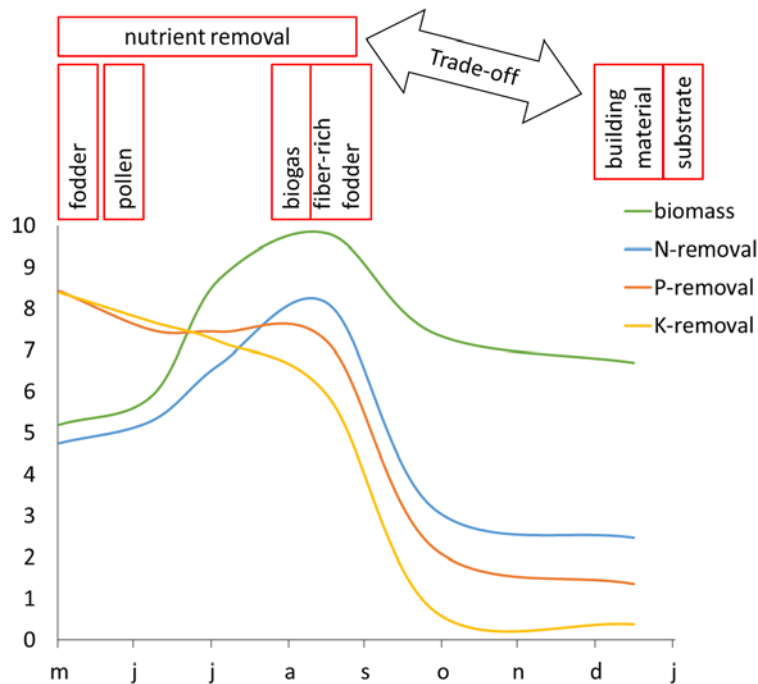


Figure 35. Trade-off between harvesting period, biomass yield, biomass application and sustainable nutrient removal of Typha (adapted from Geurts et al. 2017a).

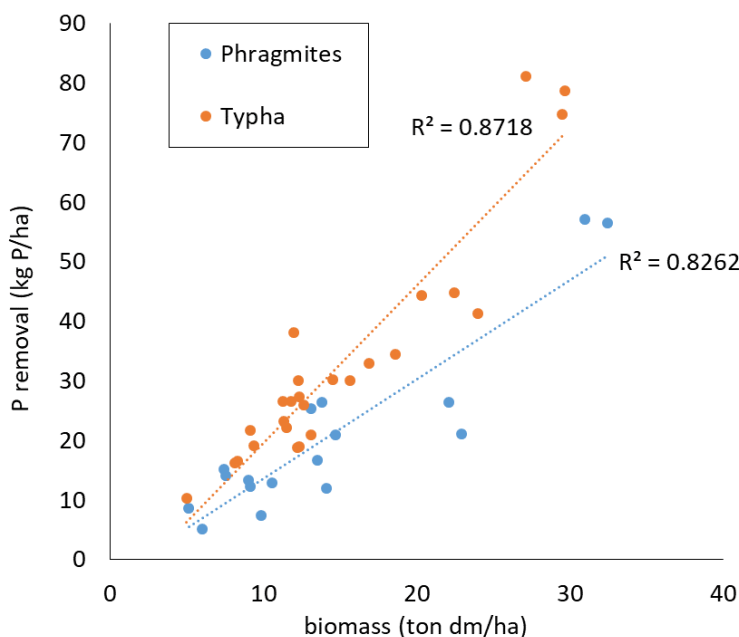


Figure 36. Peak biomass yield and P removal rates in a field gradient with spontaneous development of Phragmites and Typha after rewetting (adapted from Geurts et al. 2017a).

Harvesting machinery

Different harvesting machines for harvesting biomass from wet soils are available already (Figure 37; Svedarsky et al. 2016). The type of machine that should be used (big/small, with/without wetland tracks, etc.) depends on the cost efficiency, quality requirements of the harvested biomass, and disturbance of the soil (Schröder et al. 2015; Dahms, 2018). Farmers could invest in harvesting machines together to reduce the costs or specialized harvesting companies could settle in all peat meadow areas.



Figure 37. Harvesting machinery developed for biomass harvest in wet peatlands. Pictures by Jeroen Geurts, Hanze Wetlands, Christian Fritz and Tobias Dahms.

Within the Cinderella project, Hanze Wetlands adapted an existing wetland track machine specifically for *Typha* (Figure 37E & 36F). In Zegveld experience has been gained with harvesting fresh *Typha* biomass in the growing season (Figure 37A). *Typha* was harvested with a 2-wheeled reaper-binder, *Typha* bundles were transported to the farm and shredded for making silage. In Germany, *Typha* has been harvested in winter several times with Saiga harvesters (Figure 37D), balloon-tired harvesting machines (Pfadenhauer & Wild 2001; Georgiev et al. 2014; Aldert van Weeren pers. comm.).

3.8 Establishment costs, policy support, and market development

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The establishment costs of paludiculture depend on site conditions, scale, lifetime, available (water) infrastructure, and the purpose of paludiculture in each specific case. There is an urgent need for policy facilitation, further market development, and well-documented, large-scale, and long-term pilots. Codes of good agricultural practice need to be defined for peat soils, including higher water tables and the accounting for provided ecosystem services, to achieve implementation of climate smart agriculture on organic soils.

Depending on the main aim of paludiculture (production – ecosystem services – biodiversity) and the starting conditions, establishment costs may be low, intermediate or high. When a site is already wet, target species are already present and spontaneous development of paludicrops occurs, there will be no costs or only low costs for seeding/planting open spots. If soil preparation only consists of soil milling, ditches are blocked or weirs are adjusted to raise the water level, and low plant densities are used (1 plant per m² or less) in combination with seeding, establishment costs will be intermediate (e.g. € 3,000-€ 5,000 per ha). If moderate or extensive construction work is conducted (excavating basins, building dikes), pumps or irrigation pipes have to be installed to control the water level, and a relatively high plant density is used, establishment costs will be high to very high (€ 8,000-€ 20,000 per ha).

Proportional establishment costs per ha also depend a lot on the scale of the site, being lower in large-scale projects. Given the fact that wet crops like rice (*Oryza sativa*) cover more than 0.4 million ha in the EU with average production costs below 500 € ha⁻¹ a⁻¹ (incl. subsidies), lowering establishment and managements costs in paludiculture seems a matter of adaption (GRISP 2013). Moreover, establishment costs need to be spread over the total lifetime of the paludiculture, which is a permanent culture that can last 10, 15 or 20 years. Experiences from long-term paludicultures are missing in Europe, but long-term cattail harvesting in Canada shows that *Typha* stands perform well under yearly harvesting and can even withstand management efforts to remove plants (Grosshans 2014; Svedarsky et al. 2016).

From the preliminary analysis of establishment costs we found that planting density and prices for plant material (e.g. seeds; broadcasted germinated seedlings or vegetative parts like rhizomes; medium-sized plants in pots) have the largest leverage effect on total establishment costs (Wichmann et al. in prep.). In addition, expensive adaptations of the water infrastructure such as structural levees and seepage screens are only recommended when these water management investments are already compulsory/recommended for climate adaption of the whole area, also without a shift from drained to non-drained agriculture.

Policy support and market development

Cultivation of *Phragmites* and *Typha* on wet peatlands is increasingly recognized as agricultural land use. For large-scale implementation, there is a high need to ensure general eligibility of wetland adapted crops for agricultural payments in the 1st and 2nd Pillar of the CAP. Agricultural authorities are recommended to (see also Wichmann 2018):

- develop real incentives for balancing regulating and provisioning ecosystem services by remunerating reduced GHG emissions (e.g. Carbon Credits) and the provision of other services (e.g. nutrient retention, water storage) in addition to any biomass revenues;
- run long-term schemes (e.g. 15-20 years) to convince farmers, provide planning security and ensure continuity of climate and environmental benefits;
- make use of and refine the “tool box” already offered within CAP 2nd Pillar to provide incentives for all steps of implementation: establishment, rewetting, management & harvest, marketing, knowledge transfer & advise, cooperation at landscape scale;
- learn from extended experiences in other peatland-rich regions and consider region-specific circumstances (e.g. site conditions, socio-economy, attitude of farmers and local people) to develop tailored solutions that are accepted by stakeholders, result-orientated and good value-for-money.

There is an urgent need to facilitate the growth of markets for products from wet peatlands (construction and insulation material, bio-energy, food and fodder), to developed incentives to increase the paludiculture area, and to bridge the gap between biomass production and demand, e.g. by fixed higher prices, guarantee of sales or prescribed share in public procurement. It is also essential to have more certainty about the long-term yields of different paludicrops and the long-term income from paludiculture, by well-documented large-scale and long-term pilots. Small-scale projects can be valuable if they produce high-quality applications, such as human food, medicines, pollen or founder material for new cultivations (e.g. peat moss). Building certificates for construction and insulation materials from paludicrops will be a small investment for governments, but necessary for further market development.

Counterproductive funding of drainage-based land use on peatlands (like direct payments, rewards for organic farming, etc.) must be phased out to achieve coherence of agricultural and climate policy and to demonstrate to farmers that a paradigm shift is indispensable. Codes of good agricultural practice need to be defined for peat soils, including water tables near surface (Wichtmann et al. 2018). The polluter pays principle must be consequently applied to achieve implementation of climate smart agriculture on organic soils, including the accounting for GHG emissions from peatland use.

4 References

- Abel, S., Couwenberg, J., Dahms, T. & Joosten, H. (2013). The database of potential paludiculture plants (DPPP) and results for Western Pomerania. *Plant Diversity and Evolution*, 130(3-4), 219-228.
- Aliotta, G., Della Greca, M., Monaco, P., Pinto, G., Pollio, A. & Previtiera, L. (1990). In vitro algal growth inhibition by phytotoxins of *Typha latifolia* L. *Journal of Chemical Ecology*, 16(9), 2637-2646.
- Arets, E. J. M. M., van der Kolk, J. W. H., Hengeveld, G. M., Lesschen, J. P., Kramer, H., Kuikman, P. J. & Schelhaas, M. J. (2018). Greenhouse gas reporting for the LULUCF sector in the Netherlands: methodological background, update 2018 (No. 113). Statutory Research Tasks Unit for Nature & the Environment.
- Armstrong, J., Armstrong, W. & Putten, W. D. (1996). *Phragmites* die-back: bud and root death, blockages within the aeration and vascular systems and the possible role of phytotoxins. *New Phytologist*, 133(3), 399-414.
- Armstrong, J., Afreen-Zobayed, F., Blyth, S. & Armstrong, W. (1999). *Phragmites australis*: effects of shoot submergence on seedling growth and survival and radial oxygen loss from roots. *Aquatic Botany*, 64(3-4), 275-289.
- Armstrong, J. & Armstrong, W. (2001). An overview of the effects of phytotoxins on *Phragmites australis* in relation to die-back. *Aquatic Botany*, 69(2-4), 251-268.
- Asada, T., Warner, B. G. & Aravena, R. (2005). Nitrogen isotope signature variability in plant species from open peatland. *Aquatic Botany*, 82(4), 297-307.
- Augustin, J. & Merbach, W. (1998). Greenhouse gas emissions from fen mires in Northern Germany: quantification and regulation. In: Merbach, W. & Wittenmayer, L. (Red.): Beiträge aus der Hallenser Pflanzenernährungsforschung. Halle: Verlag Grauer, pp. 97–110.
- Berglund, Ö. & Berglund, K. (2010). Distribution and cultivation intensity of agricultural peat and gyttja soils in Sweden and estimation of greenhouse gas emissions from cultivated peat soils. *Geoderma*, 154(3-4), 173-180.
- Bhullar, G.S., Edwards, P. J. & Venterink, H.O. (2014). Influence of different plant species on methane emissions from soil in a restored Swiss wetland. *PLoS One*, 9(2), e89588.
- Biancalani, R. & Avagyan, A. (2014). Towards climate-responsible peatlands management. *Mitigation of Climate Change in Agriculture Series 9*. Food and Agriculture Organization of the United Nations (FAO).
- Boers, A. M. & Zedler, J. B. (2008). Stabilized water levels and *Typha* invasiveness. *Wetlands*, 28(3), 676-685.
- Börjesson, P. and Berndes, G., 2006. The prospects for willow plantations for wastewater treatment in Sweden. *Biomass and Bioenergy*, 30(5), pp.428-438.
- Bourgeois, B., Hugron, S. & Poulin, M. (2012). Establishing a moss cover inhibits the germination of *Typha latifolia*, an invasive species, in restored peatlands. *Aquatic botany*, 100, 76-79.
- Brix, H., Sorrell, B. K. & Orr, P. T. (1992). Internal pressurization and convective gas flow in some emergent freshwater macrophytes. *Limnology and Oceanography*, 37(7), 1420-1433.
- Brix, H. (1994). Functions of macrophytes in constructed wetlands. *Water Science and Technology*, 29(4), 71-78.
- Brix, H., Dyhr-Jensen, K. & Lorenzen, B. (2002). Root-zone acidity and nitrogen source affects *Typha latifolia* L. growth and uptake kinetics of ammonium and nitrate. *Journal of Experimental Botany*, 53(379), 2441-2450.

- Brix, H. (2003). Plants used in constructed wetlands and their functions. In: Proceedings of the 1st international seminar on the use of aquatic macrophytes for wastewater treatment in constructed wetlands, Lisboa, Portugal (May 2013). pp. 1-30.
- Brix, H., Lorenzen, B., Mendelsohn, I. A., McKee, K. L. & Miao, S. (2010). Can differences in phosphorus uptake kinetics explain the distribution of cattail and sawgrass in the Florida Everglades? *BMC plant biology*, 10(1), 23.
- Couwenberg, J. & Fritz, C. (2012). Towards developing IPCC methane 'emission factors' for peatlands (organic soils). *Mires & Peat*, 10.
- Couwenberg, J., K.-F. Reichelt & G. Jurasinski. Vegetation as a proxy for greenhouse gas emissions from peatlands: an update of the GEST list. Submitted to *Mires & Peat*.
- Crepeau, K. L. & Kuivila, K. M. (2000). Rice pesticide concentrations in the Colusa basin drain and the Sacramento River, California, 1990–1993. *Journal of Environmental Quality*, 29(3), 926-935.
- Dahms T. (2018). Harvesting: field test report. Report D6.1 of the CINDERELLA-project. Greifswald Mire Centre, University of Greifswald, Germany.
- Den Hartog, C. & S. Segal (1964). A New Classification of the Water-plant Communities. *Acta Botanica Neerlandica* 13: 367-393.
- Deru, J. G. C., van Eekeren, N. J. M., Kloen, H., Dijkman, W., van den Akker, J. J. H., de Goede, R. G. M., Schouten, T.; Rutgers, M.; Smits, S.; Jagers Op Akkerhuis, G.A.J.M., Dimmers, W. J., Keidel, H.; Lenssinck, F.A.J. & Bloem, J. (2012). Bodemindicatoren voor duurzaam bodemgebruik in de veenweiden. Ecosysteemdiensten van landbouw-en natuurpercelen in het veenweidegebied van Zuid-Holland, Noord-Holland en Utrecht. Deel A Onderzoeksrapportage (No. 2012-005 LbD). Louis Bolk Instituut.
- Dingemans, B. J., Bakker, E. S. & Bodelier, P. L. (2011). Aquatic herbivores facilitate the emission of methane from wetlands. *Ecology*, 92(5), 1166-1173.
- Dragoni, F., Giannini, V., Ragolini, G., Bonari, E. & Silvestri, N. (2017). Effect of Harvest Time and Frequency on Biomass Quality and Biomethane Potential of Common Reed (*Phragmites australis*) Under Paludiculture Conditions. *BioEnergy Research*, 10(4), 1066-1078.
- Driver, P.D., Barbour, E.J. & Michener, K. (2011). An integrated surface water, groundwater and wetland plant model of drought response and recovery for environmental water management. In: 19th International Congress on Modelling and Simulation, Perth, Australia. pp. 12-16.
- Dubbe, D. R., Garver, E. G. & Pratt, D. C. (1988). Production of cattail (*Typha* spp.) biomass in Minnesota, USA. *Biomass*, 17(2), 79-104.
- Dyhr-Jensen, K. & Brix, H. (1996). Effects of pH on ammonium uptake by *Typha latifolia* L. *Plant, Cell & Environment*, 19(12), 1431-1436.
- Eickenscheidt, T., Heinichen, J. & Drösler, M. (2015). The greenhouse gas balance of a drained fen peatland is mainly controlled by land-use rather than soil organic carbon content. *Biogeosciences*, 12(17), 5161-5184.
- Fritz, C., Pancotto, V.A., Elzenga, J., Visser, E.J., Grootjans, A.P., Pol, A., Iturraspe, R., Roelofs, J.G.M. & Smolders, A.J.P. (2011). Zero methane emission bogs: extreme rhizosphere oxygenation by cushion plants in Patagonia. *New Phytologist*, 190(2), 398-408.
- Fritz, C., J. Geurts, S. Weideveld, R. Temmink, N. Bosma, F. Wichern, F. Smolders & L. Lamers (2017). Meten is weten bij bodemdaling-mitigatie. Effect van peilbeheer en teeltkeuze op CO₂-emissies en veenoxidatie. *Bodem* 27 (2): 20-22.
- Garver, E. G., Dubbe, D. R. & Pratt, D. C. (1988). Seasonal patterns in accumulation and partitioning of biomass and macronutrients in *Typha* spp. *Aquatic Botany*, 32(1-2), 115-127

- Gaudig, G., Krebs, M. & Joosten, H. (2017) *Sphagnum* farming on cut-over bog in NW Germany: Long-term studies on *Sphagnum* growth. *Mires and Peat*, Vol. 20, Art. 4.
- Gelbrecht, J., Zak, D. & Augustin, J. (2008). Phosphor- und Kohlenstoff-Dynamik und Vegetationsentwicklung in wiedervernässten Mooren des Peenetales in Mecklenburg-Vorpommern - Status, Steuergrößen und Handlungsmöglichkeiten. Leibnitz-Institut für Gewässerökologie und Binnenfischerei. IGB-Bericht 26.
- Georgiev, G., Theuerkorn, W., Krus, M., Kilian, R. & Grosskinsky, T. (2014). The potential role of cattail-reinforced clay plaster in sustainable building. *Mires Peat*, 13, 1-13.
- Geurts, J., C. Fritz, L. Lamers, A. Grootjans & H. Joosten (2017a). Paludicultuur houdt de polder schoon - zuiveren van oppervlaktewater en uitmijnen van fosfaatrijke bodems met riet- en lisdodde. *H₂O-Online*. 23 augustus 2017.
- Geurts, J., R. Vroom, C. Fritz, J. Pijlman, M. Bestman, N. van Eekeren, K. van Houwelingen, F. Lenssinck (2017b). Natte teelten: plant- en zaai methoden van lisdodde. *V-focus* 2017 (6): 24-26.
- Giannini, V., Oehmke, C., Silvestri, N., Wichtmann, W., Dragoni, F. & Bonari, E. (2016). Combustibility of biomass from perennial crops cultivated on a rewetted Mediterranean peatland. *Ecological Engineering*, 97, 157-169.
- Giannini, V., Silvestri, N., Dragoni, F., Pistocchi, C., Sabbatini, T. & Bonari, E. (2017). Growth and nutrient uptake of perennial crops in a paludicultural approach in a drained Mediterranean peatland. *Ecological Engineering*, 103, 478-487.
- Gorham, E. (1991). Northern peatlands: role in the carbon cycle and probable responses to climatic warming. *Ecological applications*, 1(2), 182-195.
- Goulden, M.L., Litvak, M. & Miller, S.D. (2007). Factors that control *Typha* marsh evapotranspiration. *Aquatic Botany*, 86(2), 97-106.
- Grace, J.B. & Wetzel, R.G. (1981). Habitat partitioning and competitive displacement in cattails (*Typha*): experimental field studies. *The American Naturalist*, 118(4), 463-474.
- Grace, J.B. & Harrison, J.S. (1986). The biology of Canadian weeds: 73. *Typha latifolia* L., *Typha angustifolia* L. and *Typha x glauca* Godr. *Canadian Journal of Plant Science*, 66(2), 361-379.
- GRISP (Global Rice Science Partnership) (2013). Rice almanac, 4th edition. Los Baños (Philippines): International Rice Research Institute. 283 p.
- Grosshans, R. (2014). Cattail (*Typha* spp.) biomass harvesting for nutrient capture and sustainable bioenergy for integrated watershed management.
- Günther, A., Huth, V., Jurasinski, G. & Glatzel, S. (2015). The effect of biomass harvesting on greenhouse gas emissions from a rewetted temperate fen. *GCB Bioenergy*, 7(5), 1092-1106.
- Günther, A., Jurasinski, G., Albrecht, K., Gaudig, G., Krebs, M. & Glatzel, S. (2017). Greenhouse gas balance of an establishing *Sphagnum* culture on a former bog grassland in Germany. *Mires & Peat*, 20.
- Harpenslager, S.F., E. van den Elzen, M.A.R. Kox, A.J.P. Smolders, K.F. Ettwig & L.P.M. Lamers (2015). Rewetting former agricultural peatlands: Topsoil removal as a prerequisite to avoid strong nutrient and greenhouse gas emissions. *Ecological Engineering* 84: 159–168.
- Harpenslager, S.F., Overbeek, C.C., van Zuidam, J.P., Roelofs, J.G., Kosten, S. & Lamers, L.P.M. (2017). Peat capping: Natural capping of wet landfills by peat formation. *Ecological Engineering*.
- Haslam, S. M. (1971). The development and establishment of young plants of *Phragmites communis* Trin. *Annals of Botany*, 35(5), 1059-1072.

- Heinz, S.I. (2002). Population biology of *Typha latifolia* L. and *Typha angustifolia* L.: establishment, growth and reproduction in a constructed wetland. Dissertation Technische Universität München. Shaker Verlag, Aachen.
- Hooijer, A., Page, S., Jauhiainen, J., Lee, W.A., Lu, X.X., Idris, A., Anshari, G. (2012). Subsidence and carbon loss in drained tropical peatlands. *Biogeosciences*, 9, 1053–1071.
- Joosten, H., Tapio-Biström, M.L. & Tol, S. (2012). Peatlands: guidance for climate change mitigation through conservation, rehabilitation and sustainable use. Food and Agriculture Organization of the United Nations.
- Joosten, H. (2015). Peatlands, climate change mitigation and biodiversity conservation: An issue brief on the importance of peatlands for carbon and biodiversity conservation and the role of drained peatlands as greenhouse gas emission hotspots. Nordic Council of Ministers.
- Joosten, H., Gaudig, G., Tanneberger, F., Wichmann S. & Wichtmann, W. (2016). Paludiculture: sustainable productive use of wet and rewetted peatlands. In: Bonn, A., Allott, T., Evans, M., Joosten, H., Stoneman, R. (Eds), Peatland restoration and ecosystem services: Science, policy, and practice, Cambridge University Press, Cambridge, 339-357.
- Joosten, H., Tanneberger, F. & Moen, A. (2017). Mires and peatlands of Europe. Status, distribution and conservation. 780 pages. Schweizerbart Science Publishers, Stuttgart.
- Jordan, T. E. & Whigham, D. F. (1988). The importance of standing dead shoots of the narrow leaved cattail, *Typha angustifolia* L. *Aquatic Botany*, 29(4), 319-328.
- Jordan, T. E., Whigham, D. F. & Correll, D. L. (1990). Effects of nutrient and litter manipulations on the narrow-leaved cattail, *Typha angustifolia* L. *Aquatic Botany*, 36(2), 179-191.
- Jurasinski, G., Günther, A., Huth, V., Couwenberg, J. & Glatzel, S. (2016). In: Wichtmann, W., C. Schröder & H. Joosten (2016). Paludiculture – productive use of wet peatlands. Schweizerbart Science Publishers, Stuttgart 79-93.
- Karki, S., Elsgaard, L., Kandel, T.P. & Lærke, P.E. (2015). Full GHG balance of a drained fen peatland cropped to spring barley and reed canary grass using comparative assessment of CO₂ fluxes. *Environmental monitoring and assessment*, 187(3), 62.
- Kechavarzi, C., Dawson, Q. & Leeds-Harrison, P.B. (2010). Physical properties of low-lying agricultural peat soils in England. *Geoderma*, 154(3-4), 196-202.
- Land, M., Granéli, W., Grimvall, A., Hoffmann, C.C., Mitsch, W.J., Tonderski, K.S. & Verhoeven, J.T. (2016). How effective are created or restored freshwater wetlands for nitrogen and phosphorus removal? A systematic review. *Environmental Evidence*, 5(1), 9.
- Lamers, L.P.M., Falla, S.J., Samborska, E.M., Van Dulken, I.A.R., Van Hengstum, G.V. & Roelofs, J.G.M. (2002). Factors controlling the extent of eutrophication and toxicity in sulfate-polluted freshwater wetlands. *Limnology and Oceanography*, 47(2), 585-593.
- Leifeld, J. (2013). Prologue paper: soil carbon losses from land-use change and the global agricultural greenhouse gas budget. *Sci. Total Environ.* 465, 3–6.
- Leifeld, J. & Menichetti, L. (2018). The underappreciated potential of peatlands in global climate change mitigation strategies. *Nature communications*, 9(1), 1071.
- Lenssen, J.P., Menting, F.B., van der Putten, W.H. & Blom, C.W. (1999). Effects of sediment type and water level on biomass production of wetland plant species. *Aquatic Botany*, 64(2), 151-165.
- Li, F. M. & Hu, H. Y. (2005). Isolation and characterization of a novel antialgal allelochemical from *Phragmites communis*. *Applied and environmental microbiology*, 71(11), 6545-6553.

- Li, S., Pezeshki, S.R. and Goodwin, S., 2004. Effects of soil moisture regimes on photosynthesis and growth in cattail (*Typha latifolia*). *Acta Oecologica*, 25(1-2), pp.17-22.
- Loeb R., Geurts, J., Bakker, L., Van Leeuwen, R., Van Belle, J., Van Diggelen, J., Faber, A., Kooijman, A., Brinkkemper, O., Van Geel, B., Weijs, W., Van Dijk, G., Loermans, J., Cusell, C., Rip, W. & Lamers, L. (2016). Verlanding in laagveenpetgaten: Speerpunt voor natuurherstel in laagvenen. Rapport nr. 2016/OBN208-LZ. In opdracht van Vereniging van Bos- en Natuurterreineigenaren
- Lucassen, E.C.H.E.T., P.J. Westendorp, E.J.H. Bohnen-Verbaarschot, M. Poelen, A.J.P. Smolders (2017). Sturende factoren in de ontwikkeling van rietmoeras. *Landschap* (2017) 34(3): 119-127.
- Luske, B. & Van Eekeren, N. (2015). Potential of fodder trees in high-output dairy systems. *Grassland Science in Europe*, 20, 250-252.
- Mikha, M. M. & Rice, C. W. (2004). Tillage and manure effects on soil and aggregate-associated carbon and nitrogen. *Soil Science Society of America Journal*, 68(3), 809-816.
- Münzer, W. (2001). Bestandsentwicklung und Produktionstechnik. In J. Pfadenhauer, U. Wild (Red), Rohrkolbenanbau in Niedermooren. Integration von Rohstoffgewinnung, Wasserreinigung und Moorschutz zu einem nachhaltigen Nutzungskonzept. Abschlussbericht zum DBU-Projekt Nr. 10628, Technische Universität München.
- Oelke, E. A., Porter, R. A., Grombacher, A. W. & Addis, P. B. (1997). Wild rice-new interest in an old crop. *Cereal Foods World*, 42(4), 234-247.
- Oertli, B. & Lachavanne, J.B. (1995). The effects of shoot age on colonization of an emergent macrophyte (*Typha latifolia*) by macroinvertebrates. *Freshwater Biology*, 34(3), 421-431.
- Penko, J.M. & Pratt, D.C. (1987). Insect herbivory in Minnesota *Typha* stands. *Journal of Freshwater Ecology*, 4(2), 235-244.
- Pfadenhauer, J. & Wild, U. (2001). Rohrkolbenanbau in Niedermooren—Integration von Rohstoffgewinnung, Wasserreinigung und Moorschutz zu einem nachhaltigen Nutzungskonzept. Abschlussbericht zum DBU-Projekt Nr. 10628, Technische Universität München.
- Pijlman, J., J. Geurts, R. Vroom, M. Bestman, C. Fritz & N. van Eekeren. The effects of harvest date and interval on the yield, nutritional value and mineral contents of the paludiculture crop cattail (*Typha latifolia* L.). Under review in *Mires & Peat*.
- Pohl, M., Hoffmann, M., Hagemann, U., Giebels, M., Albiac Borraz, E., Sommer, M. & Augustin, J. (2015). Dynamic C and N stocks – key factors controlling the C gas exchange of maize in heterogenous peatland. *Biogeosciences*, 12(9), 2737-2752.
- Pratt, D. C., Dubbe, D. R., Garver, E. G. & Johnson, W. D. (1988). Cattail (*Typha* spp.) biomass production: Stand management and sustainable yields: Final report, 1984--1988 (No. ORNL/Sub-84-89674/1). Oak Ridge National Lab., TN (USA); Minnesota Univ., St. Paul (USA); Minnesota Univ., Crookston (USA).
- Regional Water Authority Hunze en Aa's (2018). <https://www.hunzeenaas.nl/about/voldoendewater/Paginas/Droogte.aspx>
- Richert, M., Saarnio, S., Juutinen, S., Silvola, J., Augustin, J. & Merbach, W. (2000). Distribution of assimilated carbon in the system *Phragmites australis*-waterlogged peat soil after carbon-14 pulse labelling. *Biology and fertility of soils*, 32(1), 1-7.
- Rivard, P.G. & Woodard, P.M. (1989). Light, ash, and pH effects on the germination and seedling growth of *Typha latifolia* (cattail). *Canadian journal of botany*, 67(9), 2783-2787.

- Saltmarsh, A., Mauchamp, A. & Rambal, S. (2006). Contrasted effects of water limitation on leaf functions and growth of two emergent co-occurring plant species, *Cladium mariscus* and *Phragmites australis*. *Aquatic Botany*, 84(3), 191-198.
- Sarneel, J. M., Huig, N., Veen, G. F., Rip, W. & Bakker, E. S. (2014). Herbivores enforce sharp boundaries between terrestrial and aquatic ecosystems. *Ecosystems*, 17(8), 1426-1438.
- Schollema, P.P., Vegter, U., Wannigen, H. & Zoer, B. (2004). Duurzamer waterbeheer en nieuwe kansen voor natuur in het Hunzedal. *De Levende Natuur*, 105(6), 221-226.
- Schrier-Uijl, A. P., Kroon, P. S., Hendriks, D. M. D., Hensen, A., Van Huissteden, J., Berendse, F. & Veenendaal, E. M. (2014). Agricultural peatlands: towards a greenhouse gas sink-a synthesis of a Dutch landscape study. *Biogeosciences*, 11(16), 4559.
- Schröder, C., Dahms, T., Paulitz, J., Wichtmann, W. & Wichmann, S. (2015). Towards large-scale paludiculture: addressing the challenges of biomass harvesting in wet and rewetted peatlands. *Mires and Peat*, 16(13), 1-18.
- Segers, R. (1998). Methane production and methane consumption: a review of processes underlying wetland methane fluxes. *Biogeochemistry*, 41(1), 23-51
- Singh, G., Kumar, D., Marwaha, T. S. & Singh, A. K. (2009). Influence of tillage, water regimes and integrated nitrogen management practices on soil quality indices in rice (*Oryza sativa* L.) in the Indo-Gangetic plains. *Archives of Agronomy and Soil Science*, 55(4), 439-450.
- Sorrell, B. K., & Armstrong, W. (1994). On the difficulties of measuring oxygen release by root systems of wetland plants. *Journal of Ecology*, 177-183.
- Sorrell, B. K., Brix, H., Schierup, H. H. & Lorenzen, B. (1997). Die-back of *Phragmites australis*: influence on the distribution and rate of sediment methanogenesis. *Biogeochemistry*, 36(2), 173-188.
- Sorrell, B.K., Brix, H., Tanner, C. & Clarkson, B. (2013). Nutrient enrichment effects on photosynthesis in the wetland plants *Typha orientalis* and *Phormium tenax*. *Aquatic Science at the Interface*, conference proceedings.
- Stewart, H., Miao, S.L., Colbert, M. & Carraher, C. E. (1997). Seed germination of two cattail (*Typha*) species as a function of Everglades nutrient levels. *Wetlands*, 17(1), 116-122.
- STOWA Delta factsheet (2018).
http://deltaproof.stowa.nl/Publicaties/deltafact/Beprijzen_van_water_voor_de_landbouw.aspx
- Svedarsky, D., Bruggman, J., Ellis-Felege, S., Grosshans, R., Lane, V., Norrgard, R., Knutsen, G., Clarke, R., Ripplinger, D., Ostland, A. & Lewis, J. (2016). Cattail Management in the Northern Great Plains: Implications for Wetland Wildlife and Bioenergy Harvest. University of Minnesota, Minneapolis, USA.
- Temmink, R. J. M., Fritz, C., van Dijk, G., Hensgens, G., Lamers, L. P. M., Krebs, M., Gaudig, G. & Joosten, H. (2017). *Sphagnum* farming in a eutrophic world: The importance of optimal nutrient stoichiometry. *Ecological Engineering*, 98, 196-205.
- Ter Heerdt, G. (2016). Establishment of different riparian plant communities from the same soil seed bank. Thesis, Rijksuniversiteit Groningen.
- Tiemeyer, B., Albiac Borraz, E., Augustin, J., Bechtold, M., Beetz, S., Beyer, C., Drösler, M., Ebli, M., Eickenscheidt, T., Fiedler, S., Förster, C., Freibauer, A., Giebels, M., Glatzel, S., Heinichen, J., Hoffmann, M., Höper, H., Jurasinski, G., Leiber-Sauheitl, K., Peichl-Brak, M., Roßkopf, N., Sommer, M. & Zeitz, J. (2016). High emissions of greenhouse gases from grasslands on peat and other organic soils. *Global change biology*, 22(12), 4134-4149.
- Tylová, E., Steinbachová, L., Votrubová, O., Lorenzen, B. & Brix, H. (2008). Different sensitivity of *Phragmites australis* and *Glyceria maxima* to high availability of ammonium-N. *Aquatic Botany*, 88(2), 93-98.

- Ulrich, K. E. & Burton, T. M. (1985). The effect of nitrate, phosphate and potassium fertilization on growth and nutrient uptake patterns of *Phragmites australis* (Cav.) Trin. ex Steudel. *Aquatic Botany*, 21(1), 53-62.
- Van Beek, C. L., Pleijter, M. & Kuikman, P. J. (2011). Nitrous oxide emissions from fertilized and unfertilized grasslands on peat soil. *Nutrient cycling in agroecosystems*, 89(3), 453-461.
- Van den Berg, M., Ingwersen, J., Lamers, M. & Streck, T. (2016). The role of *Phragmites* in the CH₄ and CO₂ fluxes in a minerotrophic peatland in southwest Germany. *Biogeosciences*, 13(21), 6107-6119.
- Van den Berg, M., Weideveld, S., Fritz, C., Geurts, J. & Lamers L. (2018). Monitoring bodemdaling, veenoxidatiesnelheden en broeikasgasemissies in de Friese veenweiden. Tussenrapportage. In opdracht van Wetterskip Fryslân. Radboud Universiteit Nijmegen, maart 2018.
- Van der Laan, K., M. Carree, G. Van Duinen, C. Fritz, J. Geurts, M. Bestman, N. Van Ekeren, J. Janssen & M. Kerkhoff (2018). Pilotproject Paludicultuur Peelvenen 2017. Verslag over 2017. In opdracht van Provincie Noord-Brabant en Waterschap Aa & Maas.
- Van der Sluis, T., Poppens, R. P., Krausvitnii, P., Rii, O., Lesschen, J. P., Galytska, M. & Elbersen, H. W. (2013). Reed harvesting from wetlands for bioenergy: technical aspects, sustainability and economic viability of reed harvesting in Ukraine (No. 2460). Alterra Wageningen UR.
- Van der Toorn, J., Hemminga, M. A. & Patten, B. C. (1994). Use and management of common reed (*Phragmites australis*) for land reclamation (The Netherlands). *Wetlands and shallow continental water bodies Vol. I*, 363-371.
- Van Duinen, G.A., C. Fritz & E. de Hullu (2018). Perspectieven voor natte landbouw in het Internationale Natuurpark Veenland - Pilot Paludicultuur. Rapport Stichting Bargerveen & Radboud Universiteit Nijmegen.
- Veen, G. F., Sarneel, J. M., Ravensbergen, L., Huig, N., Paassen, J., Rip, W. & Bakker, E. S. (2013). Aquatic grazers reduce the establishment and growth of riparian plants along an environmental gradient. *Freshwater Biology*, 58(9), 1794-1803.
- Verhagen, A., Van den Akker, J. J. H., Diemont, W. H., Schrijver, R. A. M., Wosten, H. M., Blok, C., Joosten, J.H.J., Schouten, M.A., Den Uyl, R.M. & Verweij, P. A. (2010). Peatlands and carbon flows. Outlook and importance for the Netherlands (No. WAB--500102027). Netherlands Environmental Assessment Agency PBL.
- Vonk, J., van der Sluis, S. M., Bannink, A., van Bruggen, C., Groenestein, C. M., Huijsmans, J. F. M., Kolk, J.W.H. van der, Luesink, H.H., Oude Voshaar, S.V., Sluis, S.M. & Velthof, G. L. (2018). Methodology for estimating emissions from agriculture in the Netherlands –update 2018 (No. 115). Statutory Research Tasks Unit for Nature & the Environment.
- Wallor, E. & Zeitz, J. (2016). How properties of differently cultivated fen soils affect grassland productivity—A broad investigation of environmental interactions in Northeast Germany. *Catena*, 147, 288-299.
- White, S.D., B.M. Deegan & G.G. Ganf (2007). The influence of water level fluctuations on the potential for convective flow in the emergent macrophytes *Typha domingensis* and *Phragmites australis*. *Aquatic Botany* 86(4), 369-376.
- Wichmann, S. (2018). Economic incentives for climate smart agriculture on peatlands in the EU. University of Greifswald, Partner in the Greifswald Mire Centre. Report, 38 p.
- Wichtmann, W. and Joosten, H. (2007). Paludiculture: peat formation and renewable resources from rewetted peatlands. *IMCG Newsletter*, 3, pp.24-28.
- Wichtmann, W., Tanneberger, F., Wichmann, S. and Joosten, H. (2010). Paludiculture is paludifuture: Climate, biodiversity and economic benefits from agriculture and forestry on rewetted peatland. *Peatlands International*, 1(2010), pp. 48-51.

- Wichtmann, W., Oehmke, C., Bärish, S., Deschan, F., Malashevich, U. & Tanneberger, F. (2014). Combustibility of biomass from wet fens in Belarus and its potential as a substitute for peat in fuel briquettes. *Mires and Peat*, 1, 1-10.
- Wichtmann, W., C. Schröder & H. Joosten (2016). *Paludiculture – productive use of wet peatlands*. Schweizerbart Science Publishers, Stuttgart.
- Wichtmann, W., Abel, S., Drösler, M., Freibauer, A., Harms, A., Heinze, S., Jensen, R., Kremkau, K., Landgraf, L., Peters, J., Rudolph, B.-U., Schiefelbein, U., Ullrich, K. & M. Winterholler (2018): Gute fachliche Praxis der Bewirtschaftung von Moorböden – Positionspapier (Langfassung) –Natur und Landschaft 93(8).
- Wieder R.K., Linton M.N. & Heston K.P. (1990). Laboratory mesocosms studies of Fe, Al, Mn, Ca, and Mg dynamics in wetlands exposed to synthetic acid coal mine drainage. *Water, Air and Soil Pollution* 51, 181-196.
- Wilcox, D.A., Apfelbaum, S.I. & Hiebert, R.D. (1984). Cattail invasion of sedge meadows following hydrologic disturbance in the Cowles Bog wetland complex, Indiana Dunes National Lakeshore. *Wetlands*, 4(1), 115-128.
- Wild, U., Kamp, T., Lenz, A., Heinz, S. & Pfadenhauer, J. (2001). Cultivation of *Typha* spp. in constructed wetlands for peatland restoration. *Ecological engineering*, 17(1), 49-54.
- Wilson, D., Blain, D., Couwenberg, J., Evans, C. D., Murdiyarso, D., Page, S. E., Renou-Wilson, F., Rieley, J.O., Sirin, A., Strack, M. & Tuittila, E. S. (2016). Greenhouse gas emission factors associated with rewetting of organic soils. *Mires and Peat*, 17.
- Windham, L. (2001). Comparison of biomass production and decomposition between *Phragmites australis* (common reed) and *Spartina patens* (salt hay grass) in brackish tidal marshes of New Jersey, USA. *Wetlands*, 21(2), 179-188.
- Wu, X. D., Wang, G. X., Li, Z. G., Xia, J., Wei, H. N., Xu, K. & Zhou, F. (2012). Effects of drought stress on growth and chlorophyll fluorescence parameters of *Typha orientalis*. *J Ecol Rural Environ*, 28, 103-107.
- Xie, F. & Vroom, R.J.E., Geurts, J.J.M., Chojnowska, A., Smolders, A.J.P., Lamers, L.P.M. & Fritz, C. *Typha latifolia* paludiculture efficiently extracts nutrients and reduces greenhouse gas emissions in rewetted peatlands. Under review in *Ecological Engineering*.
- Yu, Z. C. (2012). Northern peatland carbon stocks and dynamics: a review. *Biogeosciences*, 9(10), 4071-4085.
- Yu, B. L., Xin, R. L., Zhi, S. Z., Xiao, J. L. & Jin, W. (2016). The adaptive significance of differences of root morphology, anatomy and physiology from three ecotypes of reed (*Phragmites communis* Trin.). *Sciences in Cold and Arid Regions*, 8(3): 196-204.
- Zak, D., Wagner, C., Payer, B., Augustin, J. & Gelbrecht, J. (2010). Phosphorus mobilization in rewetted fens: the effect of altered peat properties and implications for their restoration. *Ecological Applications*, 20(5), 1336-1349.
- Zak, D., Meyer, N., Cabezas, A., Gelbrecht, J., Mauersberger, R., Tiemeyer, B., Wagner, C. & McInnes, R. (2017). Topsoil removal to minimize internal eutrophication in rewetted peatlands and to protect downstream systems against phosphorus pollution: a case study from NE Germany. *Ecological Engineering*, 103, 488-496.
- Zak, D., Goldhammer, T., Cabezas, A., Gelbrecht, J., Gurke, R., Wagner, C., Reuter, H., Augustin, J., Klimkowska A. & McInnes, R. (2018). Top soil removal reduces water pollution from phosphorus and dissolved organic matter and lowers methane emissions from rewetted peatlands. *Journal of Applied Ecology*, 55(1): 311-320.
- Zeitz, J. & Velty, S. (2002). Soil properties of drained and rewetted fen soils. *Journal of Plant Nutrition and Soil Science*, 165(5), 618-626.

5 Bijlage: persbericht CINDERELLA project

Paludicultuur: innovatieve, klimaatvriendelijke biomassa productie op vernatte veengronden

Landbouw op ontwaterde veengronden leidt tot bodemdaling, een enorme uitstoot van CO₂ en andere broeikasgassen, en uitspoeling van meststoffen, waarbij het landbouwgebied uiteindelijk verloren gaat. In het CINDERELLA project is onderzocht of paludicultuur – productief landgebruik op natte en opnieuw vernatte veenbodems met o.a. lisdodde, riet en veenmos – een economisch haalbaar, duurzaam en klimaatneutraal alternatief biedt voor reguliere landbouw op ontwaterd veen. De Radboud Universiteit heeft samen met partners uit Duitsland, Denemarken en Zweden gezocht naar een optimale combinatie van maatschappelijke diensten: gewasopbrengsten, klimaatwinst, waterzuivering en waterberging.

Met veldmetingen en experimenten is onderzocht hoe een paludicultuur opgestart moet worden, opbrengsten duurzaam verhoogd kunnen worden en uitstoot van broeikasgassen en meststoffen verminderd wordt. De uitkomsten zijn vertaald naar een handleiding met randvoorwaarden voor een succesvolle permanente cultuur op nat veen, die tijdens velddagen, workshops en congressen is gedeeld met boeren, waterbeheerders en andere belanghebbenden.

Testen op veldschaal laten zien dat het telen en oogsten van paludicultuurgewassen technisch en economisch haalbaar is bij een optimaal water- en bodembeheer, zeker wanneer naast de biomassaopbrengst ook de geleverde maatschappelijke diensten meegerekend worden. Hiermee kan paludicultuur een waardevolle bijdrage leveren aan een betere leefomgeving door het verminderen van overstromingsrisico's, tegengaan van bodemdaling, zuivering van voedselrijk oppervlaktewater en verbinding van landbouw met biodiversiteit. Afhankelijk van het doel ligt de focus op biomassaopbrengst of andere maatschappelijke diensten, waaronder klimaatwinst en biodiversiteit.

Voedselrijk landbouwwater verhoogt de opbrengst van paludicultuurgewassen en wordt tegelijkertijd gezuiverd. Hierdoor worden de uitspoeling van meststoffen en uitstoot van CO₂ en andere broeikasgassen substantieel (15-40 ton CO₂.eq per hectare per jaar) verlaagd in vergelijking met de gangbare landbouwpraktijk. Als 20% van de veenweidegebieden omgezet wordt in paludicultuur, levert dit een emissiereductie op van 1,2 tot 2 miljoen ton CO₂ per jaar, vergelijkbaar met de uitstoot van 400.000-700.000 personenauto's!

Daarnaast zijn proeven gedaan met de toepassing van paludicultuurgewassen als veevoer, bouw- en isolatiemateriaal, brandstof en substraat. Opscaling van paludicultuur is afhankelijk van marktontwikkeling, draagvlak in de agrarische sector en klimaatbewustzijn bij consumenten. Op dit moment verhindert wet- en regelgeving echter de toepassing van paludicultuur op grote schaal. Ook zijn de subsidieregelingen die voor de reguliere landbouw bestaan, nog niet toegankelijk voor boeren die willen overstappen op paludicultuur. Dat is nog een rem op de transitie naar een duurzaam landgebruik op veen.

Kortom, paludicultuur heeft veel potentie om veenpolders klimaatbestendig te maken en biedt goede kansen voor een koppeling tussen natuurinclusieve landbouw, circulaire economie en een gezonde leefomgeving.