Land Use Policy 152 (2025) 107500

Contents lists available at ScienceDirect

Land Use Policy

journal homepage: www.elsevier.com/locate/landusepol

# Measures to reduce land subsidence and greenhouse gas emissions in peatlands: A Dutch case study

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ARTICLE INFO

*Keywords:*
Land subsidence
Carbon cycling
Groundwater management
Land use
Climate change mitigation
Climate change adaptation

ABSTRACT

Worldwide, peatlands suffer from land subsidence and greenhouse gas emissions due to artificial drainage inducing peat decomposition. Under anthropogenic climate change, these issues require measures to reduce the emission of greenhouse gases and protect low-lying areas from increasing flood risk. Tighter control of groundwater levels is required, both within existing agricultural systems and through the development of new agricultural systems suitable for farming under high groundwater levels or inundation. The complexity and value-laden nature of the issue warrants the development of a comprehensive overview of potential and side effects of measures. In this paper such an overview is synthesized based on a mixed-method approach for a special case, The Netherlands. The Dutch peatlands comprise extensive land areas in the low-lying west and north of The Netherlands. The case is exceptional as most of these peatlands lie below sea level, sustain world-class intensive dairy farming and are subject to multiple other environmental, economic and societal challenges. Here, land subsidence increases flood risk, salt-water intrusion and the costs of water management, particularly under global climate change. To mitigate land subsidence, both technical measures and alternative land uses can be envisaged. However, the literature about these is fragmented, complicating a careful identification and selection of measures. To address this knowledge gap, we review 27 technical measures and alternative land use options and synthesize evidence and insights for 15 effects. Technical measures allowing continuation of existing dairy farming provide relatively low-risk interventions for farmers, but will only reduce, not stop land subsidence and greenhouse gas emissions. Alternative land-use options, particularly paludiculture, are in a start-up stage of development and can stop land subsidence. However, more research is required to reduce and control methane and potential nitrous oxide emissions during inundation required for crops such as (narrowleaf) cattail and azolla. Paludiculture can provide ecosystem services related to water management and nutrient status, as well as raw materials for a bio-based economy. Gradual transitions in space and time between farming and nature can be envisaged, providing incentives to diversify land use in the Dutch peatlands. This case study identifies key questions and provides valuable insights for peatland management worldwide. Reducing land subsidence and greenhouse gas emissions from peatlands is feasible, but requires thoughtful interventions that cautiously make and align trade-offs between various interests and uncertainties.

## 1. Introduction

Large-scale land use changes have caused and intensified global anthropogenic warming for centuries if not millennia (Ruddiman et al., 2020). In particular, drainage of peatlands causes peat oxidation, hence the release of carbon dioxide into the atmosphere. It is estimated that

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https://doi.org/10.1016/j.landusepol.2025.107500
Received 11 December 2023; Received in revised form 31 January 2025; Accepted 3 February 2025
Available online 14 February 2025

peatlands worldwide store 500–700 Gt of carbon (C), compared to 860 Gt C in the atmosphere, and release 645 Mt C $yr^{-1}$ (401–1025 Mt C $yr^{-1}$) through soil respiration (Ma et al., 2022). This equates to approximately 5 % of global annual anthropogenic carbon emissions, of which the majority is caused by the burning of fossil fuels.

Under drainage conditions, emissions from peatlands are dominated by carbon dioxide ($CO_2$) formed during peat decomposition (Aben et al., 2024; Couwenberg et al., 2011; Evans et al., 2021; Tiemeyer et al., 2020). Wetter conditions will reduce oxidation and hence $CO_2$ emissions, but may at the same time increase methane ($CH_4$) emissions (Zak and McInnes, 2022). Moreover, minerotrophic (nutrient-rich) and fertilized peatlands are potentially dramatic sources of nitrous oxide ($N_2O$), a potent greenhouse gas (GHG) (Butterbach-Bahl et al., 2013). Non-fossil $CH_4$ and $N_2O$ have a 20-year $CO_2$-equivalent ($CO_2$-eq) global warming potential (GWP) of 79.7 and 273 (GWP-20), respectively; and a 100-year $CO_2$-eq GWP of 27.0 and 273 (GWP-100), respectively (Forster et al., 2021). There is some debate on which GWP should be used in reporting. GHG emissions due to land use changes tend to be reported using GWP-100, though this may be inappropriate if short-term and dramatic aspects of climate change are considered.

Apart from drainage, peat decomposition is enhanced by anthropogenic warming itself. Higher temperatures increase microbial activity and more intense droughts additionally lower groundwater levels (GL), inducing a positive feedback to this global warming (Ma et al., 2022). Drainage also causes land subsidence, due to peat oxidation, irreversible shrinkage in the unsaturated zone of peat soils and partially reversible deformation in the saturated zone (Erkens et al., 2021; Koster et al., 2018; Schothorst, 1977). Under global climate change, with more erratic rainfall and rising sea levels, sinking peatlands increase the risk of flooding.

Hence, reduced drainage of peatlands will not only mitigate climate change, but also reduce the need for climate adaptation. Under the Paris Agreement, GHG emissions need to be cut dramatically, while local and national policies try to curb land subsidence under climate adaptation programs. These efforts are essential to breach a vicious spiralling towards ongoing climate warming in increasingly vulnerable areas.

Less variable, high GLs abate land subsidence and GHG emissions. A recent review on future land use in peatlands suggests that a theoretical GL of $4 \pm 3$ cm below the surface provides the optimum of relatively low $CO_2$ and $CH_4$ emissions (Freeman et al., 2022), but variability between sites is huge (Ma et al., 2022). It is essential not only to raise annual mean GL, but also to maintain high GLs during dry summers (Boonman et al., 2022; Erkens et al., 2021). Emissions of $N_2O$ from peatlands are less well understood, but evidence suggests that those tend to be minimized at stable GLs as well, in combination with low or no fertilization (Freeman et al., 2022). Peatlands that have been cultivated for centuries, like the Dutch peatlands, tend to be rich in nitrogen, causing large $N_2O$ pulses during GL fluctuations and acute inundation. All in all, this suggests that multiple water management strategies can be applied. Boonman et al. (2022) propose to keep GL between 20 and 30 cm below the surface to prevent accidental flooding, while Antonijević et al. (2023) provide initial evidence that $CH_4$-emissions from inundated fields can be reduced dramatically by cultivating $CH_4$-oxidizing plant species, such as cattail and sedge.

To achieve less variable and higher GLs, Freeman et al. (2022) suggest two types of wetland agriculture systems, that is, reduced drainage in conventional systems and crop cultivation fully adapted to wet conditions: paludiculture (Wichtmann et al., 2016). The first system requires technical measures in need of optimization (i.e., system optimization), while the second system requires the development of a completely new agricultural system, including yield control and market formation (i.e., system transformation). Both systems require (a mix of) individual measures, intended to reduce land subsidence and GHG emissions, while retaining or creating profitable agricultural systems and contributing to positive side effects. Where technical measures can support existing farmers during and after the transition, paludiculture requires time and funding for experimenting, community building and gradual upscaling of those initiatives that turn out to provide a desirable contribution to the peatland landscapes of the future. Those landscapes will be more diverse than at present (Freeman et al., 2022), including various types of agriculture alongside (semi-)natural, urban, horticulture and permaculture initiatives.

Land subsidence and GHG emissions in peatlands constitute a wicked problem (Van den Ende et al., 2023) as advocated by Rittel and Webber (1973). Although strong reductions in land subsidence and GHG emissions can be regarded as a collective good, disagreement about how and how much this should be strived for is rife. Also, the uncertainties with respect to the performance and side effects of technical measures and the opportunities of paludiculture are large. Any action taken can irreversibly change aspects of and perspectives on the problem, and may mitigate, increase or create other environmental and societal challenges. Hence, it is essential to accept the wickedness of the problem and learn from societal opposition (Pesch and Vermaas, 2020) through interaction with a diverse group of stakeholders, including the least powerful. Such an approach to addressing land subsidence and GHG emissions in peatlands requires a comprehensive and transparent overview of available measures, their potential and side effects.

However, so far the analysis of measures to reduce land subsidence and GHG emissions in peatlands has been limited to a comparison of a few technical measures, land-use options or agricultural systems. Studies tend to focus on specific cases and aim to identify the 'best' solution for that case, (explicitly and/or implicitly) assuming a particular set of objectives and values and the legitimacy of a particular group of stakeholders (Van Hardeveld et al., 2020; Van Hardeveld et al., 2018; Van Hardeveld et al., 2019; Van Mulken et al., 2023a,b). A more comprehensive review and synthesis of evidence and insights regarding individual technical measures and land-use options will clarify the spectrum of interventions available to reduce land subsidence and GHG emissions in peatlands, while at the same time addressing other environmental and societal challenges. Such an analysis is a prerequisite for improving the understanding of the potential association between various measures at the landscape level. It will sketch a horizon of what reductions in land subsidence and GHG emissions are possible at what cost or, maybe rather, provide what opportunities, and provide an assessment of the risks of implementing specific measures. It will identify key questions for ongoing research and provide a fair baseline for value-driven interaction with stakeholders and the general public as advocated by Hegger et al. (2023) and during decision making.

In this paper we present a case study on the Dutch peatlands (Fig. 1). These peatlands represent an exceptional case of more than a thousand years of peatland degradation. Today, about half of the coastal-deltaic plain of The Netherlands lies below mean sea level. With the deepest point in a former peat excavation site at 6.76 m below sea level, water management challenges are already severe, including flood risk and saltwater intrusion. The land continues to subside, with a strong contribution from oxidizing peat under drained agriculture (Koster et al., 2018). Hence, if no interventions take place, water management issues will only increase under sea level rise induced by anthropogenic warming.

The Dutch government is keen to reduce peatland subsidence by increasing GL (Van den Born et al., 2016). In a recent letter to parliament, the Dutch Minister of Infrastructure and Water Management described his intention to raise the priority of water and soil management in spatial planning (Harbers and Heijnen, 2022). The Dutch Climate Agreement states that those peatland areas that are currently in use as pastures, the so called peat meadow areas, are required to reduce their GHG emissions by 1.0 Mt $CO_2$-eq $yr^{-1}$ (Nijpels, 2019), out of approximately 4 Mt $CO_2$-eq $yr^{-1}$ (19 t $CO_2$-eq $yr^{-1}$ $ha^{-1}$) (Arets et al., 2019), by 2030. On a national scale, this is intended to contribute towards a reduction of 49 % and 95 % in GHG emissions in 2030 and 2050, respectively. Specific targets for the Dutch peatlands in 2050 have not been set yet, though the Dutch Climate Agreement indicates that the targets of 2030 should be achieved by 'prioritizing' (Dutch: 'centraal

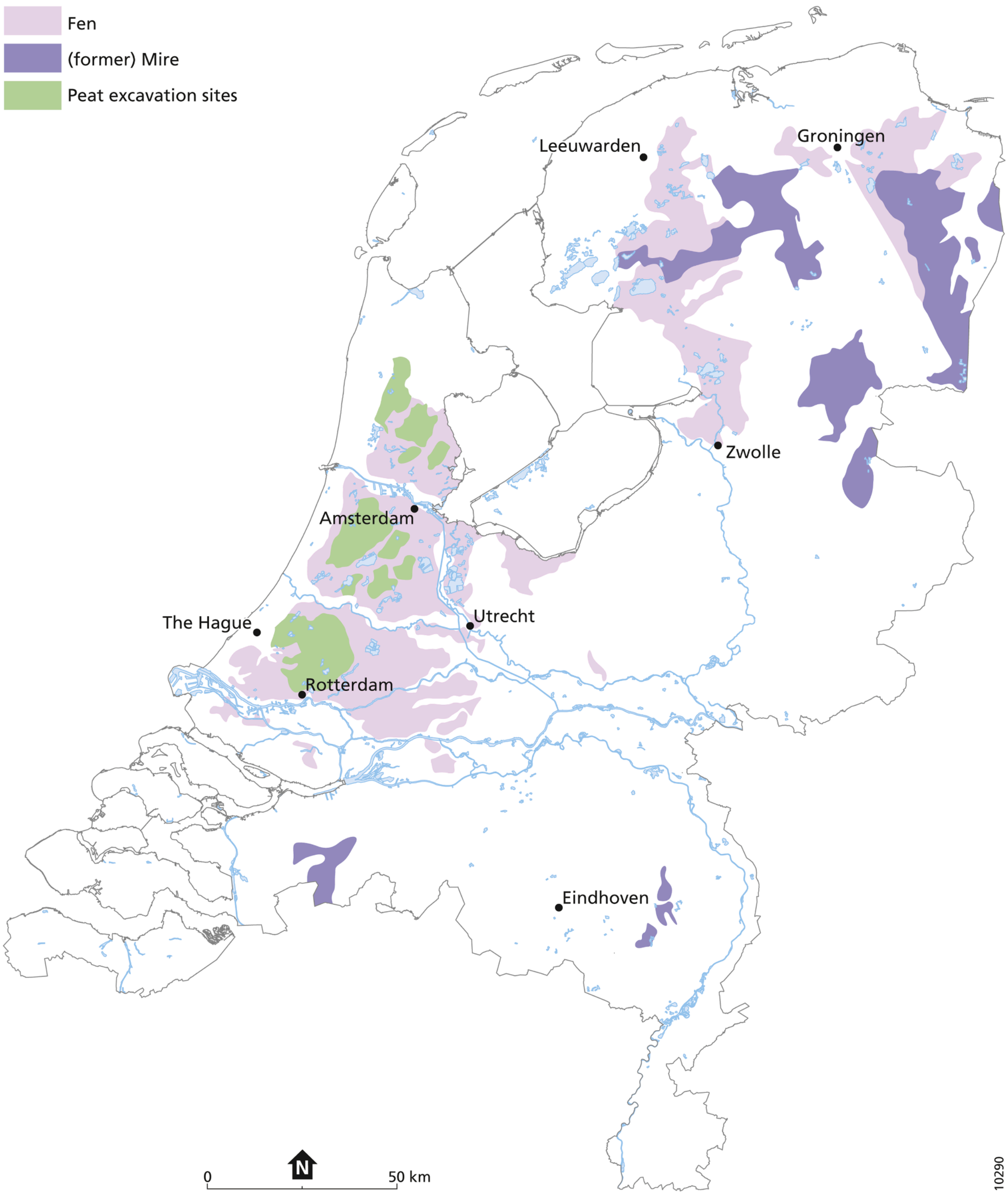


**Fig. 1.** The Dutch peatlands (graphic design: A.W. Markus, Utrecht University).

stellen') the outlook to 2050 (Nijpels, 2019).

Besides land subsidence and GHG emissions, Dutch agricultural peatlands face many other challenges. On the environmental side, water quantity during dry summers (Ministerie van Infrastructuur en Milieu, 2015), water quality (Van Gaalen et al., 2020), and nitrogen deposition in Natura 2000 sites (Vink and Van Hinsberg, 2019) require urgent action. On the economic and societal side, farmer's income and strong dependence of prevailing dairy farming on the world market (Verburg et al., 2022) in conjunction with urban land claims for housing, recreation and energy production define political tensions (Overbeek and Terluin, 2006). Reducing land subsidence and GHG emissions in the Dutch peatlands can be pivotal in addressing multiple of these challenges.

We have two objectives in this paper:

(1) to contribute to the understanding of technical measures and alternative land-use options to reduce land subsidence and GHG emissions in peatlands worldwide by reviewing those in the Dutch peatlands;
(2) to construct a framework for research and decision making in peatland management by synthesizing evidence and insights on intended and side effects of the measures and land-use options as such and in conjunction with each other.

## 2. Study area

Peat formation on the coastal-deltaic plain of The Netherlands peaked between 6000 and 2000 BP (Berendsen et al., 2019; Vos, 2015). In the western and northern parts of the country, wetlands dissected by dynamic river channels developed behind coastal barrier islands. Along the channels riparian forests and fens allowed the development of minerotrophic (nutrient-rich) peat, while at some distance from both sea and rivers ombrotrophic (nutrient-poor), *Sphagnum* peat was formed in mires. Depending on the distance from marine and fluviatile sources of sediment, the peat layers are intercalated with and/or covered by clay layers. In the most recent millennia clastic sedimentation increased in response to deforestation in Germany (Erkens, 2009).

Systematic cultivation of the Dutch peatlands began in the 10th century (Borger, 2010). Colonists started cultivation along river channels and gradually extended their fields further into the peatland. As field width was stated in the contract with the landlord, highly regular landscapes consisting of rectangular fields bordered by ditches developed. Originally, crops could be cultivated, but as water extraction led to land subsidence and hence higher GL, land use changed to meadows. In proximity of major cities commercial dairy farming, including cheese-making, became the dominant agricultural system.

Between the Late Middle Ages and the late 19th century, most ombrotrophic peat was extracted and used as fuel (Stol, 2010). Lakes developed due to this extraction, particularly in the west, and were subsequently reclaimed. These peat excavation sites are currently polders at 4 to almost 7 m below sea level (Fig. 1), but as they now have a marine clay soil they do not belong to the Dutch peatlands anymore. Due to the excavation of ombrotrophic peat, most of the remaining peatlands consist of minerotrophic peat, developed in riparian forests dominated by black alder (Berendsen et al., 2019).

In the remaining peatlands land subsidence of multiple meters resulted from compaction, compression, shrinkage and peat oxidation over the centuries (Berendsen et al., 2019). Currently, these peatlands cover about 274,000 ha (or 6 %) of The Netherlands (Arets et al., 2019). They are well below sea level and require artificial water management including pumping stations and dikes. The topsoil has been influenced by floods, farmers and peat mineralization. In many locations floods left a clay-rich topsoil, while farmers added sediment available from clearing ditches.

About 207,000 ha of the Dutch peatlands are used for agriculture, mostly dairy farming (Arets et al., 2019). The long tradition of dairy farming is this region contributes to the perceived cultural and historical value of this type of farming and associated landscapes. Dairy cows grazing rectangular green meadows, bordered by ditches, in a panoramic landscape with unobstructed views is regarded as 'typically Dutch'. At the same time, under government and market pressure in relation to growing populations and food shortage during World War II, this dairy farming gradually developed into an intensive and highly mechanized type of agriculture. According to Verburg et al. (2022), limited governance in the early 21st century has intensified these developments, leaving the Dutch peatlands now with a multitude of environmental problems, including land subsidence, GHG and nitrogen emissions, and water quality and quantity issues.

Currently, multiple research and innovation programs are underway to improve the understanding of how to reduce land subsidence and GHG emissions in the Dutch peatlands, in particular Living on Soft Soils (LOSS[1]), Netherlands Research Program on Greenhouse Gas Dynamics in Peatlands and Organic Soils (NOBV[2]), Regio Deal Land Subsidence Groene Hart[3] and Peatland Innovation Programme Netherlands (VIPNL[4]). LOSS focuses on land subsidence, NOBV and VIPNL focus on GHG emissions, while the Regio Deal is a regional land subsidence program in the rural peatland area surrounded by the major cities of Rotterdam, The Hague, Amsterdam and Utrecht, in the west of The Netherlands. It is of particular importance to assess the impact of typically Dutch peat soil characteristics, such as clay covers, high levels of peat mineralization and soil modification by farmers, on GHG emissions. Any measure studied in these programs will have to be evaluated on side effects, if it will make any chance for large-scale implementation. Governance and legal challenges associated with systemic change are also studied within LOSS (Van den Ende et al., 2023; Van Gils and Groothuijse, 2021; Van Gils et al., 2021).

## 3. Methodology and methods

### 3.1. Methodology

The methodology employed is the case study. A case study can be defined as "an intensive study of a single unit for the purpose of understanding a larger class of (similar) units" (Gerring, 2004, p. 342). In this study, the unit is the nation-state of The Netherlands and the larger class of (similar) units consists of other governmental entities faced with land subsidence and/or GHG emissions in peatlands. Intentionally, a case study differs from a non-case study in several ways, in which these differences should be understood as tendencies rather than sharp distinctions. By its very nature a case study provides more in-depth understanding at the expense of breadth and boundedness (Gerring, 2004). It is more focused on description and comparability than on causality and representativeness, more on mechanisms than on effects (Gerring, 2004). Through their characteristic exploratory strategies case studies play a key role in theory generation, where non-case studies tend to focus on verification or falsification of existing theory (Gerring, 2004).

This case study is fundamentally explorative, bringing together a wide variety of initiatives, ideas and policy considerations with the aim of clarifying the playing field for agricultural and landscape transition in the Dutch peatlands. It does not have the intention to identify a 'best' solution through a positivist approach, but rather tries to understand the nature and value of the existing and developing diversity in solutions through an interpretivist approach (Harrison et al., 2017). Inherent of a case study, the research studies the Dutch situation in its own right and at the same time as an example of the more general transitions in peatlands worldwide. Where relevant it draws in evidence from locations outside The Netherlands.

### 3.2. Research plan

First, 27 measures to reduce land subsidence and GHG emissions were selected for evaluation through literature review, discussions with experts and stakeholders, and a survey of ongoing projects and pilot studies in The Netherlands (Fig. 2). It is intended to be comprehensive, that is, to include most, if not all, measures with at least some experimental history in The Netherlands, and beyond if possibly relevant for the Dutch context. If recent research on specific measures has outdated previous publications, focus has been given to recent publications. As many of the publications on projects and pilot studies in The Netherlands are grey literature reports or even websites in Dutch, the search for evidence and insights has been intense and multifaceted.

Discussions among the authors and with experts and stakeholders and an analysis of the website of the International Mire Conservation Group (IMCG, https://www.imcg.net/) yielded a group of key publications to start from. These included NOBV documents (Boonman et al., 2022; Erkens et al., 2021; Hoogland et al., 2021; Kloosterman et al., 2021; Pijlman et al., 2021; Scholten and Troost, 2021; Speet and

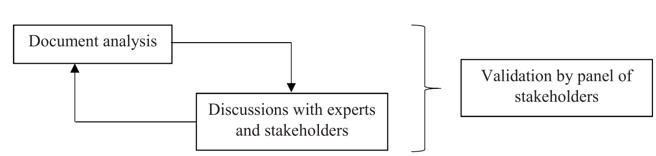


**Fig. 2.** Schematic visualization of the methodology.

[1] https://nwa-loss.nl/
[2] https://www.nobveenweiden.nl/en/
[3] https://bodemdalingdebaas.nl/
[4] https://vip-nl.nl/

Honkoop, 2021; Verhagen et al., 2021), a review on responsible agriculture in mid-latitude peatlands by Freeman et al. (2022), a book on paludiculture (Wichtmann et al., 2016) and initial work on water (drainage and) infiltration systems (WIS) by Van den Akker and Hendriks (2017) and Hoving et al. (2018, 2021, 2022). From these publications a first snowballing exercise was done using their references and the 'cited by' and 'related articles' options in Google Scholar.

Subsequently, the set of studies on paludiculture was extended by searches in Google Scholar using keywords such as "paludiculture", the names of the crops and descriptions of the effects, e.g. "paludiculture cattail greenhouse gases". Due to variable terminology, similar searches for WIS proved more difficult, but keywords such as "submerged drains" and "subsoil irrigation" have been applied. Additional searches were conducted using keywords such as "land subsidence", "ombrotrophic mire", "minerotrophic fen" and "riparian forest", in combination with effect descriptions such as "carbon sequestration", "carbon balance" and "carbon sink". To capture the grey literature, websites of relevant Dutch ministries and research organizations were scanned and in Google searches were conducted using Dutch keywords such as "Louis Bolk Instituut", "veenweide innovatie", "klei-in-veen", "natte teelten" and "weidevogels".[5] From relevant publications more work was found using snowballing as described before. Also, newly found publications often identified new keywords and unknown stakeholders. Continuous interaction with stakeholders helped to find small and ongoing experiments, and to better understand the dynamics of debates in the literature and community.

The selected measures were grouped into four categories. First, there are technical measures to improve the control on the groundwater level or to change physical or chemical properties of the soil, which more or less allows the continuation of the current land use, mostly intensive dairy farming. Second, there are paludiculture options where crops or cattle more suitable for wet conditions are being cultivated. Third, there are alternative semi-natural and highly technical options already present in the Dutch peatlands. Fourth, there are options to (re)develop or expand natural ecosystems.

Subsequently, 15 effects of those measures were identified, again through the literature review, discussions with experts and stakeholders, and preliminary results of ongoing projects and pilot studies described above, but also through a survey of agricultural topics receiving major political attention as well as recent, current and future urban land claims reported in national newspapers such as Trouw and de Volkskrant. Similar to the measures, this list of effects is intended to reflect all relevant major issues concerning the Dutch peatlands. The first effect considered is the influence of each measure on groundwater level, which has a major impact on the subsequent environmental, economic, societal and political effects considered.

For each measure, the available evidence on each effect was classified using labels indicating the degree or nature of the contribution or the adverse impact the measure provides to the particular effect (Table 1). For readability, the labels presume an intended direction of change for each effect, based on prevailing policy documents. The available evidence to be classified was collected using document analysis and discussions with experts and stakeholders (Fig. 2). All statements in this paper are based on documented evidence as referenced in the Results section, but experts provided guidance and identification of biases during the complex reviewing process. For clarification the kind of underlying evidence of each individual label is indicated in Table S1, distinguishing between direct and associated field evidence, direct lab evidence, derived from modelling, logical inference (from related evidence or by definition) and expert assessment (based on the combined evidence presented in this paper). For GHG emissions, balance estimates were made for $CO_2$, $CH_4$ and $N_2O$ combined under (hypothetical) optimized conditions. These optimized conditions were derived from successful pilot studies or, if unavailable, theoretical considerations, and may not be feasible in all parts of the Dutch peatlands. Changes in the risk of $N_2O$ emissions can also be derived indirectly from the evidence available for the side effect 'fertilization', as reduced fertilization will decrease the amount of nitrogen available, hence the potential for $N_2O$ formation. Please note that field evidence does not necessarily provide the most robust evidence, as it often represents only one or a few cases for highly complex and variable effects, while for example logical inference can simply be a matter of how the measure is defined.

**Table 1**
Explanation of the qualitative labels assigned to the various combinations of intervention and effect in Table 2.

| Label | Abbreviation | Explanation |
|---|---|---|
| c | contribution | The available evidence converges towards the notion that the intervention does provide a substantial contribution to the intended effect. |
| sc | strong contribution | The available evidence converges towards the notion that the contribution of the intervention is substantially stronger than the contribution of other measures in this study. |
| n | no contribution | The available evidence converges towards the notion that the intervention does not provide a substantial contribution to the intended effect. |
| a | adverse impact | The available evidence converges towards the notion that the intervention has an adverse impact on the intended effect. |
| sa | strong adverse impact | The available evidence converges towards the notion that the adverse impact of the intervention is substantially stronger than the adverse impact of other measures in this study. |
| c/a | contribution or adverse impact | The available evidence converges towards the notion that whether the intervention provides a substantial contribution to or has an adverse impact on the intended effect depends on the way of implementation. |
| n/c | potential contribution | The available evidence converges towards the notion that whether the intervention provides a substantial contribution to the intended effect depends on the way of implementation. |
| ? | inconclusive | The available evidence is inconclusive with regard to the intervention's potential contribution to or adverse impact on the intended effect. |
| I | inundation | The intervention requires (the risk of) inundation. |
| R | land rise | The intervention does not just reduce land subsidence, but will initiate rebound by renewed peat formation and/or sedimentation. |
| L | life-cycle dependent | The net GHG balance of the intervention depends on the life cycle of the produced natural resources. |
| S | possible GHG sink | In the long term the intervention can develop into a net GHG sink. |

Though all measures are in a phase of testing and optimization, the evidence on technical measures, alternatives and nature is more consistent than that on paludiculture options. Some of this difference is illustrated in the labelling, e.g. the use of ? and /. However, where paludiculture options received unambiguous labels, the variability in the underlying evidence tends to be higher than that of the labels for the other three groups of measures.

Results were validated by a panel of 26 stakeholders involved in the LOSS project on land subsidence (Fig. 2). The LOSS project is a Dutch Research Agenda (NWA) project, of which a strong link between society and science is an essential part. The consulted group of stakeholders included policy makers at various governmental levels, representatives of interest groups, experts and consultants. This group of stakeholders validated the key findings and their input led to only minor textual amendments in the manuscript.

[5] These keywords refer to relevant institutes (e.g. Louis Bolk Instituut), initiatives (e.g. veenweide innovatie), measures (e.g. klei-in-veen, natte teelten) and effects (e.g. weidevogels).

### 3.3. Measure identification

The measures to reduce land subsidence and GHG emissions selected for evaluation are listed in Table 2. **Technical measures** aimed at increasing groundwater level include trench infiltration, passive water (drainage and) infiltration systems (WIS), active WIS, raised ditch water level and dynamic ditch water level. Raising ditch water levels, either by active intervention or as a result of gradual land subsidence without ditch water level adjustment (Van den Born et al., 2016), can be considered as a first step towards increasing groundwater level. However, during dry summers the water table will still drop substantially in the centre area of the meadows, while during wet winters the meadows may flood. WIS try to reduce both effects by installing drainage pipes at approx. 20 cm below ditch water level, allowing drainage under wet conditions and infiltration under dry conditions (Kiwa, Nederland, 2021; Van den Akker and Hendriks, 2017; Van den Akker et al., 2018). To improve the performance of these WIS, the system of pipes has been integrated with a pump and a reservoir (Hoving et al., 2018). The water level in the reservoir can be lowered or raised to respectively drain in wet periods or infiltrate in dry periods to maintain a stable high groundwater level; these systems are called active WIS (Boonman et al., 2022). Attempts to reduce costs have given rise to the introduction of infiltration through trenches parallel to the ditches and to dynamic ditch water level strategies including high levels during summer (Erkens et al., 2021; Pijlman et al., 2021).

Technical measures aimed at changing the physical or chemical properties of the soil include clay-in-peat, mineral clay or sand cover, acidification and salinization. Clay-in-peat is an innovative technique trying to develop clay-peat complexes, which may be more resistant to decay than the existing peat soil, through the illuviation of specific clay types available from dredging at nearby sites (Van Agtmaal et al., 2019). The application of a mineral cover, either sediment dredged from nearby ditches, channels or harbours or obtained from sandy layers below the peat itself, may in combination with an adequate groundwater level protect underlying peat from oxidation (Bakema et al., 2022; Dijk, 2025; Speet and Honkoop, 2021). Acidification and salinization may decrease microbial activity and soil processes, hence reduce peat mineralization (Speet and Honkoop, 2021).

**Paludiculture** options include a wide range of crops and cattle. For this review crops and cattle have been selected that provide a varied overview of the potential of paludiculture in The Netherlands, providing construction material (cattail, reed, elephant grass, willow, black alder), fodder (azolla, wild rice), biofuel (elephant grass), food (wild rice, cranberry, water buffalo, food forest) and substrate (peat moss) (Bestman et al., 2019a; Crouwers and Harleman, 2025; Ferguson and Lovell, 2014; Gremmen et al., 2022; Huth et al., 2018; Koornneef, 2021; Mettrop and Oosterveld, 2019; Moons, 2021; Pijlman et al., 2021; Speet and Honkoop, 2021; Wichtmann et al., 2016). Most of the selected options have already been or are currently being piloted in the Dutch peatlands.

**Alternative** semi-natural and highly technical options include semi-natural meadows, greenhouses, solar panels and urban area. Semi-natural meadows are wet, oligotrophic meadows that can attract so-called ‘meadow’ bird species. Construction of greenhouses, fields of solar panels and urban area is currently taking place in the heavily urbanized west of The Netherlands. Greenhouse cultivation of fruit, vegetables and flowers has a long history in areas close to The Hague, Rotterdam and Schiphol Airport. Solar panels contribute to the ongoing transition to a sustainable energy regime, while soaring housing prices have given rise to a house building boom and expansion of urban areas.

Options to (re)develop or expand **natural ecosystems** include the development of ombrotrophic mires, minerotrophic fens and riparian forests. Historically, the coastal-deltaic plain of The Netherlands was dominated by riparian forests and minerotrophic fens along the river channels and ombrotrophic *Sphagnum* mires beyond (Berendsen et al., 2019). Due to the extraction of mainly ombrotrophic peat for fuel production, most of the remaining peat is minerotrophic. The excavation sites transformed into lakes, which were often reclaimed or developed into minerotrophic fens. Hence, the development of ombrotrophic mires, minerotrophic fens and riparian forests as nature reserves can be considered a re-creation of native ecosystems. In fact, all four National Parks (NP) in the Dutch peatlands are either regenerating excavation sites consisting of lakes and surrounding fens (NP De Alde Feanen, NP Weerribben-Wieden) or mires (NP De Groote Peel), or freshwater tidal riparian forests (NP De Biesbosch). Additional Natura 2000 sites are regenerating excavation sites as well.

### 3.4. Effect selection

The effects of measures to reduce land subsidence and GHG emissions selected for evaluation are listed in Table 2. The impact on GL is the first effect considered, being a key variable to understand multiple other effects. As both the average GL and its variability, particularly summer GL, are of importance, the labels represent the degree to which average, summer and stability of GL are increased. Subsequently, the impact on land subsidence is considered, being the key variable under concern. Here, the labels reflect an assessment of the combined effect of the measure on reducing peat oxidation, shrinkage, compression and peat formation.

Labels for GHG emissions reflect an assessment of the combined effect on reducing $CO_2$, $CH_4$ and $N_2O$ emissions. The potential impact of the measure on the availability of water, water quantity, is of particular importance in dry summers. Water quality and fertilization are interrelated, as a reduction in fertilization can improve water quality.

The main biodiversity issue in the Dutch peatlands concerns so called ‘meadow’ bird species, such as the black-tailed godwit (*Limosa limosa*), northern lapwing (*Vanellus vanellus*), common redshank (*Tringa tetanus*), ruff (*Calidris pugnax*), Eurasian oystercatcher (*Haematopus ostralegus*) and Eurasian skylark (*Alauda arvensis*) (Pijlman et al., 2021). These meadow birds, near threatened or of least concern worldwide, are characteristic of the cultural Dutch peatland landscape, but their numbers have been strongly falling since the 1970s.

Rewetting of peatlands can increase the risk of disease for both cattle and humans. For example, the parasite *Fasciola hepatica*, dwelling in freshwater conditions, causes liver fluke (fascioliasis) on infection of cows, sheep and goats (Pijlman et al., 2021), and can also be transferred to humans (Aksoy et al., 2005). This disease has dire consequences for animal well-being, produce (milk, meat) and resistance to other diseases. Also, the development of extensive wetlands in proximity of major cities poses a risk of mosquito breeding, which may, particularly under global warming, increase the incidence of mosquito-borne diseases.

The technical feasibility of a measure depends on the degree to which its anticipated effect has already been proven in practice, whereas the economic viability refers to the expected cost-benefit balance. The impact of a measure on world food production and potential increases in (the intensity of) agricultural land use elsewhere have been evaluated, taking account of the worldwide concern over food security in the near future under a growing world population and increasing environmental pressure (Mora et al., 2020).

From an urban perspective, the opportunities for recreation in newly developed landscapes are of importance, while from a cultural perspective, the historical value of those landscapes require consideration. Finally, based on the full analysis, an assessment was made of the long-term viability of each measure.

## 4. Results

In this section we describe the results of classifying the available evidence for 27 measures on 15 effects.

**Table 2**
Comparison of technical measures and land-use options to reduce land subsidence and GHG emissions.

Labels are *qualitative classifications* of evidence available for or applicable to conditions *optimized* for reducing land subsidence and GHG emissions in *appropriate locations*.

| | | number | groundwater level | land subsidence | GHG emissions | available water quantity | water quality | fertilization (N and P deposition) | population meadow birds | disease risk | technical feasibility | economic viability | food production | land use elsewhere | recreation | historical landscape conservation | viability in the long term? |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| technical measures | trench infiltration | 1 | c | c | ? | sa | n | n | c | a | c | c | n | n | n | c | a |
| | passive water infiltration systems (WIS) | 2 | c | c | c | a | n | n | c | n | c | c | n | n | n | c | n |
| | active WIS | 3 | sc | sc | sc | a | n | n | c | n | sc | n | n | n | n | c | c |
| | high ditch water level | 4 | c | c | c | a | n | n | c | n | c | n | a | n | n | c | a |
| | dynamic ditch water level | 5 | c | c | c | a | n | n | c | n | c | c | n | n | n | c | a |
| | clay-in-peat | 6 | n | ? | ? | n | n | n | n | n | ? | ? | n | n | n | c | ? |
| | mineral cover | 7 | n | c | c | n | n | n | ? | n | c | a | c | n | n | c | c |
| | acidification | 8 | n | c | c | n | a | n | a | n | c | ? | n | n | n | c | a |
| | salinization | 9 | n | c | c | c | a | n | a | n | c | n | n | n | n | c | n |
| paludiculture | cattail | 10 | I | sc | L | c/a | c/a | n/c | ? | a | c | ? | a | a | ? | a | c |
| | reed | 11 | I | sc | L | c/a | c/a | n/c | ? | a | c | ? | a | a | ? | a | c |
| | azolla | 12 | I | sc | ? | c/a | c/a | n/c | ? | a | ? | ? | c | n | a | a | ? |
| | wild rice | 13 | I | sc | ? | c/a | c/a | n/c | ? | a | ? | ? | c | n | ? | a | ? |
| | elephant grass | 14 | sc | sc | c | c/a | c/a | n/c | ? | n | ? | ? | a | a | ? | a | c |
| | willow | 15 | sc | sc | c | c/a | c/a | n/c | a | n | ? | ? | a | a | ? | a | c |
| | cranberry | 16 | sc | sc | c | a | c | c | a | n | ? | ? | c | n | c | a | c |
| | water buffalo | 17 | c | c | c | a | n | n | n | n | ? | ? | a | n | c | a | ? |
| | food forest | 18 | sc | sc | c | c/a | c | c | a | n | c/a | ? | c | n | c | a | c |
| | black alder | 19 | sc | sc | sc | c/a | c | c | a | n | c | ? | a | a | c | a | ? |
| | peat moss cultivation | 20 | sc | sc | sc | c/a | sc | sc | c? | n | ? | ? | a | a | ? | a | c |
| alternative | semi-natural meadows | 21 | c | c | c | a | c | c | sc | n | c | 0 | a | a | c | c | n |
| | greenhouses | 22 | c | n | c | a | c | c | sa | n | c | c | sc | n | sa | a | n |
| | solar panels | 23 | c | c | c | a | c | c | sa | n | c | c | sa | a | sa | a | a |
| | urban area | 24 | c | n | c | a | c/a | c | sa | n | c | c | sa | a | a | a | ? |
| nature | ombrotrophic mire | 25 | sc | R | S | c/a | sc | sc | c/a | n | ? | n | sa | a | sc | n | c |
| | minerotrophic fen | 26 | I | R | S | c | c/a | sc | c/a | n | c | n | sa | a | sc | c | c |
| | riparian forest | 27 | c | R | S | c | sc | sc | a | n | c | n | sa | a | sc | n | c |

The labels assigned to 15 intended effects indicate (strong) contribution (c, sc), no contribution (n), (strong) adverse impact (a, sa) and inconclusive (?). Special cases are indicated by a capital letter, that is, inundation (I), land rise (R), life-cycle dependent (L) and possible GHG sink (S, in the long term; in the short term there may be increases in $N_2O$ and $CH_4$ emission). Phase of development is indicated by gold shading, based on ranking and grouping of the ranks in four equal classes, where darker colours indicate more advanced stages of development (see Discussion for explanation). Labels are *qualitative classifications* of evidence available for or applicable to conditions *optimized* for reducing land subsidence and GHG emissions in *appropriate locations*.

### *4.1. Technical measures*

Technical measures are intended to reduce land subsidence and GHG emissions, while mostly retaining existing land use and farming intensity. Hence, these measures tend to contribute to reducing land subsidence and GHG emissions, with no effect on water quality, fertilization, land use elsewhere and recreation (Table 2). The measures contribute to the technical feasibility of addressing land subsidence and GHG emissions and to historical landscape conservation (Table 2). However, there is some debate on the effectiveness and the other effects of those measures.

In particular, fierce debate has arisen over the effectiveness of WIS (Couwenberg, 2018a,b; Van den Akker et al., 2018). These discussions emphasize the crucial importance of adequate ditch water level for correct operation of passive WIS, as infiltration can only occur if water pressure is high enough. In itself WIS have been designed to reduce GL during winter and increase GL during summer, to improve access to the land during winter, and reduce peat oxidation during summer. Hence, as a technical measure to reduce land subsidence and GHG emissions, WIS affect *summer* GL, not necessarily *mean* GL. By reducing GL drops during dry summers, WIS can reduce land subsidence and GHG emission, but to achieve a more substantial effect WIS should be considered in combination with raised ditch water level. In such arrangement, WIS predominantly serve to improve the precision of water management, allowing a raise in ditch water level without regular flooding.

Evidence shows that WIS do indeed reduce intra-annual variability in GL, particularly in dry-summer years, and that this reduces irreversible shrinkage in the unsaturated zone and partially reversible deformation in the saturated zone of the peat soil (Erkens et al., 2021). This reduces land subsidence. Increased GLs in summer also reduce peat oxidation, hence land subsidence and GHG emissions. Reductions in GHG emissions, up to 28 $\pm$ 15 % (6.6 $\pm$ 6.2 t $CO_2$ $ha^{-1}$ $yr^{-1}$) at a site in Vlist in dry-summer year 2020, have been reported, but obtained results vary strongly (Aben et al., 2024; Boonman et al., 2022; Erkens et al., 2021; Weideveld et al., 2021). Some of this variation relates to differences in ditch water level. For example, in the study by Weideveld et al. (2021) ditch water levels were kept at −60 cm, which is anyway too low to reduce GHG emissions to acceptable levels (Erkens et al., 2021; Evans et al., 2021; Freeman et al., 2022). Aben et al. (2024) demonstrate that the GHG emission effect of WIS predominantly relates to their effect on summer *and* mean GL.

Natural causes of variability relate to seepage and meteorological variability. In the study by Erkens et al. (2021), $CO_2$ fluxes are comparable for the test and control site at their paired site in Rouveen. This relates to a hydrological situation of seepage, where passive WIS predominantly drain rather than infiltrate. Such a key role of seepage in the success or failure of WIS was also deduced by Boonman et al. (2022) when comparing results for paired sites in Vlist and Assendelft. By far, the best results were obtained in years with dry summers, particularly in 2020 (Boonman et al., 2022).

More variability is induced by variations in soil parameters, such as peat type, mineral fraction and ambient conditions (Kechavarzi et al., 2010; Van Asselen et al., 2009). These may explain strong variability in performance of WIS between different paired sites and years with apparently comparable meteorological conditions. For example, WIS-derived reductions in GHG emissions in Vlist and Assendelft were much higher and more consistent than those at paired sites in Zegveld and Aldeboarn (Erkens et al., 2021). As soil microbial communities tend to thrive under moist, warm and nutrient-rich conditions (Kechavarzi et al., 2010), the intensity of peat oxidation is particularly sensitive to the water-filled pore space (WFPS). Attempts to model the net ecosystem carbon balance using soil temperature and WFPS, based on observations from Vlist and Assendelft, obtain best fits when assuming peat oxidation to peak at WFPS fractions between 0.6 and 0.8, with a very sharp increase in peat oxidation from 1.0 (saturated) to 0.8 (Boonman et al., 2022). Hence, small variability in soil properties influencing WFPS in the unsaturated zone of the peat soil can have large impacts on WIS performance. Also, infiltration of warm surface water through WIS raises soil temperature, which may limit the obtained reduction in peat oxidation (Boonman et al., 2022), but this was not confirmed by Aben et al. (2024). Though soil parameters play a complex role in influencing WIS performance, the net effect seems to be dominated by the degree to which WIS manage to control GL during dry summers.

A concern with the application of WIS in combination with high ditch water levels is the potential emission of $N_2O$ due to intense fertilization in dairy farming. Though GLs are much more controlled under WIS, high ditch water levels increase GL and are likely to increase the frequency of flooding during rain storms that are more erratic under global climate change. Nitrogen-rich soils that are wet but not inundated or that are acutely inundated are known to have high $N_2O$ emissions (Butterbach-Bahl et al., 2013). However, evidence on $N_2O$ emissions under WIS, high ditch water levels and fertilization is currently very limited. $N_2O$ emissions are very difficult to measure due to the erratic nature of the emissions themselves and of the inducing rain storms.

To improve the performance of WIS, active WIS have been developed. These systems have been shown to control GL more precisely (Hoving et al., 2018, 2021, 2022), to the extent that during dry periods actual GL very closely matches ditch water level at sites in Assendelft and Zegveld (Erkens et al., 2021). A target GL above ditch water level can even be achieved. Spectacular reductions in GHG emissions up to 83 $\pm$ 25 % (15.8 $\pm$ 5.6 t $CO_2$ $ha^{-1}$ $yr^{-1}$) in dry-summer year 2020 have been reported for Assendelft, but those numbers require further scrutiny (Boonman et al., 2022; Erkens et al., 2021). It has been suggested that even more precision can be obtained by anticipating drought using weather forecasts and data on crop transpiration (Faber, 2022). At the same time, concerns over the high costs of WIS have given rise to pilot projects using trench infiltration. These projects have had limited success and may pose an increased risk for $CH_4$ emissions and animal disease (Erkens et al., 2021; Gremmen et al., 2022; Hoving et al., 2022).

A major problem of WIS and trench infiltration is that, if land subsidence and GHG emissions are intended to be reduced to close to zero, those measures tend to perform best at high ditch water levels, while resulting high GLs can reduce grass yields and trafficability. This reduces food production and economic viability. Hence, for the long term active WIS that can control GL precisely enough to both mitigate land subsidence and GHG emissions, and allow continuation of intensive dairy farming seems more promising than passive WIS.

Also, WIS and trench infiltration in combination with raised ditch water level pose a substantial demand on water quantity, particularly in dry summers. Increasing summer GL by 30–40 cm would increase overall water demand by about 18 % (Rozemeijer et al., 2019), though variability between sites is substantial. This implies an influx of nutrient-rich water from outside the peatlands, raising peat oxidation through enhanced microbial activity (Erkens et al., 2021; Kechavarzi et al., 2010). Also, water quality can be reduced through phosphorus leaching and erosion of ditch banks under higher GLs (Pijlman et al., 2021). However, positive effects can be expected for meadow birds. Increased GLs, particularly in spring, provide better conditions for hatchlings to survive (Faber, 2022; Visser et al., 2017).

Research into technical measures aimed at changing the physical or chemical properties of the soil has been very limited. Clay-in-peat lab tests did deliver evidence on reduced peat oxidation (Van Agtmaal et al., 2019, 2020), but ongoing pilot studies (e.g. Proeftuin Krimpenerwaard, 2025; Veenweiden Innovatiecentrum Zegveld, 2025) did not yet yield promising field evidence. Clay-in-peat will not stop peat oxidation, but may contribute to its reduction while improving crop yield, particularly in combination with other measures.

Application of a mineral cover can greatly improve the agricultural qualities of the soil, also in the long term. Though it causes compression of the underlying peat, it can subsequently protect the underlying peat from oxidation, hence stop further land subsidence and GHG emissions. According to Bakema et al. (2022), for clay a cover of at least 30 cm and for sand a cover of at least 50–70 cm may be able to prevent oxygen from entering the underlying peat, depending on potential cracking of the soil during summer droughts. However, recent work comparing an experimental and control site in Switzerland did not find a statistically significant reduction in peat oxidation at the site with a mineral cover and suggests that it is essential to concurrently raise GL to saturate the underlying peat (Paul et al., 2024). Sediment transport is very expensive and causes GHG emissions, so if an adequate source of sediment is not available from beneath or from a nearby site, this measure does not seem economically viable.

The potential of acidification and salinization requires research into finding the optimum of minimum peat oxidation and maximum crop yield. Using saline water can reduce the demand for freshwater during dry summers, but may also corrode pumps and other metal parts of the drainage system.

### 4.2. Paludiculture

Paludiculture options employ crops and cattle suitable for cultivation under strongly increased GLs or inundation required to reduce land subsidence and GHG emissions (Tanneberger et al., 2021; Wichtmann et al., 2016). This kind of agriculture does only have a very limited commercial history in The Netherlands. These measures tend to contribute strongly to reducing land subsidence, but have adverse impacts on historical landscape conservation, while technical feasibility and economic viability are currently difficult to assess (Table 2). With only a few pilot studies in The Netherlands, paludiculture is still very much in a start-up phase, which distinguishes this group of measures from the other groups.

A major problem of paludiculture is the emission of $CH_4$ (and potentially $N_2O$) if fields need to be inundated (Erkens et al., 2021; Gremmen et al., 2022; Zak and McInnes, 2022). This emission can be aggravated by submerged plants (Convention on Wetlands, 2021), crops that act as a bypass for $CH_4$ ('shunt species', possibly e.g. cattail) (Couwenberg and Fritz, 2012), the decay of organic matter on-site and an influx of warm and carbon-rich water to maintain water levels (Antonijević et al., 2023). On the other hand, it can be reduced by limiting the duration of flooding, particularly during summer (Drösler et al., 2013; Evans et al., 2016), or instead regular flooding with sulphate-containing (e.g. slightly brackish) water (Vile et al., 2003). It can also be reduced by cultivating crops, or non-commercial plants among the crops, that sequester carbon and oxidize $CH_4$, such as cattail and sedge (Antonijević et al., 2023), although cattail may also act as a bypass for $CH_4$, aggravating emissions (Couwenberg and Fritz, 2012). Recent studies (Buzacott et al., 2024; Van den Berg et al., 2024) achieved negative GHG balances for cattail cultivation near Zegveld and Assendelft in The Netherlands. Where emissions remain during cultivation, these may be balanced in the lifecycle if resulting products, such as cattail, reed, willow and black alder, are processed to construction material (Huth et al., 2018; Lahtinen et al., 2022). This construction material itself stores carbon and the use of bio-based construction material evades much of the GHG emissions associated with the production of conventional construction material. Lahtinen et al. (2022) report net negative GHG balances of $-6$ t $CO_2$-eq $ha^{-1}$ and $-3$ t $CO_2$-eq $ha^{-1}$, based on GWP-100 factors, for paludiculture product systems of cattail board and reed growing media, respectively.

Ongoing experiments are trying to increase crop yield for paludiculture, in which invasive species and foraging geese can be a problem. More research to achieve a better optimum between $CH_4$ (and other GHG) emissions and crop yield is required. Reed has a high tolerance for changing GLs and can generate high yields without inundation (Fritz et al., 2014; Geurts et al., 2019). Broadleaf cattail may also be cultivated successfully without inundation (Geurts and Fritz, 2018). Other crops that do not need inundation, such as elephant grass, willow, cranberry, black alder and peat moss, have no, only very limited or a not yet successful experimental history in The Netherlands (Bestman et al., 2019a,b; Crouwers and Harleman, 2025; Mettrop and Oosterveld, 2019). Another (native) crop not requiring inundation, but without experimental history in The Netherlands, is sedge (Wichtmann et al., 2016).

More research is also needed to understand the effects of *variable* GLs on survival and yield of various paludiculture crops and on GHG emissions (particularly $N_2O$), both to reduce $CH_4$ emission and to explore the flexibility of crops to deal with variation in water availability. Paludiculture arrangements that can store water to mitigate drought and provide a transition zone between intensive dairy farming and wet nature need to be developed. Alternatively, poor water management in paludiculture, including increased evapotranspiration, can reduce water availability. Similar to WIS, this would increase the need for inflow of nutrient-rich water from outside the peatlands.

Paludiculture crops (e.g. cattail, reed, azolla) can be used to remove nitrogen and phosphate from existing soils and residual flows (Geurts et al., 2017; Gremmen et al., 2022). These applications are suitable in temporal or spatial transition zones between intensive dairy farming and (semi-)natural landscapes. Such arrangements will also improve water quality.

An issue during transition to paludiculture is the potential need to remove the topsoil, which may improve yield and reduce GHG emissions. Such removal generates an immediate reduction in surface level (Bestman et al., 2019b). Also, depending on the subsequent use of the removed topsoil, this may generate fast $CO_2$ emissions. However, with no intervention this land subsidence and GHG emissions will happen anyway. Harpenslager et al. (2015) report laboratory experiments in which the removal of the topsoil actually reduced GHG and nutrient emissions, and suggest to reuse the removed topsoil in adjacent subsiding agricultural areas. On the contrary, Van den Berg et al., (2024)) report reduced crop yield and high $CH_4$ emissions after topsoil removal.

Edible paludiculture crops contribute to world food production, but paludiculture crops that are used for construction material, biofuel or substrate may cause land use elsewhere to intensify, particularly in our world of ongoing population growth (Mora et al., 2020). Paludiculture has the potential to reduce land subsidence and GHG emissions to approximately zero, or even provide land rise and a carbon sink, hence is probably more viable in the long term than intensive dairy farming. The effects of paludiculture on biodiversity, meadow bird population and recreation need more research, though observations of e.g. breeding stilts and the Dutch tundra vole in an experimental cattail field close to Amsterdam are promising (Buijs, 2023). The risk of water-borne disease may be reduced by adequate separation of dairy farming and paludiculture, though large-scale inundation of fields close to major cities may pose human risks, such as diseases transferred by mosquitos.

Eccentric paludiculture measures include water buffalo and food forest. Water buffalo may provide a more recreational alternative to intensive dairy farming (Boer 'n, 2025), as well as grazing in wetlands (Wiegleb and Krawczynski, 2010). Food forests, or food swamps, can provide experimental space to explore new paludiculture crops, as well as opportunities for community building and natural science and personal growth education (Albrecht and Wiek, 2021; Ferguson and Lovell, 2014; Moons, 2021).

All in all, paludiculture can provide multiple ecosystem services and societal benefits. Rather than market formation as suggested by Speet and Honkoop (2021) and Verhagen et al. (2021), paludiculture is in need of governance. It is not yield that can currently be optimized to commercial demands, but rather ecosystem services that need to be improved, diversified and monetarized. Only then an assessment can be made whether it is at all worthwhile to optimize yields, and if so whether any of the options can be economically viable in an open world market. Alternatively, paludiculture can provide its ecosystem services and societal benefits, with some commercial income to cover costs.

### 4.3. Alternative options

The alternative options listed in Table 2 reflect existing initiatives in the Dutch peatlands that may not be originally intended, but can be shaped to reduce land subsidence and GHG emissions. Semi-natural meadows, with higher GLs, are a first attempt to reduce the intensity of dairy farming, while retaining the historical landscape and boosting meadow bird population (Pijlman et al., 2021). However, the limited control over GL in such systems still poses the risk of strong drops in GL during dry summers, causing land subsidence and GHG emissions. Greenhouses provide another type of high-tech farming, but with a higher degree of precision that may constrain land subsidence and GHG emissions better. Solar panels contribute to sustainable energy generation, but require full control over the GL and appropriate construction to prevent land subsidence and GHG emissions. In this respect, more research is required on how microclimates amended by solar panels affect peat decomposition. To save space, they can be integrated in greenhouses and roofs of buildings. Expansion of urban areas into peatlands needs to be done properly to reduce land subsidence and GHG emissions to a minimum.

### 4.4. Natural ecosystems

Options to (re)develop or expand natural ecosystems provide opportunities to reverse land subsidence and GHG emissions into land rise and carbon sinks (Dybala et al., 2018; Wichtmann et al., 2016). Also, they provide opportunities to improve general water management, including water quality, as well as recreational areas, particularly within the heavily urbanized west of The Netherlands. Currently, most of the nature reserves in the Dutch peatlands consist of minerotrophic fens, where paludiculture crops like cattail, reed and sedge are naturally occurring. The development of ombrotrophic mires may be difficult given currently high levels of nitrogen deposition (Vink and Van Hinsberg, 2019) and the limited success of peat moss cultivation in The Netherlands (Mettrop and Oosterveld, 2019). On the other hand, riparian forests can provide additional flooding space for the main rivers, reducing flood risk of urban areas and allowing both sedimentation and peat formation for land rise (Van der Deijl et al., 2019). More research is required on optimizing the GHG balance and hydrological consequences of such natural ecosystems, both during transition and in the long term. Considerations discussed in the context of paludiculture, such as vegetation effects and the removal of the topsoil on GHG emissions, are also relevant here.

Expansion of natural ecosystems will boost biodiversity, but not necessarily meadow birds adapted to grasslands rather than swamps. In the long term it provides a more resilient landscape that, particularly in the west, may meet urban needs such as recreation better than agriculture. It makes sense to develop those natural ecosystems in the locations of their original occurrence, that is, along river channels riparian forests and minerotrophic fens, and beyond ombrotrophic mires. Blending with paludiculture seems obvious, where riparian forests can host food forests, while minerotrophic fens and ombrotrophic mires can produce specific paludiculture crops, such as cattail, reed, sedge and peat moss.

## 5. Discussion

In this paper we reviewed 27 measures for 15 effects (Table 2). We identified 4 groups of measures, that is, technical measures, paludiculture, alternatives and nature. It became evident that there are major differences in the nature of measures with regard to their phase of development and potential economic and societal benefits. In this section we compare the measures (5.1–5.4), integrate and conceptualize the interactions between issue and intervention diversity (5.5–5.8) and explore the generalizability of this study (5.9–5.10).

To allow comparative analysis, we ranked the measures along two axes, that is, from fairly developed to start-up stage and from intensive farming (or urban) to nature. The ranks along the former axis reflect uncertainties due to knowledge gaps, including lack of evidence on or understanding of inter-site variability and optimal implementation. The ranks along the latter axis reflect the degree to which a particular measure is intended to and capable of employing natural (agro) ecological processes, as opposed to measures that are primarily intended to support existing intensive farming (or urban demands) through the use of advanced technological interventions. The results of this ranking are visualized in Table 2 and Fig. 3.

### 5.1. Actual or anticipated effects of technical measures

Technical measures intend to modify current intensive farming towards less unsustainable practices. Measures that successfully raise and control GL (Table 2, measures 2–5) are relatively far in their development. There is convincing evidence that stabilizing GLs reduces shrinkage and deformation of the peat soils (Erkens et al., 2021). Peat oxidation requires further understanding through process modelling to fully grasp the role of local hydrology, substrate and ambient conditions during peat oxidation. Seepage can disturb the functioning of WIS (Boonman et al., 2022; Erkens et al., 2021), while peat oxidation varies among substrates of varying peat type, mineral fraction and clay cover thickness (Van Asselen et al., 2009). Peat oxidation tends to peak at moist, warm and nutrient-rich conditions (Kechavarzi et al., 2010) and can be highly sensitive to minor fluctuations in WFPS (Boonman et al., 2022), but it has not yet been mapped extensively under what circumstances and at what frequency such conditions arise. WIS are particularly effective during dry summers and can support a transition to higher GLs. Evans et al. (2021) suggest that every rise in GL by 10 cm within a peat layer would reduce $CO_2$ emissions by at least 3 t $CO_2$ $ha^{-1}$ $yr^{-1}$. Following this line of argument, a GL rise of 10 cm in all cultivated Dutch peatlands would reduce $CO_2$ emissions by 0.6 Mt $yr^{-1}$, achieving 60 % of the Dutch Climate Agreement target for 2030. Aben et al. (2024) confirm the order of these numbers based on experiments in the Netherlands.

Ongoing (NOBV) research has quantified the amount of peat oxidation in the unsaturated zone of peat soils managed by passive or active WIS in the Subsurface Organic Matter Emission Registration System (SOMERS) (Boonman et al., 2022; Erkens et al., 2021, 2022). Within SOMERS, distinction is made between three Dutch regions representing different hydrological conditions. For each region, $CO_2$ emissions have been modelled for up to eight soil archetypes, six parcel widths (40–140 m) and three types of measure (no measure, passive WIS, active WIS). These initial results suggest approximately linear relationships between GL and GHG emissions similar to those reported by Evans et al. (2021). Upward seepage influences the functioning of WIS negatively, while clay covers and high mineral fractions reduce $CO_2$ emissions. So far SOMERS does not distinguish between different peat types, nor is it able to adequately predict variations in soil moisture content, temperature and nutrient status. As SOMERS represents a modelling approach it smooths out some of the local and incidental extremes, as evidenced by the underlying data (Erkens et al., 2021) and sharp rises in $CO_2$ emissions when GL drops below −20 cm observed by Couwenberg et al. (2011) and Tiemeyer et al. (2020).

Measures aimed at changing the physical and chemical properties of the soil (Table 2, measures 6–9) vary with respect to their development. Enhancing the mineral cover and salinization are treatments that reflect existing situations in the current peatlands, hence do not present a high risk of unexpected outcomes. Clay-in-peat and acidification reflect actual variations in mineral fraction across the peatlands and natural differences between ombrotrophic and minerotrophic peat

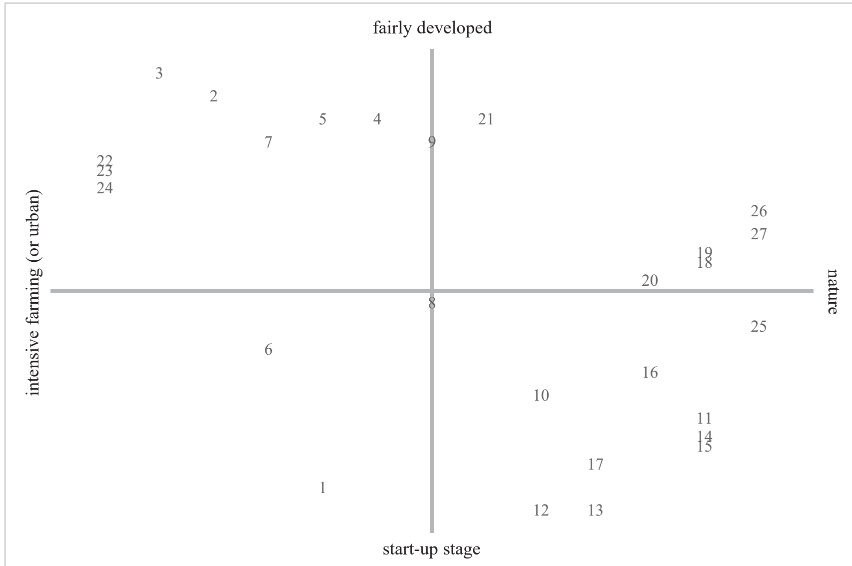


**Fig. 3.** Approximate position of all 27 measures listed in Table 2 if ranked for development phase and farming intensity. Where points overlap, they have been slightly offset along the y-axis.

environments, respectively. However, as a measure to reduce peat oxidation and hence land subsidence and GHG emissions, their experimental record is small and differs from natural counterparts. This implies some risk of unexpected outcomes if widely implemented. More experimental evidence is warranted. As enhancing the mineral cover and clay-in-peat will improve agricultural soil quality, these measures more strongly support intensive farming than the chemical treatments that reduce agricultural soil quality.

### 5.2. Actual or anticipated effects of paludiculture

Paludiculture (Table 2, measures 10–20) intends to achieve a more pronounced application of ecological processes in agriculture, hence improve the agroecological integrity, by turning agricultural peatlands into wetlands and employing the potential of wet environments to grow particular crops. Because cattail and azolla tend to thrive at high levels of fertilization, these crops are particularly suitable for purifying residual flows from intensive dairy farming (Geurts et al., 2017; Gremmen et al., 2022). Cattail can also be employed to remove nitrogen and phosphate from soils during transition from highly intensive dairy farming to less intensive farming or nature. Though agroecologically more sound, the cultivation of cattail and azolla seems to be an integral part of a system of intensive farming. Where topsoil is removed before cultivation of cattail, initial land subsidence and emissions of GHG can be substantial, depending on whether and how it is recycled (Geurts and Fritz, 2018). Moreover, experimental studies show high emissions of $CH_4$ and potentially $N_2O$ emissions if these crops require inundation (Erkens et al., 2021; Gremmen et al., 2022). However, these emissions can be reduced by improved GL control and intercropping of $CH_4$ sequestering and oxidizing plants such as sedge (Antonijević et al., 2023), as well as compensated within the lifecycle for cattail (Lahtinen et al., 2022).

Wild rice, water buffalo, cranberry and peat moss cultivation represent the gradual change from intensive farming towards full agroecological integrity. Experimental evidence for these measures is however very limited. Initial evidence and handbook logic suggest that wild rice and water buffalo can only be a variation within a landscape of intensive farming, as they require and emit fertilizers (Bestman et al., 2019b; Deverel et al., 2016). Also, due to inundation high $CH_4$ and potentially $N_2O$ emissions can be expected for wild rice. Cranberry and peat moss on the other hand require a very low nutrient status, while high GLs without inundation reduce land subsidence without substantial $CH_4$ and $N_2O$ emissions (Crouwers and Harleman, 2025; Mettrop and Oosterveld, 2019). If a low nutrient status can be maintained, quite a challenge within a highly urbanized landscape of intensive dairy farming, then these paludiculture crops may prove a valuable agroecological approach that may even be fully economically viable.

Cattail, reed, elephant grass, willow, food forest and black alder can be fully integrated within a (semi-) natural peat environment. They can be employed to develop hydrological transition zones between (relatively) intensive farming and nature reserves, urban spaces and floodplains. However, variation of GL, including inundation, within these transition zones to prevent flooding and anticipate drought elsewhere may give rise to substantial $CH_4$ and $N_2O$ emissions (Butterbach-Bahl et al., 2013; Freeman et al., 2022). More research is required on how and to what extent these GHG emissions can be reduced by precise water quantity and quality management, and cultivation of specific plants. The economic viability of the cultivation of above-mentioned crops depends on the dynamics of their value in developing bio-based market chains and on the degree to which ecosystem services with regard to hydrology and GHG emissions are priced (Geurts et al., 2019). Food forests within semi-natural transition zones may be enriched by swampy peat forming environments and non-food crops. They can provide a place of innovation, where the potential of new crops can be discovered, and also a place of community building and education, supporting natural science education, emotional well-being and personal growth (Albrecht and Wiek, 2021; Ferguson and Lovell, 2014; Moons, 2021). The economic viability of such a concept depends on the degree to which funds for innovation, social cohesion and education are allocated.

Ongoing (NOBV) research intends to quantify $CH_4$ emissions during the cultivation of various paludiculture crops in relation to intended effects, such as crop yield and water storage or withdrawal. As mitigation of hydrological dynamics, including the retention of water during wet spells and provision of water to WIS during dry spells, may be an important ecosystem service that paludiculture can provide, such an understanding of the impact of dynamic water levels on GHG emissions is essential.

The cultivation of paludiculture crops is in a start-up stage. Major progress has been made in mitigating GHG emissions, integration in landscape transitions, upscaling of plots to fields, field management techniques and market development. Further reductions in GHG emissions and improved harvest control are important, as well as thoughtful economic integration. So far, most experiments are aimed at eutrophic crops that associate well with intensive dairy farming, such as cattail, reed and azolla. Also, there is a tendency to aim for commercial monoculture production of a particular crop. This has given rise to an inadequate and incomplete perspective on the potential of paludiculture crops in The Netherlands. Narrowleaf cattail and azolla may not have a long-term, widespread potential because of fertilization requirements and $CH_4$ emissions, while reed has a very low market value, hence is unlikely to ever provide a profitable business model. The cultivation of wild rice has some history in California, while there are some successful water buffalo farms in The Netherlands, but both are also associated with fertilizer requirements or emissions. On the other extreme, cranberry and peat moss cultivation have been implemented, but require a low nutrient status, which is very difficult to achieve in the current environment. More experimental evidence is required for paludiculture crops and arrangements that are primarily selected for the provision of ecosystem services with regard to hydrology and GHG emissions, such as elephant grass, willow, food forest and black alder. Also, more emphasis on engineering the paludiculture fields in such a way that GHG emissions are reduced as much as possible, e.g. by smart employment of water management and vegetation effects, is warranted. Considering the distinction between intensive farming and nature as a gradual scale, as exemplified in Fig. 3 and by Mettrop et al. (2022), will be key in finding an adequate balance between agricultural production and wider environmental and societal benefits.

### 5.3. Actual or anticipated effects of alternative options

Semi-natural meadows (Table 2, measure 21) are historical alternatives to the highly fertilized meadows used in intensive farming. In that respect they are an integral part of the system of intensive farming and pose a low risk for unexpected outcomes. However, if GL is not managed properly, high peat oxidation can still be expected during dry summers. The main advantages of semi-natural meadows are the fairly nostalgic protection of historical landscapes and meadow birds. It is less intensive farming in the old-fashioned way.

The other alternative measures (Table 2, measures 22–24) represent expansion of urban activities into rural peatlands. They do not improve the ecological integrity of the peatlands, but may result from urban pressures. Any implementation requires careful attention to limit environmental damage, including land subsidence and GHG emissions.

### 5.4. Actual or anticipated effects of natural ecosystems

Nature reserves (Table 2, measures 25–27) provide the opportunity to change land subsidence into land rise, in which the newly developing peat acts as a GHG sink. In the highly urbanized country of The Netherlands, new or extended nature reserves are essential to improve the ecological functioning of peatland landscapes, including enhanced water management and biodiversity, and to provide more space for recreation. Historically the coastal-deltaic plain of The Netherlands was characterized by riparian forests and minerotrophic fens in the floodplains, and ombrotrophic mires beyond. In the current environment, being minerotrophic due to agricultural and urban pollution, development of ombrotrophic mires may not be realistic. Rather it makes sense to focus on the development of riparian forests and minerotrophic fens. However, research on the implementation of these developments is very limited, particularly with respect to riparian forests. There is no evidence on GHG balances during the transition from current highly fertilized agricultural land towards such ecosystems. As inundation and fluctuating water levels are inherent of these systems, $CH_4$ and $N_2O$ emissions can be expected. Within the scope of the NOBV, studies into GHG balances of peatland nature reserves are foreseen, though GHG balances during transition to nature are only studied indirectly through paludiculture experiments.

### 5.5. Phase of development

The evaluated measures vary in phase of technical and economic development. Although for most measures some field evidence is available, it remains very difficult to assess economic viability. For technical measures, continuation of existing land use provides some kind of framework to assess cost-benefit balances, but only under the assumption of current market conditions. Any potential costs for remaining GHG emission or other environmental damage (such as land subsidence) are not considered in such a case. For paludiculture options, multiple variables are at stake. If paludiculture options would be optimized for the world market, it is unclear what bottom line should be taken for delivery of which ecosystem services. Here the question turns around, from whether the change in land use still allows economically viable agriculture under world market conditions to how much we appreciate which ecosystem services are being delivered.

To some degree this uncertainty and value of ecosystem services can be quantified in terms of financial risk and environmental (e.g. carbon, blue) credits (Geurts et al., 2019). On the other hand, enforcement of environmental norms may reduce land prices or turn existing land use unviable, leaving no other option than paludiculture or extensive use. Land can be owned by farmers, who taking advantage of environmental credits still try to run a profitable business. Land can also be owned by other organizations, such as nature organizations, that employ farmers to manage the landscape. These processes may provide some support in nurturing and steering change. However, at the same time they may obscure a true assessment of societal values and ignore advantages or disadvantages that remain unquantified, such as the innovation potential of particular measures in the face of the agroecological transition. These processes may also favour adverse or hamper favourable spatial processes. For example, displacement of dairy farming to non-peatland areas can be a political choice, but should not be an artefact result of a complex governance approach. Stakeholder involvement will be essential to develop a regional assessment framework that provides guidance on the best matches between measures, effects and landscapes.

### 5.6. Landscape diversity

The diversity of potential measures discussed in this paper matches well with the diversity of issues prevalent in Dutch rural peatland areas. If land subsidence and GHG emissions from peat are to be reduced substantially, rather than halted or reversed, technical measures provide relatively low risk options. For example, the $CO_2$-emission reduction of 1.0 Mt aimed for in 2030 by the Dutch Climate Agreement (Nijpels, 2019) may be achieved by controlled raising of GL over the entire Dutch agricultural peatlands by 15–20 cm. However, in the long term, when land subsidence and GHG emissions may have to be reversed to adapt to rising sea levels and reduce atmospheric GHG concentrations, widespread implementation of measures that are currently in a start-up stage of development may be required. Also, the current context of strong challenges in water management, nitrogen emission and urban pressure already demands interventions that cannot be achieved by technical measures only.

An increase in diversity of land-use practices in the Dutch peatlands will allow more effective mitigation of environmental issues, including land subsidence and GHG emissions, particularly in the long term. Such an increase has been coined as an increase in the *solution space* (Fig. 4) by Haasnoot et al. (2020), essential for addressing slowly developing ("creeping") crises and wicked problems (Van den Ende et al., 2023). It provides future generations with a larger variety of options beyond the start-up stage. Landscape diversity compares in this regard well to biological, economic and societal diversity. More diversity yields a more dynamic, agile and resilient system, able to learn, adapt and change in response to internal and external factors (Mealy et al., 2019; Oliver et al., 2015). Hence, increasing landscape diversity in the Dutch peatlands can be a policy aim in itself.

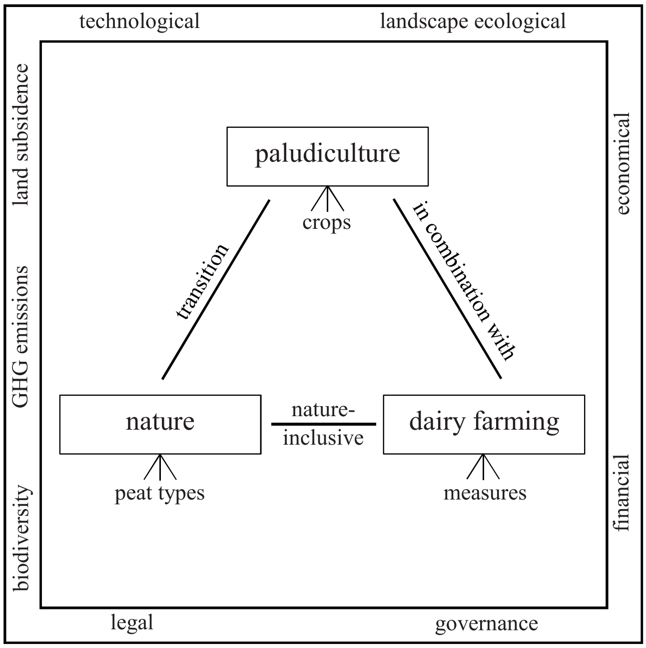


**Fig. 4.** Potential solution space for mitigation of environmental issues in the Dutch peatlands, illustrating the various options for dairy farming, paludiculture, nature and combinations or gradual transitions between them. The choice between the various options is negotiated by attributing value and/or interest to the perspectives in the outer rim of the diagram, while the flexibility of these perspectives adds to the solution space itself.

Efforts to address environmental issues and norms, urban pressure and economic constraints can lead to the implementation of different measures in different areas. Increased water storage to mitigate dry summers, while at the same time providing enough overflow capacity to prevent flooding during summer storms, can be accomplished within the existing system of dairy farming, but may also very well be realized through the implementation of paludiculture in strategic locations. Improved water quality can be accomplished through technological means, but may also be (partly) realized through cultivation of paludiculture crops such as cattail and azolla. Remaining GHG emissions may be compensated outside the peatlands or by technological means, but may also be (partly) compensated through a gradual transition of particular areas towards natural GHG sinks. In locations where environmental costs already outweigh the benefits of intensive farming, alternatives have to be sought, while attempts to reduce industrial GHG emissions and increased prices of raw materials during the Ukraine war stimulate cultivation of paludiculture crops for a more self-reliant, biobased economy.

Implementation of a variety of measures, increasing landscape diversity, is an obvious result of addressing a variety of issues in peatlands that are diverse in physical and societal characteristics. In Dutch governance, such interventions are negotiated in so-called area-oriented processes (Dutch: 'gebiedsprocessen'). These dialogues between governmental organizations and local stakeholders attempt to prioritize and integrate a variety of perspectives. In Fig. 4 these perspectives are indicated on the outer rim. They include environmental aims (such as land subsidence, GHG emissions and biodiversity), technological and landscape-ecological concerns, constraints and opportunities, the specific legal and governmental context, and economical and financial considerations. Each unique set of perspectives demands unique solutions that can be marked on gradual scales between dairy farming (with a local choice of technical measures), paludiculture (with a local choice for specific crops and local priorities for ecosystem services) and nature (adapted to the prevalent peat type). Initiatives to integrate environmental aims and dairy farming have been explored, for example by adapting water management to support the breeding of meadow birds. They have been coined 'nature-inclusive' farming (see e.g. Vermunt et al., 2022) and constitute a principle that can be extended to include multiple environmental objectives. The implementation of a diverse set of measures will also spread the risk posed by the uncertainties in their performance.

Diversification will reduce the future probability of again ending up in a lock-in situation like the present, where only one type of land use dominates the peatlands. However, to some degree it remains a political choice to what extent this diversification will happen, particularly because opposing land uses may require technological interventions to regulate water levels appropriately. Aiming for diversification is also a matter of scale and economy. Small-scale diversification may be easy from an entrepreneurial point of view, but can be technologically impossible, while large-scale diversification, for example the transition of an entire polder to paludiculture, will require very strong governance. Here, the willingness of farmers to make the change will depend on prevailing models of cost-and-benefit sharing between public and private entities.

### 5.7. Upscaling

Most measures imply substantial rises in GL. Large-scale implementation of WIS and/or paludiculture therefore implies a strong rise in water demand (Rozemeijer et al., 2019). Some of this increase can be addressed by retention of water in soils and paludiculture fields during wet spells. However, when it comes to mitigating summer drought, which is key in reducing land subsidence and GHG emissions in peatlands, this retention will not be enough. More retention will increase evapotranspiration and downward seepage, particularly during dry summers when needs are highest. Also, high ditch water levels and GLs reduce the capacity to store water during occasional intense summer storms. Water quality may also be impacted, as more retention reduces the opportunities for water renewal to prevent accumulation of nutrients in surface waters. Consequently, it will be more difficult to maintain a delicate balance between influx and removal of nutrient-rich water in polders. Research on upscaling of measures is currently very limited and needs urgent attention.

### 5.8. Key considerations

The findings of this paper converge towards key considerations to take into account when implementing technical measures and land-use change, and when addressing the analysed (side) effects. The implementation of technical measures and land-use change faces questions on three levels: (i) what is fundamental to achieve technical optimization for the best results at parcel-level (technical aspects), (ii) what is essential to make the best match between option and the natural environment (landscape fit), and (iii) how do options align with deliberate strategies regarding associated interests (societal choice)? Key considerations per question are listed for each type of land use in Table 3. These considerations derive from three different epistemological approaches to the underlying evidence. Technical optimization is a question of engineering, landscape fitting is a matter of logical-empiricist understanding on landscape functioning, and identification of the inherent societal choice is based on a critical reading of the body of relevant research.

Table 3 shows that paludiculture and nature have the potential to compensate remaining GHG emissions from dairy farming, but require better understanding and deliberate management to reduce land subsidence and GHG emission as well as careful positioning in the landscape to make the best hydrological, edaphic and ecological fit. In developing and implementing a wide variety of options, a broad spectrum of societal interests are addressed. The existing socio-technical regime and its associated food production can be reformed gradually, while building a transformative biobased economy will provide economic

**Table 3**
Overview of key considerations with regard to technical and landscape implementation as well as underlying societal choices for three land use scenarios: dairy farming, paludiculture and nature.

| *epistemology* | engineering | logical-empiricism | critical |
|---|---|---|---|
| *categories of considerations (must be considered together)* | technical aspects | landscape fit | societal choice |
| *three land-use scenarios* (*increasing potential to reduce land subsidence and GHG emissions* ↓) | | | |
| option 1: dairy farming | – SOMERS provides guidance at parcel-level, on whether local conditions are suitable for the implementation of WIS.<br>– Conditional: GL should be raised to at least -40 cm. | – Allows conservation of historical landscapes.<br>– Substantial clay covers limit GHG emissions.<br>– WIS most effective if no or downward seepage | – Allows continuation of the existing socio-technological regime.<br>– Supports food production. |
| option 2: paludiculture | – Precise GL control and intercropping of methane sequestering and oxidizing plants are required.<br>– Intercropping of submerged plants and shunt species, decay of organic matter on-site and influx of warm and carbon-rich water should be prevented.<br>– Storage of carbon in the lifecycle of resulting products should be considered. | – Best hydrological fit if upward seepage<br>– Crops such as peat moss and cranberry require low nutrient status.<br>– Opportunity: crops such as cattail, reed and azolla can mitigate high nutrient status.<br>– Opportunity: can be employed in spatial and temporal transitions between dairy farming and nature<br>– Opportunity: if carbon sink, then potential compensation for surrounding dairy farming | – Contributes to transformative biobased economy.<br>– Adds to diversification. |
| option 3: nature (conservation, restoration or development) | – Management should be jointly based on carbon sequestration, land subsidence reduction and biodiversity. | – Locations where land subsidence and/or GHG emissions are particularly problematic.<br>– Opportunity: if carbon sink, then potential compensation for surrounding dairy farming | – Provides opportunities for urban recreation.<br>– Supports ecological dynamics.<br>– Can improve human-non-human relationships. |

The considerations align with different epistemological approaches. Technical implementation can be optimized using an engineering approach, landscape integration follows logical-empiricist findings and understanding underlying societal choices derives from critical research.

diversification. Nature development supports societal demands for recreation, improved ecological functioning and restoration of more equal human-non-human relationships.

Thinking the other way round, addressing the analysed (side) effects requires a tight alignment between action for reducing land subsidence and GHG emissions on the one hand and improved management of water quantity and quality on the other hand (Table 4). Paludiculture can act as a cost-effective approach to support or be combined with hydrological interventions of increased storage and overflow capacity, as well as reduced nutrient-loading of surface waters. Market reform and development is key to prevent sandwiching of famers between increasingly tight environmental regulations and the merciless demands of international markets. Among others, this market reform can relate to protection of regional markets, monetarizing environmental services, reduction of dairy consumption, alternative ways of milk production and increasing revenues from recreation. Finally, it is important to at least partially reframe the nostalgic association of dairy farming with historical landscapes and associated meadow birds to a more consistent ecological understanding of the early- and prehistorical peatland landscape with its associated biodiversity.

### *5.9. Generalizability*

This paper discussed measures for the Dutch peatlands, characterized by intense dairy farming within a highly urbanized landscape. In other peatlands interests and values can be fundamentally different. Hence, the applicability of the findings to other peatlands requires a process of reflexive (value-conscious) transfer to specific contexts. The technical measures particularly apply to intense dairy farming, and may be too expensive or not relevant for less intensive farming. In peatlands where crops are cultivated, raising GL may impact harvest to such a degree that existing farming loses its economic viability. In such cases, there is a strong need for research aimed at enhancing and diversifying the paludiculture options. The selection of paludiculture crops in this study is based on ongoing pilot studies that are biased towards crops that associate well with dairy farming (e.g. cattail, azolla), nearby urban markets (e.g. cranberry) and horticulture (e.g. peat moss). In more remote and forested peatlands it makes sense to focus on the cultivation of raw materials for the bio-based economy, or even biofuels, as well as the development of large-scale natural GHG sinks.

Existing evidence highlights the importance of meteorology, seepage conditions and soil clay content in determining the effectiveness of measures. The frequent occurrence of (warm and) dry periods and downward seepage increase the urgent need for and potential of intervention. As GHG emissions appear to be negatively related to soil clay content and cover, peat soils with low clay contents should be given priority in both research and action. Also, nutrient-rich peat soils may be more susceptible to oxidation through increased microbial activity.

The peculiarities of the Dutch case imply that what may work in The Netherlands, may not work elsewhere, and vice versa. At present, Dutch research and authorities tend to focus on technical measures to achieve the 1.0 Mt $CO_2$-eq $yr^{-1}$ reduction target of the Dutch Climate Agreement, while research in other countries, e.g. Germany, Finland and the USA, tends to be more focused on paludiculture and peatland restoration

**Table 4**
Overview of key considerations concerning the analysed (side) effects.

| | key considerations |
|---|---|
| land subsidence & GHG emissions | — Continuation of dairy farming with technical measures can reduce land subsidence and GHG emissions substantially, but will not stop land subsidence, nor meet the Dutch Climate Agreement target concerning GHG emissions for 2050.<br>— Paludiculture and nature provide more potential to stop (or reverse) land subsidence and meet the Dutch Climate Agreement target concerning GHG emissions for 2050, but require more research to optimize land subsidence and GHG emissions in conjunction with other environmental and economic objectives. |
| hydrology & nutrients | — The operation of key technical measures, such as WIS and raised ditch water level, require storage of water to anticipate dry summers as well as overflow capacity in case of summer storms.<br>— Paludiculture and nature have to be designed and operated in such a way that they can cope with variable water levels, in response to varying meteorological conditions *and* to support correct operation of technical measures of adjacent dairy farms.<br>— Paludiculture can be implemented to purify nitrogen-loaded residual flows from dairy farms and urban sewage systems, and to reduce nitrogen concentrations in soils transitioning to nature. |
| biodiversity & historical landscapes | — Dairy farming will continue with technical measures where historical landscapes and associated meadow birds require conservation.<br>— Paludiculture and nature provide opportunities to support a different kind of biodiversity and a return to early historical and prehistorical landscapes. |
| operationality | — Technical implementation and reduction of disease risk requires site-specific iterative engineering and further research, particularly with regard to paludiculture and nature.<br>— Dairy farming with technical measures requires market reform to cover the costs associated with the implementation of and yield reduction due to the measures.<br>— Paludiculture requires the development of biobased market chains that provide a reliable demand for raw materials.<br>— Additional market developments, such as carbon and blue credits, a reduction in land price, subsidies based on farming marginal lands and orientation on regional markets (that can be manipulated) are important to strengthen the business model of the farms of the future. |
| concerns at higher scale level | — Reduction in dairy consumption and alternative milk production (without cows) will reduce land demands for food production worldwide.<br>— Nature development close to urban centres can provide additional spaces for recreation. |

The effects are grouped in five categories: land subsidence & GHG emissions, hydrology & nutrients (available water quantity, water quality, fertilization), biodiversity & historical landscapes (population meadow birds, historical landscape conservation), operationality (disease risk, technical feasibility, economic viability) and concerns at higher scale (food production, land use elsewhere, recreation).

(Chimner et al., 2016; Rana et al., 2024; Tanneberger et al., 2021). Though physical and human factors between The Netherlands and other countries may differ in a way that legitimates this difference in approach, it may not be wise to assume an either-or approach.

All in all, this paper highlights the spectrum of choices that are made when transitioning peatlands to climate resilient and climate neutral landscapes. Mapping the solution space of any particular regional-scale peatland area will not only allow better association of measures at the landscape scale (as also advocated by Hambäck et al., 2023), but also provide a fair baseline for addressing the wickedness of the transition.

### 5.10. The case study revisited

This case study consists of a meta study of mostly experiments with a limited robustness. That is, the results of the experiments are highly dependent on (only partly controlled) context-specific conditions, (unpredictable) meteorological events and (partly unconscious) engineering design choices, which limits the degree to which the experiments can be replicated. Also, where these experiments tend to strive for confirmation of theoretical considerations within a specific context and set-up, this case study set out to provide a synthesis from which new insights can emerge. Along with its focus on comparability rather than representativeness, it may seem to bear some fuzziness, that is actually an illumination of the fuzziness of playing field of the agricultural and landscape transitions in peatlands itself.

Yet, an attribute of the case study methodology is its looseness, which is essential for new conceptualizations to arise, but which may also give rise to scepticism (Gerring, 2004; Harrison et al., 2017). Here, the main question is to what extent branching in the endeavour has caused a disproportionate focus on particular measures, effects or contextual variables or even caused blind spots. Stakeholder and expert involvement strongly reduced this risk. Also, case studies tend to overreport rather than underreport, which is illustrated by the inclusion of many minor experiments in this paper. The measures and effects that have been compared do not need to be a balanced representation of the current state of affairs, but should rather provide guidance to what can or might be. Hence, the potential weaknesses of the case study methodology actually generated the most valuable assets of this paper.

Finally, what may be considered as a robust finding is the lack of robustness in the potential to predict GHG emission in response to the implementation of specific measures. This is fundamental: the relationship between GL and GHG emission is very noisy. Some of this noise can be addressed by intense site investigation and addressing the site's peculiarities. However, a substantial part of this noise is persistent, and can only be mitigated by monitoring and iterative engineering. Additionally, as the noise is fairly random if measures are implemented adequately, it will average out over larger areas. This can be understood as a plea for action, for learning-by-doing, for iterative engineering, rather than for repeatedly testing an inherently noisy relationship.

## 6. Conclusion

This paper reviewed and synthesized evidence and insights on technical measures and alternative land-use options to reduce land subsidence and GHG emissions in the Dutch peatlands as an exceptional case of peatland degradation. A matrix listing 27 measures and 15 effects was constructed that provides a framework for further discussions on the effectiveness of measures, the complexity of implementation, potential for interaction between measures at the landscape level and key questions for future research, both in The Netherlands and beyond. It also provides a first framework to support discussions between stakeholders, but should not be used as convincing evidence to justify policy choices. Any transition of plots or regions requires local, quantitative and qualitative research to address the various aspects of the envisioned transition.

The results show that technical measures have the advantage of reducing (but not halting) land subsidence and GHG emissions, while reductions in economic viability are limited. However, understanding the influence of mineral covers, peat type, mineral fraction, temperature, moisture and nutrient status on peat oxidation requires more process-oriented research. Implementation of WIS should carefully take account of local conditions, as they do not work in certain areas, for example those areas experiencing strong upward seepage. Though the best results have been obtained for dry summers, a concurrent rise in mean annual GL will be essential to meet land subsidence and GHG emission goals. Here, the main asset of WIS may turn out to be their ability to prevent regular flooding at high target GLs. Research on WIS in other countries than The Netherlands is very limited. The systems may be too expensive if farming is less intensive.

Paludiculture options can provide water buffers between commercial agricultural land, nature reserves and cities, mitigate summer drought, improve water quality and contribute to the development of a bio-based economy, while halting land subsidence. Reductions in GHG emissions due to and economic viability of paludiculture options require deliberative action. Engineering approaches with full control over water quantity and quality, and use of vegetation effects seem to hold the potential to reduce GHG emissions, while monetarizing ecosystem services can improve economic viability. Paludiculture may provide a variety of opportunities in less urban and less intensively managed peatlands around the world. Unfortunately, available evidence on paludiculture arrangements is currently somewhat biased towards crops that associate well with dairy farming, urban markets and horticulture.

Though regional association of various measures may generate conflicting demands on the water system, association can also strengthen hydrological coherence. Smart association will also increase landscape diversity of peatlands, increasing the solution space for environmental issues. Mapping the regional solution space, like in this paper, provides a fair baseline to address spatial diversity, uncertainty in performance and future developments, and disagreement based on diverging interests and values. Hence, it supports stakeholder involvement and entrepreneurship, which will be essential to make the change. More research on upscaling of measures is urgently required, as well as on reflexive, international transfer of insights from one peatland area to another.

## CRediT authorship contribution statement

**Wils Tommy H.G.:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **van den Akker Jan J.H.:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Korff Mandy:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition. Bakema Guido: Conceptualization. **Hegger Dries L.T.:** Writing – review & editing, Visualization, Project administration, Methodology, Funding acquisition, Conceptualization. **Hessel Rudi:** Writing – review & editing, Conceptualization. **van den Ende Mandy A.:** Writing – review & editing, Investigation, Conceptualization. **van Gils Martijn M.W.:** Conceptualization. **Verstand Daan:** Writing – review & editing, Conceptualization.

## Declaration of Competing Interest

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

## Acknowledgements

The research presented in this paper is part of the project Living on Soft Soils: Subsidence and Society (grant no.: NWA.1160.18.259). This project is funded by the Dutch Research Council (NWO-NWA-ORC), Utrecht University, Wageningen University, Delft University of Technology, Ministry of Infrastructure & Water Management, Ministry of the Interior & Kingdom Relations, Deltares, Wageningen Environmental Research, TNO-Geological Survey of The Netherlands, STOWA, Water Authority: Hoogheemraadschap de Stichtse Rijnlanden, Water Authority: Drents Overijsselse Delta, Province of Utrecht, Province of Zuid-Holland, Municipality of Gouda, Platform Soft Soil, Sweco, Tauw BV, NAM. The authors owe many thanks to the multiple stakeholders and experts that have shared their perspectives during the research.

## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.landusepol.2025.107500.

## Data Availability

Data are available through the referenced publications.

## References

Aben, R.C.H., Van de Craats, D., Boonman, J., Peeters, S.H., Vriend, B., Boonman, C.C.F., Van der Velde, Y., Erkens, G., Van den Berg, M., 2024. $CO_2$ emissions of drained coastal peatlands in the Netherlands and potential emission reduction by water infiltration systems. Biogeosciences 21, 4099–4118. https://doi.org/10.5194/bg-21-4099-2024.

Aksoy, D.Y., Kerimoglu, U., Oto, A., Erguven, S., Arslan, S., Unal, S., Batman, F., Bayraktar, Y., 2005. Infection with *Fasciola hepatica*. Clin. Microbiol. Infect. 11, 859–861. https://doi.org/10.1111/j.1469-0691.2005.01254.x.

Albrecht, S., Wiek, A., 2021. Food forests: their services and sustainability. J. Agric. Food Syst. Community Dev. 10, 91-105. https://doi.org/10.5304/jafscd.2021.103.014.

Antonijević, D., Hoffmann, M., Prochnow, A., Krabbe, K., Weituschat, M., Couwenberg, J., Ehlert, S., Zak, D., Augustin, J., 2023. The unexpected long period of elevated $CH_4$ emissions from an inundated fen meadow ended only with the occurrence of cattail (*Typha latifolia*). Glob. Change Biol. 29, 3678–3691. https://doi.org/10.1111/gcb.16713.

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., 2019. Greenhouse gas reporting of the LULUCF sector in The Netherlands. Methodological background, update 2019. Wageningen University & Research, Wageningen. https://doi.org/10.18174/472433.

Bakema, G., Heidema, N., De Groot, W., Visscher, I., Maas, G., 2022. Maatregelen reductie $CO_2$-uitstoot niet-klassieke veengronden Groningen/Drenthe. Wageningen Environmental Research, Wageningen. https://doi.org/10.18174/579565.

Berendsen, H.J.A., Stouthamer, E., Cohen, K.M., Hoek, W.Z., 2019. Landschap in delen. De fysisch-geografische regio's. Perspectief Uitgevers, Voorthuizen.

Bestman, M., Geurts, J., Egas, Y., Van Houwelingen, K., Lenssinck, F., Koorneef, A., Pijlman, J., Vroom, R., Van Eekeren, N., 2019a. Natte teelten voor het veenweidegebied. Verkenning van de mogelijkheden van lisdodde, riet, miscanthus en wilg. Louis Bolk Instituut Bunnik.

Bestman, M., Van Eekeren, N., Egas, Y., Geurts, J., Van Houwelingen, K., Koorneef, A., Lenssinck, F., Pijlman, J., Vroom, R., 2019b. Eindrapportage Veen Voer en Verder. Louis Bolk Instituut, Bunnik.

Boer 'n Buffel, 2025. De wereld verbeteren begint bij een buffel. Boer 'n Buffel, Amstelveen. ⟨https://www.boernbuffel.nl/⟩. Last accessed 28 January 2025.

Boonman, J., Hefting, M.M., Van Huissteden, C.J.A., Van den Berg, M., Van Huissteden, J., Erkens, G., Melman, R., Van der Velde, Y., 2022. Cutting peatland $CO_2$ emissions with water management practices. Biogeosciences 19, 5707–5727. https://doi.org/10.5194/bg-19-5707-2022.

Borger, G.J., 2010. Agrarisch veenlandschap. In: Barends, S., Baas, H.G., De Harde, M.J., Renes, J., Rutte, R., Stol, T., Van Triest, J.C., De Vries, R.J., Van Woudenberg, F.J. (Eds.), Het Nederlandse landschap. Een historisch-geografische benadering. Uitgeverij Matrijs, Utrecht, pp. 62–79.

Buijs, E., 2023. Value Creation by Growing Cattail, Perspectives, Policy Direction. Gemeente Amsterdam, Amsterdam.

Butterbach-Bahl, K., Baggs, E.M., Dannenmann, M., Kiese, R., Zechmeister-Boltenstern, S., 2013. Nitrous oxide emissions from soils: how well do we understand the processes and their controls? Philos. Trans. R. Soc. B: Biol. Sci. 368, 20130122. https://doi.org/10.1098/rstb.2013.0122.

Buzacott, A.J.V., Van den Berg, M., Kruijt, B., Pijlman, J., Fritz, C., Wintjen, P., Van der Velde, Y., 2024. A Bayesian inference approach to determine experimental *Typha latifolia* paludiculture greenhouse gas exchange measured with eddy covariance. Agric. For. Meteorol. 356, 110179. https://doi.org/10.1016/j.agrformet.2024.110179.

Chimner, R.A., Cooper, D.J., Wurster, F.C., Rochefort, L., 2016. An overview of peatland restoration in North America: where are we after 25 years? Restor. Ecol. 25, 283–292. https://doi.org/10.1111/rec.12434.

Convention on Wetlands, 2021. Global Guidelines for Peatland Rewetting and Restoration. Ramsar Technical Report No. 11. Secretariat of the Convention on Wetlands, Gland, Switzerland.

Couwenberg, J., 2018a. Meta-analyse van de effecten van onderwaterdrainage op de waterstand. Greifswald Mire Centre, Greifswald.

Couwenberg, J., 2018b. Some facts on submerged drains in Dutch peat pastures. IMCG Bull. June/July, 9-21.

Couwenberg, J., Fritz, C., 2012. Towards developing IPCC methane 'emission factors' for peatlands (organic soils). Mires Peat 10, 3.

Couwenberg, J., Thiele, A., Tanneberger, F., Augustin, J., Bärisch, S., Dubovik, D., Liashchynskaya, N., Michaelis, D., Minke, M., Skuratovich, A., Joosten, H., 2011. Assessing greenhouse gas emissions from peatlands using vegetation as a proxy. Hydrobiologia 674, 67–89. https://doi.org/10.1007/s10750-011-0729-x.

Crouwers, B., Harleman, G., 2025. The Cranberry Company teelt cranberry's in de Krimpenerwaard. The Cranberry Company, Haastrecht. Last accessed 28 January 2025. ⟨https://www.thecranberrycompany.nl/⟩.

Deverel, S.J., Ingrum, T., Leighton, D., 2016. Present-day oxidative subsidence of organic soils and mitigation in the Sacramento-San Joaquin Delta, California, USA. Hydrogeol. J. 24, 569–586. https://doi.org/10.1007/s10040-016-1391-1.

Dijk, S., 2025. Pilot ophogen landbouwgrond. Eems-Dollard 2050, Groningen. ⟨https://eemsdollard2050.nl/project/ophogen-landbouwgrond-programma-eems-dollard-2050/⟩. Last accessed 28 January 2025.

Drösler, M., Adelmann, W., Augustin, J., Bergman, L., Beyer, C., Chojnicki, B., Förster, C., Freibauer, A., Giebels, M., Görlitz, S., Höper, H., Kantelhardt, J., Liebersbach, H., Hahn-Schöfl, M., Minke, M., Petschow, U., Pfadenhauer, J., Schaller, L., Schägner, P., Sommer, M., Thuille, A., Wehrhan, M., 2013. Klimaschutz durch Moorschutz. Schlussbericht des BMBF-Vorhabens: Klimaschutz - Moornutzungsstrategien 2006-2010. TIB/UB-Hannover, Hanover.

Dybala, K.E., Matzek, V., Gardali, T., Seavy, N.E., 2018. Carbon sequestration in riparian forests: a global synthesis and meta-analysis. Glob. Change Biol. 25, 57–67. https://doi.org/10.1111/gcb.14475.

Erkens, G., 2009. Sediment dynamics in the Rhine catchment. Quantification of fluvial response to climate change and human impact. Utrecht University, Utrecht.

Erkens, G., Melman, R., Jansen, S., Boonman, J., Hefting, M., Keuskamp, J., Bootsma, H., Nougues, L., Van den Berg, M., Van der Velde, Y., 2022. Subsurface organic matter emission registration system (SOMERS). Beschrijving SOMERS 1.0, onderliggende modellen en veenweidenrekenregels. Stichting Toegepast Onderzoek Waterbeheer (STOWA), Amersfoort.

Erkens, G., Van Asselen, S., Hommes-Slag, S., Melman, R., Kooi, H., Van Essen, H., Van den Berg, M., Aben, R., Fritz, C., Boonman, C., Velthuis, M., Heuts, T., Nouta, R., Hessel, R., Van de Craats, D., Massop, H., Gerritsen, P., Van 't Hull, Velthof, J., Van den Akker, G., Van Houwelingen, J., Van der Velde, K., Boonman, Y., Lootens, J., Van Huissteden, R., Hefting, K., Hutjes, M., Kruijt, R., Harpenslager, B., Van Dijk, S. F., Van de Riet, G., Smolders, F, B., 2021. Nationaal Onderzoeksprogramma Broeikasgassen Veenweiden (NOBV). Data-analyse 2020-2021. Stichting Toegepast Onderzoek Waterbeheer (STOWA), Amersfoort.

Evans, C., Morrison, R., Burden, A., Williamson, J., Baird, A., Brown, E., Callaghan, N., Chapman, P., Cumming, A., Dean, H., Dixon, S., Dooling, G., Evans, J., Gauci, V., Grayson, R., Haddaway, N., He, Y., Heppell, K., Holden, J., Hughes, S., Kaduk, J., Jones, D., Matthews, R., Menichino, N., Misselbrook, T., Page, S., Pan, G., Peacock, M., Rayment, M., Ridley, L., Robinson, I., Rylett, D., Scowen, M., Stanley, K., Worrall, F., 2016. Final report on project SP1210: lowland peatland systems in England and Wales – evaluating greenhouse gas fluxes and carbon balances. UK Centre for Ecology & Hydrology, Lancaster.

Evans, C.D., Peacock, M., Baird, A.J., Artz, R.R.E., Burden, A., Callaghan, N., Chapman, P.J., Cooper, H.M., Coyle, M., Craig, E., Cumming, A., Dixon, S., Gauci, V., Grayson, R.P., Helfter, C., Heppell, C.M., Holden, J., Jones, D.L., Kaduk, J., Levy, P., Matthews, R., McNamara, N.P., Misselbrook, T., Oakley, S., Page, S.E., Rayment, M., Ridley, L.M., Stanley, K.M., Williamson, J.L., Worrall, F., Morrison, R., 2021. Overriding water table control on managed peatland greenhouse gas emissions. Nature 593, 548–552. https://doi.org/10.1038/s41586-021-03523-1.

Faber, R.A., 2022. Eindrapportage Experiment drukdrainage en weidevogels in de polder Spengen & Agrarische effecten bij Experiment drukdrainage en weidevogelbeheer. Rijn Vecht & Venen. Agrarisch Natuur- Landschaps- en Waterbeheer. Kamerik.

Ferguson, R.S., Lovell, S.T., 2014. Permaculture for agroecology: design, movement, pratice, and worldview. A review. Agron. Sustain. Dev. 34, 251–274. https://doi.org/10.1007/s13593-013-0181-6.

Forster, P., Storelvmo, T., Armour, K., Collins, W., Dufresne, J.-L., Frame, D., Lunt, D.J., Mauritsen, T., Palmer, M.D., Watanabe, M., Wild, M., Zhang, H., 2021. The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B. (Eds.), Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 923–1054. https://doi.org/10.1017/9781009157896.

Freeman, B.W.J., Evans, C.D., Musarika, S., Morrison, R., Newman, T.R., Page, S.E., Wiggs, G.F.S., Bell, N.G.A., Styles, D., Wen, Y., Chadwick, D.R., Jones, D.L., 2022. Responsible agriculture must adapt to the wetland character of mid-latitude peatlands. Glob. Change Biol. 28, 3795–3811. https://doi.org/10.1111/gcb.16152.

Fritz, C., Lamers, L., Van Dijk, G., Smolders, F., Joosten, H., 2014. Paludicultuur - kansen voor natuurontwikkeling en landschappelijke bufferzones. Vakbl. Nat. Bos Landsch. 5, 4–9.

Gerring, J., 2004. What is a case study and what is it good for? Am. Political Sci. Rev. 98, 341–354. https://doi.org/10.1017/S0003055404001182.

Geurts, J.J.M., Fritz, C., 2018. Paludiculture pilots and experiments with focus on cattail and reed in the Netherlands. Technical report. Radboud University Nijmegen, Nijmegen. https://doi.org/10.13140/RG.2.2.12916.24966.

Geurts, J.J.M., Fritz, C., Lamers, L.P.M., Grootjans, A.P., Joosten, H., 2017. Paludicultuur houdt de polder schoon - zuiveren van oppervlaktewater en uitmijnen van fosfaatrijke bodems met riet- en lisdoddeteelt. $H_2O$ 8, 1–8.

Geurts, J.J.M., Van Duinen, G.-J.A., Van Belle, J., Wichmann, S., Wichtmann, W., Fritz, C., 2019. Recognize the high potential of paludiculture on rewetted peat soils to mitigate climate change. Landbauforsch. J. Sustain. Org. Agric. Syst. 69, 5–8. https://doi.org/10.3220/LBF1576769203000.

Gremmen, T., Van de Riet, B., Van den Berg, M., Vroom, R., Weideveld, S., Van Huissteden, K., Westendorp, P.-J., Smolders, F., 2022. Natte teelten en veeteelt bij een verhoogd (grond)waterpeil in de veenweiden: De effecten van vernattingsmaatregelen op biogeochemie & broeikasgasemissies. Innovatieprogramma Veen - Eindrapportage. Radboud Universiteit Nijmegen, Nijmegen.

Haasnoot, M., Biesbroek, R., Lawrence, J., Muccione, V., Lempert, R., Glavovic, B., 2020. Defining the solution space to accelerate climate change adaptation. Reg. Environ. Change 20, 37. https://doi.org/10.1007/s10113-020-01623-8.

Hambäck, P.A., Dawson, L., Geranmayeh, P., Jarsjö, J., Kačergytė, I., Peacock, M., Collentine, D., Destouni, G., Futter, M., Hugelius, G., Hedman, S., Jonsson, S., Klatt, B.K., Lindström, A., Nilsson, J.E., Pärt, T., Schneider, L.D., Strand, J.A., Urrutia-Cordero, P., Åhlén, D., Åhlén, I., Blicharska, M., 2023. Tradeoffs and synergies in wetland multifunctionality: a scaling issue. Sci. Total Environ. 862, 160746. https://doi.org/10.1016/j.scitotenv.2022.160746.

Harbers, M., Heijnen, V.L.W.A., 2022. Kamerbrief Water en Bodem sturend. Ministerie van Infrastructuur en Waterstaat, The Hague.

Harpenslager, S.F., Van den Elzen, E., Kox, M.A.R., Smolders, A.J.P., Ettwig, K.F., Lamers, L.P.M., 2015. Rewetting former agricultural peatlands: topsoil removal as a prerequisite to avoid strong nutrient and greenhouse gas emissions. Ecol. Eng. 84, 159–168. https://doi.org/10.1016/j.ecoleng.2015.08.002.

Harrison, H., Birks, M., Franklin, R., Mills, J., 2017. Case study research: foundations and methodological orientations. Forum Qual. Soz. Forum: Qual. Soc. Res. 18 (1). https://doi.org/10.17169/fqs-18.1.2655.

Hegger, D., Driessen, P., Stouthamer, E., Mees, H., 2023. Facilitating professional normative judgement through science-policy interfaces: the case of anthropogenic land subsidence in the Netherlands. Leg. Ethics 26, 144–162. https://doi.org/10.1080/1460728x.2023.2235184.

Hoogland, F., Roelandse, A., Velstra, J., 2021. Waterkwantiteit en waterbeheer. Een inventarisatie van de haalbaarheid van maatregelen in het veenweidegebied. Stichting Toegepast Onderzoek Waterbeheer (STOWA), Amersfoort.

Hoving, I.E., Van den Akker, J.J.H., Massop, H.T.L., Holshof, G.J., Van Houwelingen, K., 2018. Precisiewatermanagement op veenweidegrond met pompgestuurde onderwaterdrains. Wageningen Livestock Research, Wageningen. https://doi.org/10.18174/461252.

Hoving, I.E., Van Riel, J.W., Massop, H.T.L., Hendriks, R.F.A., Van den Akker, J.J.H., Van Houwelingen, K., 2021. Precisiewatermanagement op veenweidegrond met pompgestuurde onderwaterdrains: rapportage onderzoeksperiode 2016-2020. Wageningen Livestock Research, Wageningen. https://doi.org/10.18174/540343.

Hoving, I.E., Van Riel, J.W., Massop, H.T.L., Van Houwelingen, K., Bijman, M., 2022. Waterinfiltratie met drukdrains en greppels voor veenbehoud en emissiereductie: deelonderzoek 'natte veeteelt' in het Innovatie Programma Veen (2018-2021). Wageningen Livestock Research, Wageningen. https://doi.org/10.18174/557763.

Huth, V., Hoffmann, M., Bereswill, S., Popova, Y., Zak, D., Augustin, J., 2018. The climate warming effect of a fen peat meadow with fluctuating water table is reduced by young alder trees. Mires Peat 21, 1–18. https://doi.org/10.19189/MaP.2017.OMB.291.

Kechavarzi, C., Dawson, Q., Bartlett, M., Leeds-Harrison, P.B., 2010. The role of soil moisture, temperature and nutrient amendment on $CO_2$ efflux from agricultural peat soil microcosms. Geoderma 154, 203–210. https://doi.org/10.1016/j.geoderma.2009.02.018.

Kiwa Nederland B.V., 2021. Beoordelingsrichtlijn voor het KOMO procescertificaat voor het ontwerpen, de aanleg en nazorg van buisdrainage en veenweideinfiltratie. BRL1411. Kiwa Nederland B.V., Rijswijk.

Kloosterman, A., Valkman, R., Van Staveren, G., 2021. Kennisdeling. Een inventarisatie van de haalbaarheid van maatregelen in het veenweidegebied. Stichting Toegepast Onderzoek Waterbeheer (STOWA), Amersfoort.

Koornneef, A., 2021. Verkenning natte teelten Krimpenerwaard. Eindrapportage van de tweede fase (2019-2020). Veenweiden Innov. Zegveld, Zegveld.

Koster, K., Stafleu, J., Stouthamer, E., 2018. Differential subsidence in the urbanised coastal-deltaic plain of the Netherlands. Neth. J. Geosci. 97, 215–227. https://doi.org/10.1017/njg.2018.11.

Lahtinen, L., Mattila, T., Myllyviita, T., Seppälä, J., Vasander, H., 2022. Effects of paludiculture products on reducing greenhouse gas emissions from agricultural peatlands. Ecol. Eng. 175, 106502. https://doi.org/10.1016/j.ecoleng.2021.106502.

Ma, L., Zhu, G., Chen, B., Zhang, K., Niu, S., Wang, J., Ciais, P., Zuo, H., 2022. A globally robust relationship between water table decline, subsidence rate, and carbon release from peatlands. Commun. Earth Environ. 3, 254. https://doi.org/10.1038/s43247-022-00590-8.

Mealy, P., Farmer, J.D., Teytelboym, A., 2019. Interpreting economic complexity. Sci. Adv. 5, eaau1705. https://doi.org/10.1126/sciadv.aau1705.

Mettrop, I., Oosterveld, E., 2019. Proeven met natte teelten Better Wetter Fase 2. Tussentijdse rapportage van resultaten t/m 2019. Altenburg & Wymenga Ecologisch Onderzoek B.V., Feanwâlden.

Mettrop, I., Wymenga, E., De Ruyter, P., Hollants, D., 2022. Visie klimaatbestendige veenlandschappen. Coalitie Natuurlijke Klimaatbuffers, Amersfoort.

Ministerie van Infrastructuur en Milieu, Ministerie van Economische Zaken, 2015. Nationaal Waterplan 2016-2021. Ministerie van Infrastructuur en Milieu and Ministerie van Economische Zaken, The Hague.

Moons, K., 2021. Het voedselmoeras is een alternatief voor de veenweide: 'De lisdoddechips smaakte heerlijk. Trouw, 1 November 2021.

Mora, O., Le Mouël, C., De Lattre-Gasquet, M., Donnars, C., Dumas, P., Réchauchère, O., Brunelle, T., Manceron, S., Marajo-Petitzon, E., Moreau, C., Barzman, M., Forslund, A., Marty, P., 2020. Exploring the future of land use and food security: a new set of global scenarios. PloS One 15, e0235597. https://doi.org/10.1371/journal.pone.0235597.

Nijpels, E., 2019. Klimaatakkoord. Ministerie van Economische Zaken en Klimaat, Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, Ministerie van Infrastructuur en Waterstaat and Ministerie van Landbouw, Natuur en Voedselkwaliteit, The Hague.

Oliver, T.H., Heard, M.S., Isaac, N.J.B., Roy, D.B., Procter, D., Eigenbrod, F., Freckleton, R., Hector, A., Orme, C.D.L., Petchey, O.L., Proença, V., Raffaelli, D., Suttle, K.B., Mace, G.M., Martín-López, B., Woodcock, B.A., Bullock, J.M., 2015. Biodiversity and resilience of ecosystem functions. Trends Ecol. Evol. 30, 673–684. https://doi.org/10.1016/j.tree.2015.08.009.

Overbeek, M.M.M., Terluin, I.J., 2006. Rural areas under urban pressure: case studies of rural-urban relationships across Europe. Agricultural Economics Research Institute (LEI). Hague.

Paul, S., Ammann, C., Wang, Y., Alewell, C., Leifeld, J., 2024. Can mineral soil coverage be a suitable option to mitigate greenhouse gas emissions from agriculturally managed peatlands? Agric. Ecosyst. Environ. 375, 109197. https://doi.org/10.1016/j.agee.2024.109197.

Pesch, U., Vermaas, P.E., 2020. The wickedness of Rittel and Webber's dilemmas. Adm. Soc. 52, 960–979. https://doi.org/10.1177/0095399720934010.

Pijlman, J., Roelen, S., Van Eekeren, N., 2021. Biodiversiteit, bodem- en waterkwaliteit. Een inventarisatie van de haalbaarheid van maatregelen in het veenweidegebied. Stichting Toegepast Onderzoek Waterbeheer (STOWA), Amersfoort.

Proeftuin Krimpenerwaard, 2025. Klei in veen. Proeftuin Krimpenerwaard, Krimpenerwaard. 〈https://proeftuinkrimpenerwaard.nl/veenverrijking-met-klei/〉. Last accessed 28 January 2025.

Rana, P., Christiani, P., Ahtikoski, A., Haikarainen, S., Stenberg, L., Juutinen, A., Tolvanen, A., 2024. Cost-efficient management of peatland to enhance biodiversity in Finland. Sci. Rep. 14, 2489. https://doi.org/10.1038/s41598-024-52964-x.

Rittel, H.W.J., Webber, M.M., 1973. Dilemmas in a general theory of planning. Policy Sci. 4, 155–169. https://doi.org/10.1007/BF01405730.

Rozemeijer, J., Boomsma, H., Veldhuizen, A., Pouwels, J., Van den Akker, J., Kroon, T., 2019. Effecten van onderwaterdrainage op de regionale watervraag. Berekeningen met het Landelijk Hydrologisch Model. Deltares, Utrecht.

Ruddiman, W.F., He, F., Vavrus, S.J., Kutzbach, J.E., 2020. The early anthropogenic hypothesis: a review. Quat. Sci. Rev. 240, 106386. https://doi.org/10.1016/j.quascirev.2020.106386.

Scholten, M., Troost, A., 2021. Governance. Een inventarisatie van de haalbaarheid van maatregelen in het veenweidegebied. Stichting Toegepast Onderzoek Waterbeheer (STOWA), Amersfoort.

Schothorst, C.J., 1977. Subsidence of low moor peat soils in the western Netherlands. Geoderma 17, 265–291. https://doi.org/10.1016/0016-7061(77)90089-1.

Speet, F., Honkoop, W., 2021. Bedrijfsvoering. Een inventarisatie van de haalbaarheid van maatregelen in het veenweidegebied. Stichting Toegepast Onderzoek Waterbeheer (STOWA), Amersfoort.

Stol, T., 2010. Turfwinningslandschap. In: Barends, S., Baas, H.G., De Harde, M.J., Renes, J., Rutte, R., Stol, T., Van Triest, J.C., De Vries, R.J., Van Woudenberg, F.J. (Eds.), Het Nederlandse landschap. Een historisch-geografische benadering. Uitgeverij Matrijs, Utrecht, pp. 80–95.

Tanneberger, F., Appulo, L., Ewert, S., Lakner, S., Ó Brolcháin, N., Peters, J., Wichtmann, W., 2021. The power of nature-based solutions: how peatlands can help us to achieve key EU sustainability objectives. Adv. Sustain. Syst. 5, 2000146. https://doi.org/10.1002/adsu.202000146.

Tiemeyer, B., Freibauer, A., Borraz, E.A., Augustin, J., Bechtold, M., Beetz, S., Beyer, C., Ebli, M., Eickenscheidt, T., Fiedler, S., Förster, C., Gensior, A., Giebels, M., Glatzel, S., Heinichen, J., Hoffmann, M., Höper, H., Jurasinski, G., Laggner, A., Leiber-Sauheitl, K., Peichl-Brak, M., Drösler, M., 2020. A new methodology for organic soils in national greenhouse gas inventories: data synthesis, derivation and application. Ecol. Indic. 109, 105838. https://doi.org/10.1016/j.ecolind.2019.105838.

Van Agtmaal, M., Deru, J., Lenssinck, F., 2019. Klei voor behoud van veen. Verkenning mogelijkheden van koolstofvastlegging en preventie bodemdaling met klei uit de kringloop. Louis Bolk Instituut, Bunnik.

Van Agtmaal, M., Deru, J., Pijlman, J., Van Uffelen, R., Lenssinck, F., 2020. Kleibagger als bodemverbeteraar. Veenverrijking met klei voor vermindering bodemdaling en $CO_2$ emissie in de veenweiden. Bodem 2, 18–20.

Van Asselen, S., Stouthamer, E., Van Asch, T.W.J., 2009. Effects of peat compaction on delta evolution: a review on processes, responses, measuring and modeling. Earth-Sci. Rev. 92, 35–51. https://doi.org/10.1016/j.earscirev.2008.11.001.

Van den Akker, J.J.H., Hendriks, R.F.A., 2017. Diminishing peat oxidation of agricultural peat soils by infiltration via submerged drains. In: Food and Agriculture Organization of the United Nations (FAO), Proceedings of the Global Symposium on Soil Organic Carbon 2017. Food and Agriculture Organization of the United Nations (FAO), Rome, pp. 436–439.

Van den Akker, J.J.H., Hoving, I., Hendriks, R., Knotters, M., 2018. Onderwaterdrains zijn effectief. Wageningen Environmental Research, Wageningen. https://doi.org/10.18174/466227.

Van den Berg, M., Gremmen, T.M., Vroom, R.J.E., Van Huissteden, J., Boonman, J., Van Huissteden, C.J.A., Van der Velde, Y., Smolders, A.J.P., Van de Riet, B.P., 2024. A case study on topsoil removal and rewetting for paludiculture: effect on biogeochemistry and greenhouse gas emissions from *Typha latifolia*, *Typha angustifolia*, and *Azolla filiculoides*. Biogeosciences 21, 2669–2690. https://doi.org/10.5194/bg-21-2669-2024.

Van den Born, G.J., Kragt, F., Henkens, D., Rijken, B., Van Bemmel, B., Van der Sluis, S., 2016. Dalende bodems, stijgende kosten. Mogelijke maatregelen tegen veenbodemdaling in het landelijk en stedelijk gebied. Planbureau voor de Leefomgeving, The Hague.

Van den Ende, M.A., Hegger, D.L.T., Mees, H.L.P., Driessen, P.P.J., 2023. Wicked problems and creeping crises: a framework for analyzing governance challenges to addressing environmental land-use problems. Environ. Sci. Policy 141, 168–177. https://doi.org/10.1016/j.envsci.2023.01.006.

Van der Deijl, E.C., Van der Perk, M., Middelkoop, H., 2019. Pathways of water and sediment in the Biesbosch freshwater tidal wetland. Wetlands 39, 197–215. https://doi.org/10.1007/s13157-018-1071-0.

Van Gaalen, F., Osté, L., Van Boekel, E., 2020. Nationale analyse waterkwaliteit. Onderdeel van de Delta-aanpak Waterkwaliteit. Planbureau voor de Leefomgeving, The Hague.

Van Gils, M.M.W., Groothuijse, F.A.G., 2021. Juridisch instrumentarium voor de reductie van $CO_2$-emissie uit veengebieden: gefundeerd op slappe bodem? Tijdschr. voor Bouwr. 115, 928–941.

Van Gils, M.M.W., Groothuijse, F.A.G., Van Rijswick, H.F.M.W., Stouthamer, E., 2021. Bodemdaling in Nederlandse veengebieden: knelpunten voor solide beleid en besluitvorming. Milieu en Recht 18, 112–120.

Van Hardeveld, H., De Jong, H., Knepflé, M., De Lange, T., Schot, P., Spanjers, B., Teurlincx, S., 2020. Integrated impact assessment of adaptive management strategies in a Dutch peatland polder. Proc. PIAHS 382, 553–557. https://doi.org/10.5194/piahs-382-553-2020.

Van Hardeveld, H.A., Driessen, P.P.J., Schot, P.P., Wassen, M.J., 2018. Supporting collaborative policy processes with a multi-criteria discussion of costs and benefits: the case of soil subsidence in Dutch peatlands. Land Use Policy 77, 425–436. https://doi.org/10.1016/j.landusepol.2018.06.002.

Van Hardeveld, H.A., Driessen, P.P.J., Schot, P.P., Wassen, M.J., 2019. How interactive simulations can improve the support of environmental management – lessons from the Dutch peatlands. Environ. Model. Softw. 119, 135–146. https://doi.org/10.1016/j.envsoft.2019.06.001.

Van Mulken, M.W.E., Di Fant, V., Van Hardeveld, H.A., Scheifes, D.J.P., Dieperink, C., Schot, P.P., Wassen, M.J., 2023a. De toekomst van het Groene Hart. Een participatieve aanpak voor het verkennen van een duurzaam landschap. Landschap 2, 67–75.

Van Mulken, M.W.E., Van Hardeveld, H.A., Van den Ende, M.A., Koster, R., Wassen, M.J., 2023b. Op weg naar een duurzaam Groene Hart. Het ontwikkelen van een toekomstvisie met behulp van RE:PEAT. Landschap 3, 119–129.

Veenweiden Innovatiecentrum Zegveld, 2025. Klei in veen. Veenweiden Innov. Zegveld, Zegveld. 〈https://www.veenweiden.nl/activiteiten/klei-in-veen/〉. Last accessed 28 January 2025.

Verburg, R.W., Verberne, E., Negro, S.O., 2022. Accelerating the transition towards sustainable agriculture: the case of organic dairy farming in the Netherlands. Agric. Syst. 198, 103368. https://doi.org/10.1016/j.agsy.2022.103368.

Verhagen, F., De Weerd, M., Westerhof, R., 2021. Betaalbaarheid. Een inventarisatie van de haalbaarheid van maatregelen in het veenweidegebied. Stichting Toegepast Onderzoek Waterbeheer (STOWA), Amersfoort.

Vermunt, D.A., Wojtynia, N., Hekkert, M.P., Van Dijk, J., Verburg, R., Verweij, P.A., Wassen, M., Runhaar, H., 2022. Five mechanisms blocking the transition towards 'nature-inclusive' agriculture: a systemic analysis of Dutch dairy farming. Agric. Syst. 195, 103280. https://doi.org/10.1016/j.agsy.2021.103280.

Vile, M.A., Bridgham, S.D., Wieder, R.K., Novák, M., 2003. Atmospheric sulfur deposition alters pathways of gaseous carbon production in peatlands. Glob. Biogeochem. Cycles 17, 1058. https://doi.org/10.1029/2002GB001966.

Vink, M., Van Hinsberg, A., 2019. Stikstof in perspectief. In: Planbureau voor de Leefomgeving. The Hague.

Visser, T., Melman, T.C.P., Buij, R., Schotman, A.G.M., 2017. Greppel plas-dras voor weidevogels. Betekenis als habitatonderdeel voor weidevogelkuikens. Wageningen Environmental Research, Wageningen. https://doi.org/10.18174/425504.

Vos, P., 2015. Origin of the Dutch coastal landscape. Long-term landscape evolution of the Netherlands during the Holocene, described and visualized in national, regional and local palaeogeographical map series. Utrecht University, Utrecht.

Weideveld, S.T.J., Liu, W., Van den Berg, M., Lamers, L.P.M., Fritz, C., 2021. Conventional subsoil irrigation techniques do not lower carbon emissions from drained peat meadows. Biogeosciences 18, 3881–3902. https://doi.org/10.5194/bg-18-3881-2021.

Wichtmann, W., Schröder, C., Joosten, H., 2016. Paludiculture-productive use of wet peatlands. Schweizerbart Science Publishers, Stuttgart.

Wiegleb, G., Krawczynski, R., 2010. Biodiversity management by water buffalos in restored wetlands. Waldökologie, Landschaftsforschung und Naturschutz 10, 17–22.

Zak, D., McInnes, R.J., 2022. A call for refining the peatland restoration strategy in Europe. J. Appl. Ecol. 59, 2698–2704. https://doi.org/10.1111/1365-2664.14261.