

CONTROLLED DRAINAGE AND SUBIRRIGATION FOR AGRO-ECOLOGICAL TRANSITION AND CLIMATE RESILIENCE IN BOREAL AGRICULTURE

DRAINAGE CONTRÔLÉ ET IRRIGATION SOUTERRAINE POUR LA TRANSITION AGROÉCOLOGIQUE ET LA RÉSISTANCE AU CLIMAT EN AGRICULTURE BORÉALE

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ABSTRACT

Agriculture in boreal regions is increasingly challenged by climate variability, including intensified precipitation patterns, prolonged summer droughts, and changing snowmelt dynamics. In Finland, where an estimated 85% of agricultural land relies on artificial drainage, water management is a key factor influencing both productivity and environmental performance. Traditional drainage systems are primarily designed to remove excess water but are unsuitable for anything else. Controlled drainage (CD) and subirrigation (SI) represent alternative approaches that allow active regulation of groundwater levels, thereby improving hydrological control and environmental outcomes.

This study evaluates the effects of controlled drainage and subirrigation on hydrology, nutrient loading, greenhouse gas emissions, and crop performance using two experimental field sites in Finland. The Jokioinen site represents organic (peat) soils, while the Sievi site represents coarse-textured mineral soils. At Jokioinen, replicated plot-scale experiments compared conventional drainage, controlled drainage, and controlled drainage with intermittent subirrigation. At Sievi, a field-scale system combining controlled drainage and subirrigation using river water was compared to conventional drainage.

Results show that controlled drainage significantly reduces drainage discharge, leading to proportional reductions in nutrient loading. Groundwater levels tables were consistently higher under controlled systems, although strongly influenced by weather conditions. In peat soils, higher groundwater levels reduced carbon dioxide emissions, while yield impacts remained neutral. In mineral soils, subirrigation enhanced soil moisture availability during dry periods, resulting in yield increases of 6–27% in most years and up to 97% in extreme conditions. The results demonstrate that controlled drainage and subirrigation can transform conventional drainage systems into multifunctional water management solutions. These practices support agro ecological transition by reducing environmental pressures while enhancing climate resilience and resource efficiency in boreal agriculture.

Keywords: boreal regions; conventional drainage; controlled drainage; controlled drainage with intermittent subirrigation; groundwater levels.

RESUME

L'agriculture dans les régions boréales fait de plus en plus face aux défis de la variabilité du climat, notamment l'intensification des précipitations, les sécheresses prolongées en été et l'évolution de la dynamique de fonte des neiges. En Finlande, où environ 85% des terres agricoles dépendent d'un drainage artificiel, la gestion de l'eau est un facteur clé influençant à la fois la productivité et la performance environnementale. Les systèmes de drainage traditionnels sont principalement conçus pour évacuer l'eau

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excédentaire, mais sont inadapté à autre chose. Le drainage contrôlé (DC) et l'irrigation souterraine (SI) représentent des approches alternatives permettant une régulation active des niveaux d'eau souterraine, améliorant ainsi le contrôle hydrologique et les résultats environnementaux.

Cette étude évalue les effets exercés par le drainage contrôlé et l'irrigation souterraine sur l'hydrologie, la charge en nutriments, les émissions de gaz à effet de serre et le rendement des cultures en utilisant deux sites expérimentaux en Finlande. Le site de Jokioinen possède des sols organiques (tourbeux), tandis que celui de Sievi possède des sols minéraux à texture grossière. À Jokioinen, des expériences menées à l'échelle de la parcelle ont comparé le drainage conventionnel, le drainage contrôlé et le drainage contrôlé avec une irrigation souterraine intermittente. À Sievi, un système à l'échelle de la parcelle combinant le drainage contrôlé et l'irrigation souterraine en utilisant l'eau de rivière a été comparé au drainage conventionnel.

Les résultats indiquent que le drainage contrôlé réduit considérablement le débit de drainage, donnant lieu à des réductions proportionnelles de la charge en nutriments. Les niveaux des nappes phréatiques étaient systématiquement plus élevés dans les systèmes contrôlés, bien que fortement influencés par les conditions météorologiques. Dans les sols tourbeux, des niveaux plus élevés d'eau souterraine ont réduit les émissions de dioxyde de carbone, sans aucun impact sur le rendement. Dans les sols minéraux, l'irrigation souterraine a amélioré la disponibilité de l'humidité du sol pendant les périodes sèches, donnant lieu aux augmentations de rendement de 6 à 27% la plupart des années, et jusqu'à 97% dans des conditions extrêmes.

Les résultats démontrent que le drainage contrôlé et l'irrigation souterraine peuvent transformer les systèmes de drainage conventionnels en solutions multifonctionnelles relevant de gestion de l'eau. Ces pratiques soutiennent la transition agro-écologique en réduisant les pressions environnementales tout en améliorant la résistance au climat et l'efficacité des ressources dans l'agriculture boréale..

Mots-clés : Régions boréales; Drainage conventionnel; Drainage contrôlé; Drainage contrôlé avec l'irrigation souterraine intermittente; Irrigation souterraine; Niveaux de l'eau souterraine.

1. INTRODUCTION

Agricultural production in boreal regions operates under distinct hydrological and climatic constraints that differentiate it from temperate and arid agricultural systems. In Finland and similar northern environments, short growing seasons, long winters with snow accumulation, and strong seasonal variability in water availability create complex challenges for crop production. During spring, rapid snowmelt results in waterlogged soil, highlighting the need for good infiltration capacity in the soil and efficient drainage systems. Conversely, summer periods increasingly experience rainfall deficits and high evapotranspiration, leading to water stress for crops. These dynamics are expected to intensify under climate change, which is projected to increase both precipitation variability and the frequency of extreme weather events (Utriainen et al. 2025).

Artificial drainage has been widely adopted in boreal agriculture to improve soil trafficability, reduce waterlogging, and enable timely field operations. Subsurface drainage systems are prevalent, and they cover an estimated 60% of cultivated land in Finland (Paasonen-Kivekäs et al. 2016). While these systems have significantly enhanced agricultural productivity, they have also introduced environmental challenges. In organic soils such as peatlands, drainage lowers the groundwater table and accelerates the decomposition of soil organic matter (Maljanen et al. 2007, Regina et al. 2004,2014; Liimatainen et al. 2018; Heikkinen et al. 2024, Yang et al. 2025), resulting in significant carbon dioxide emissions and release of nutrients vulnerable to leaching. In mineral soils, free and rapid drainage during the growing season can result in nutrient loading into water bodies.

Approximately 11 % on Finland's arable land consists of peat soils (Räsänen et al 2023). Despite their relatively low area, they contribute significantly (50-60%) to the greenhouse gas emissions of the entire agricultural sector (Statistics Finland 2025). These emissions are a result of peat decomposition caused by agricultural measures, most notably drainage.

Controlled drainage (CD) is an adaptation of conventional drainage technology that allows the regulation of outflow through adjustable control structures. By raising the outlet level, controlled drainage raises the groundwater table and reduces drainage discharge. Subirrigation (SI) extends this concept by actively introducing water into the drainage system, enabling upward movement of water into the root zone during dry periods (Figure 1).

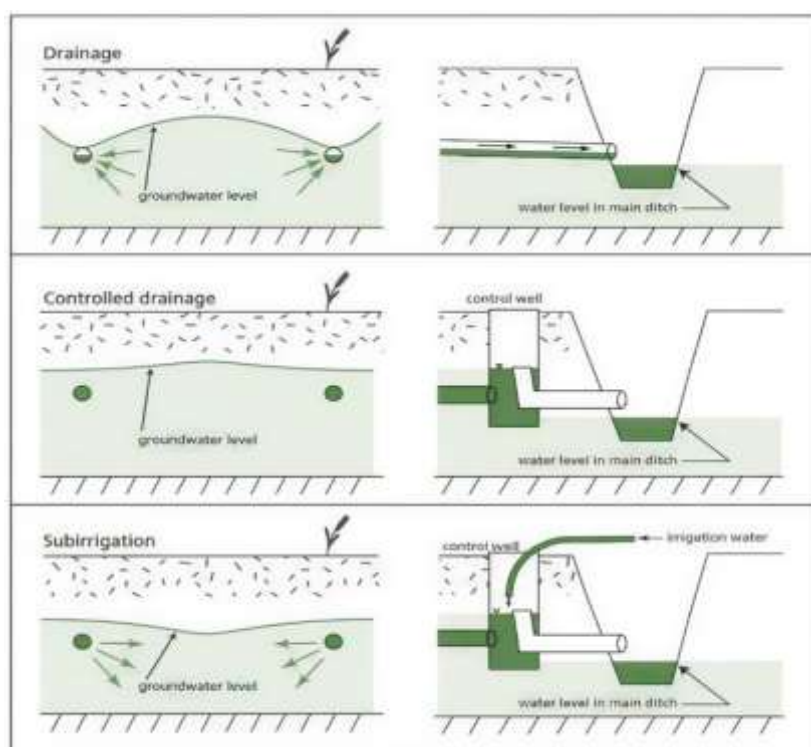


Figure 1. Principles of conventional and controlled drainage and subirrigation. Adapted from Paasonen-Kivekäs et al. (2016).

These approaches shift the role of drainage systems from passive water removal to active water management. Previous studies have suggested that controlled drainage can reduce nutrient losses and improve water use efficiency, while subirrigation can enhance crop resilience during droughts (Wesström et al. 2014). However, their effectiveness is highly dependent on local soil properties, hydrological conditions, and climatic factors.

The objective of this study is to assess the potential of controlled drainage and subirrigation as tools for agro ecological transition in boreal agriculture. Agro-ecological transition refers to the transformation of agricultural systems toward more sustainable and resilient practices that reduce environmental impacts while maintaining productivity. Using two contrasting field experiments in Finland, this study evaluates how these water management methods influence hydrology, nutrient loading, greenhouse gas emissions, and crop yield on an organic and coarse mineral soil.

2. MATERIALS AND METHODS

2.1 Study sites

2.1.1 Jokioinen peat soil site

The Jokioinen experimental field is located in southern Finland on cultivated peatland that has been in agricultural use since the mid-20th century. The soil is moderately decomposed sedge peat with thickness varying from 40 cm at one end of the field to 150 cm at the other end. Beneath the peat layer

lies mineral subsoil of heavy clay.

The experimental field was established in 2020. It consists of eight plots, each approximately 0.5 hectares in size. The plots were hydraulically isolated from each other using impermeable membranes extending to the mineral subsoil to prevent lateral water movement between the plots. Each plot was equipped with its own subsurface drainage system consisting of drains spaced at 8 m and installed at depths of approximately 110–130 cm. Half of the plots were equipped with control wells. Drainage water from each plot was conducted into a monitoring well where drain discharge was measured, and a flow-weighted aggregate water sample was collected for laboratory analysis.

There were two treatments: Conventional drainage as a reference treatment, and controlled drainage (CD). Controlled drainage was compared with conventional drainage in two replicates in both the thin and thick peat layer areas.

In the CD plots, the drainage outlet level was adjusted to a target groundwater table of approximately 20–30 cm below the soil surface during most of the growing season. Control structures were opened during wet conditions or prior to field operations when necessary. The site was cultivated with perennial grass during the measurement period.

2.1.2 Sievi mineral soil site

The Sievi experimental site is located in north-western Finland on a flat agricultural field with an average slope of less than 0.2%. The soil is classified as an Endogleyic Umbrisol according to the WRB classification system (IUSS Working Group WRB, 2014) sandy loam to fine sand, characterized by relatively high permeability and low water retention capacity in the subsoil. The topsoil is similar, but also rich in organic matter, giving the soil its name.

The total experimental area is approximately 3.55 hectares and was divided into two main sections: conventional drainage (1.25 ha) as reference and controlled drainage with subirrigation (1.07 ha). The drainage systems of the different sections were separated using an impermeable barrier around the controlled and subirrigated section to prevent lateral water movement between treatments. Drain spacing at the site is 15 m.

Subirrigation is implemented by pumping water from a nearby river into the drainage system. The pumping system has been improved over time, initially using flexible pipes and later incorporating more permanent infrastructure to improve water distribution efficiency. The pump was powered with solar panels and was only able to operate during the day. The cropping system has varied over the years and includes cereals and grass. Yield data have been collected annually to assess the agronomic effects of the treatments.

2.2 Data collection and analysis

At both study sites, hydrological monitoring included continuous measurements of drainage discharge using flow meters installed in monitoring wells. Groundwater levels were recorded regularly from observation wells. At the Sievi site, groundwater tables were monitored using observation wells installed at 0.2, 0.6, 2.5 and 7.5 m from the lateral drains. At the Jokioinen site, groundwater tables were observed between lateral drains.

Aggregate water samples were collected using automated sampling systems triggered by flow volume. Samples were analysed for nutrient concentrations, including total nitrogen, nitrate nitrogen, ammonium nitrogen, total phosphorus, and dissolved phosphorus fractions as well as suspended solids. In addition, total and dissolved carbon concentrations were analysed at the organic soil site in Jokioinen.

Crop yields were measured annually using standard agronomic methods. At the Sievi site, yield variability across distances from drains was also assessed by taking samples between lateral drains and over lateral drains in six replicate samples per experimental area and position relative to drain.

Data analysis focused on comparing treatment effects on drainage discharge, groundwater levels, nutrient loading, greenhouse gas emissions, and crop yields.

3. RESULTS

3.1 Hydrological effects

At the Jokioinen site, controlled drainage significantly reduced annual drainage discharge. The total drainage outflow from controlled plots was approximately one-third of that measured under conventional drainage (Figure 2). This reduction reflects increased water retention within the soil profile due to the elevated outlet level.

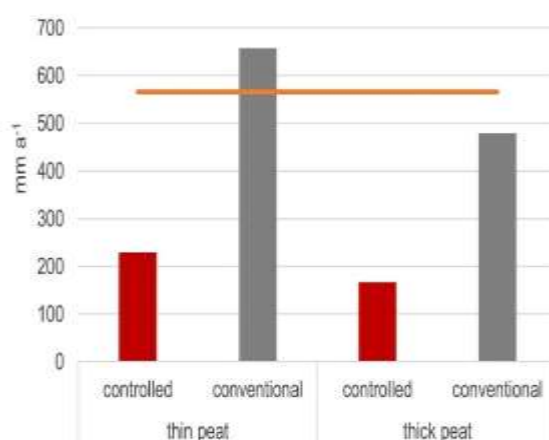


Figure 2. Annual drainage discharge on the controlled (red bars) and conventional (grey bars) plots as well as precipitation (orange line) at the Jokioinen site on the thin and thick peat areas.

Groundwater levels in controlled plots were consistently higher than in conventional plots, typically by 10–30 cm. However, groundwater levels varied strongly in response to weather conditions. During wet periods, the groundwater table rose close to the soil surface in all treatments, while during dry periods it declined despite flow control. (Figure 3)

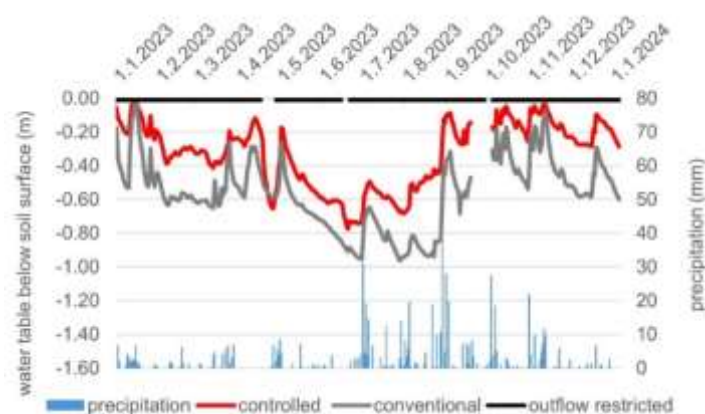


Figure 3. Example of the variation of the groundwater table, and precipitation in 2023 on the thick peat layer area in Jokioinen. n=2.

At the Sievi site, the effect of controlled drainage alone on groundwater levels was limited due to the permeable nature of the soil, as can be seen in Figure 4, when the groundwater level receded when the

irrigation stopped for the night. However, the addition of subirrigation significantly increased groundwater levels, particularly during dry periods. The influence of subirrigation extended up to 7.5 m from the drains, although the effect was strongest near the drainage pipes. On the conventionally drained area, groundwater table receded below drainage depth at all distances from the lateral drains (Figure 5).

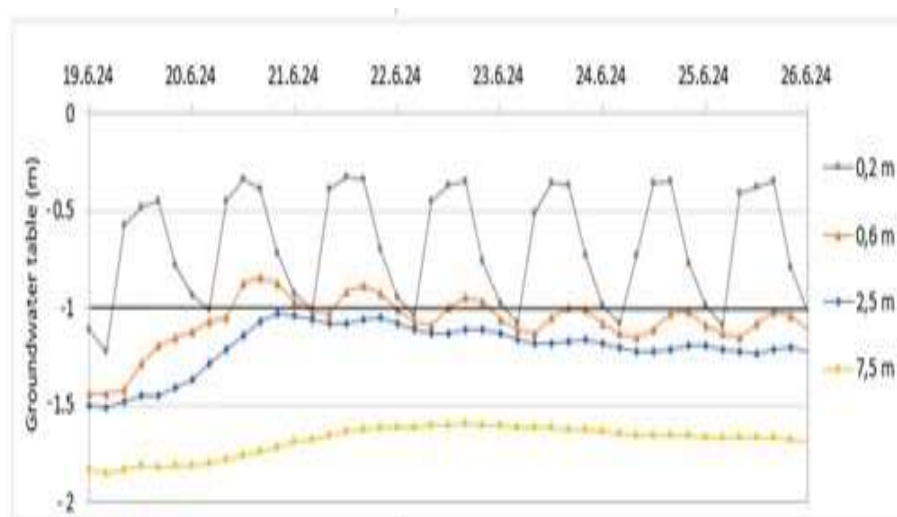


Figure 4. Groundwater table depths during subirrigation in the summer of 2024 at distances of 0.2, 0.6, 2.5, and 7.5 meters from the lateral drains under subirrigation at Sievi.

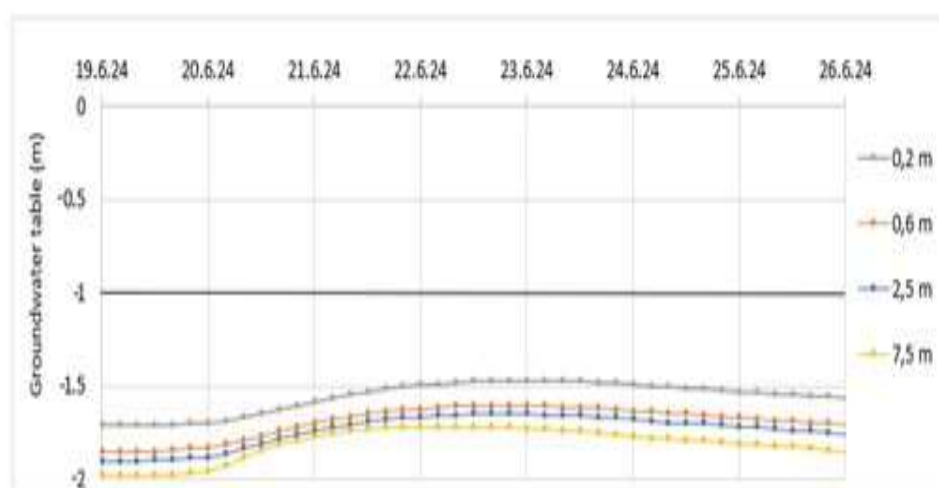


Figure 5. Groundwater table depths in the summer of 2024 at distances of 0.2, 0.6, 2.5, and 7.5 meters from the lateral drains under conventional drainage at Sievi.

3.2 Nutrient loading

Nutrient concentrations in drainage water showed relatively small differences between treatments at both sites. However, significant reductions in nutrient loading were observed due to decreased drainage discharge under controlled drainage.

At the Jokioinen site, reductions in nitrogen and phosphorus loads were proportional to the reduction in drainage volume (Table 1). This confirms that flow control effectively reduces nutrient export by limiting water movement away from the field.

Table 1. Nutrient loading at Jokioinen (n=4)

	Controlled	Conventional	Reduction (%)
Thin peat layer			
N _{tot} (kg ha ⁻¹ a ⁻¹)	5,7	21,8	74
NO ₃ -N (kg ha ⁻¹ a ⁻¹)	3,3	14,6	77
TOC (kg ha ⁻¹ a ⁻¹)	41,9	169,8	75
DOC (kg ha ⁻¹ a ⁻¹)	38,9	154,5	75
Suspended solids (kg ha ⁻¹ a ⁻¹)	361	1028	65
P _{tot} (kg ha ⁻¹ a ⁻¹)	0,37	1,13	68
PO ₄ -P (kg ha ⁻¹ a ⁻¹)	0,13	0,22	40
thick peat layer			
N _{tot} (kg ha ⁻¹ a ⁻¹)	6,2	16	61
NO ₃ -N (kg ha ⁻¹ a ⁻¹)	2,5	7,4	66
TOC (kg ha ⁻¹ a ⁻¹)	91,7	238,7	62
DOC (kg ha ⁻¹ a ⁻¹)	86,0	188,7	54
Suspended solids kg ha ⁻¹ a ⁻¹)	394	1469	73
P _{tot} (kg ha ⁻¹ a ⁻¹)	0,65	3,6	82
PO ₄ -P (kg ha ⁻¹ a ⁻¹)	0,16	0,4	61

At the Sievi site, nitrogen loads were generally lower in the controlled drainage and subirrigation treatment compared to conventional drainage (Table 2) despite the introduction of nutrients with the irrigation water indicating nutrient retention within the system. Phosphorus loads were low, as expected for the soil type, and showed limited variation between treatments.

Table 2. Average annual nutrient loading in 2021-2024 at Sievi

	Subirrigation	Conventional	Reduction, %
N _{tot} (kg ha ⁻¹ a ⁻¹)	5,2	8,3	37
NO ₃ -N (kg ha ⁻¹ a ⁻¹)	3,3	6,1	46
Suspended solids (kg ha ⁻¹ a ⁻¹)	49	60	18
P _{tot} (kg ha ⁻¹ a ⁻¹)	0,095	0,104	8,8
PO ₄ -P (kg ha ⁻¹ a ⁻¹)	0,021	0,024	9,4

3.3 Crop yields

At the Jokioinen site, crop yields under controlled drainage were similar to those under conventional drainage (data not shown). Slight reductions were observed in conditions where water levels remained excessively high, but overall differences were small. These results indicate that environmental benefits can be achieved without significant yield losses in peat soils.

At the Sievi site with mineral soil, controlled drainage combined with subirrigation led to substantial yield increases. Yield gains ranged from approximately 6% to 27% in most years. In a particularly challenging year, with poor overwintering of winter wheat and a dry early growing season, a yield increase of 97% was observed, demonstrating the strong resilience benefits of subirrigation under water-limited conditions.

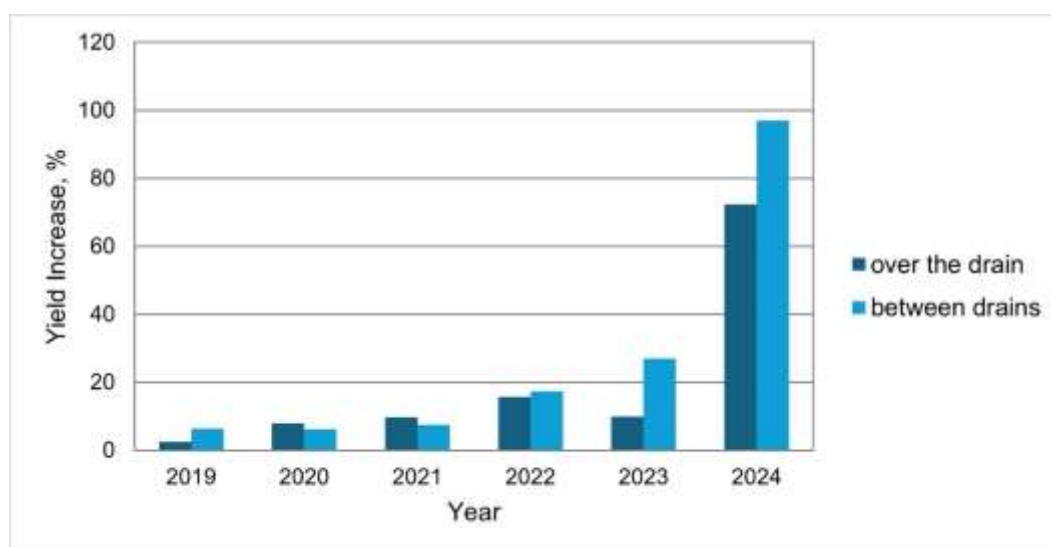


Figure 6. Yield increase expressed as percentage at the Sievi site

4. DISCUSSION

The results demonstrate that controlled drainage and subirrigation can significantly improve the environmental sustainability and resilience of agricultural systems in boreal regions. The mechanisms underlying these benefits are the regulation of water flow and storage within the soil profile, as well as reduction in oxygen availability, in the case of greenhouse gas emissions. At the Jokioinen site, greenhouse gas emissions were measured by Heikkinen et al (2024) using automated chamber systems on the area of the thick peat layer concurrently with this research. They discovered that greenhouse gas emissions were strongly influenced by groundwater levels and soil temperature. Carbon dioxide emissions increased significantly when the groundwater table was deeper and soil temperature was higher.

Raising the groundwater level through controlled drainage reduced carbon dioxide emissions by limiting aerobic decomposition of organic matter. Model-based estimates (Heikkinen et al. 2024) indicated that emissions could be reduced substantially if the groundwater table were maintained closer to the soil surface. However, in practice, the effectiveness of controlled drainage in maintaining high water tables was limited during dry periods due to strong evapotranspiration (Figure 3). The ground water table around the greenhouse gas chambers was on average 10 cm higher on controlled drainage plots than on conventionally drained plots. This resulted in a 23% reduction in CO₂ emissions.

Methane emissions were generally low and only increased under conditions of near-surface saturation. Overall, carbon dioxide emissions were the dominant component of greenhouse gas flux.

Reducing drainage discharge directly decreases nutrient transport from fields to water bodies. This is particularly important in regions where diffuse nutrient loading from agriculture contributes to eutrophication. The consistency of the relationship between drainage volume and nutrient load highlights the importance of hydrological control.

In peat soils, water management plays a crucial role in controlling greenhouse gas emissions. Lowering the groundwater table exposes organic matter to aerobic decomposition, leading to carbon dioxide emissions (Maljanen et al. 2007), Regina et al. 2004,2014; Liimatainen et al. 2018; Heikkinen et al. 2024; Yang et al. 2025). It is well established, that by maintaining higher groundwater levels, these emissions can be mitigated (Regina et al. 2004, 2014, Huang et al. 2021). The effectiveness of this approach is constrained by climatic conditions, particularly during dry periods when evapotranspiration

lowers groundwater levels. This limitation, however, is the same regardless of the method used for groundwater level management, and whether there are crops grown or the site is restored.

The contrasting results between peat and mineral soils highlight the significance of site-specific conditions and goals. In peat soils, the main benefits of controlled drainage are environmental, while yield impacts are negligible. In mineral soils, particularly those with low water retention capacity, subirrigation can provide substantial agronomic benefits by supplying water during critical growth stages. To better understand the mechanisms and factors related to the yield increase, further research both at the current sites and under different soil and management conditions are required.

The success of controlled drainage and subirrigation depends on local hydrology. Factors such as soil permeability, connectivity to surrounding areas, and availability of water sources influence system performance. These factors must be carefully considered when implementing such systems at farm scale.

5. CONCLUSIONS

Controlled drainage and subirrigation offer effective solutions for addressing the dual challenges of environmental protection and climate resilience in boreal agriculture. The key conclusions of this study are:

1. Controlled drainage significantly reduces drainage discharge, resulting in proportional reductions in nutrient loading across soil types.
2. Groundwater levels can be effectively regulated, although strongly influenced by climatic conditions.
3. In peat soils, higher groundwater tables reduce greenhouse gas emissions without major impacts on yield.
4. In mineral soils, subirrigation improves soil moisture availability and significantly increases crop yields, particularly during dry periods.
5. The effectiveness of these systems depends on local soil and hydrological conditions as well as the desired outcomes.
6. Overall, these water management practices enable a transition from conventional drainage toward multifunctional systems that support sustainable and climate-resilient agriculture.

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