

A NEW GUIDE ON CONTROLLED DRAINAGE: IMPROVING WATER MANAGEMENT, CROP PRODUCTIVITY AND ENVIRONMENTAL OUTCOMES IN BOREAL AGRICULTURE

NOUVEAU GUIDE SUR LE DRAINAGE CONTRÔLÉ : AMÉLIORATION DE LA GESTION DE L'EAU, DE LA PRODUCTIVITÉ AGRICOLE ET DES RÉSULTATS ENVIRONNEMENTAUX DANS L'AGRICULTURE BORÉALE

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ABSTRACT

Controlled drainage (CD) and subsurface irrigation (SI) have gained increasing attention in Finland as multifunctional water management practices capable of improving crop productivity while simultaneously reducing environmental pressures. In boreal agriculture, these practices are particularly relevant due to short growing seasons, high winter and spring runoff, and increasing risks of summer drought under climate change. Finland, located at the northern limit of large-scale field crop production, has a long tradition of artificial drainage: approximately 85 % of agricultural land requires drainage to remain productive, with subsurface drainage covering an estimated 60–70 % of the cultivated area.

This paper presents and analyses a newly published Finnish Guide on Controlled Drainage and Subsurface Irrigation, developed by the Association for Nature Management Education Luoko ry in collaboration with the Finnish Field Drainage Association. Rather than introducing new experimental results, the paper focuses on the guide's development process, structure, and content, as well as its role as a practical decision-support tool for farmers, drainage designers, advisors, and policymakers. The guide synthesises decades of national and international research together with Finnish field experience across mineral soils, peat soils, and acid sulfate soils—three soil groups with distinct hydrological behaviour and environmental sensitivity.

The paper—and the guide itself—aim to translate scientific knowledge into practical recommendations, integrate agronomic and environmental objectives, and emphasise the importance of site-specific conditions in the planning of controlled drainage. Particular attention is given to groundwater-level and runoff regulation as a means to reduce nutrient losses, mitigate greenhouse gas emissions from cultivated peat soils, and improve resilience to both excess water and drought. The relevance of the guide beyond Finland is also discussed, highlighting its applicability to boreal and temperate regions facing similar climatic challenges.

The paper concludes that practice-oriented guidelines play a crucial role in bridging the gap between research and implementation, and that the Finnish guide provides a transferable framework for climate-resilient agricultural water management.

Keywords: controlled drainage; subsurface irrigation; boreal agriculture; agricultural water management; climate adaptation; peat soils; acid sulfate soils.

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RESUME

Le drainage contrôlé (DC) et l'irrigation souterraine (IS) attirent plus d'attention en Finlande en tant que pratiques multifonctionnelles de gestion de l'eau, capables d'améliorer la productivité agricole tout en réduisant les pressions sur l'environnement. Dans le contexte de l'agriculture boréale, ces pratiques sont particulièrement pertinentes en raison de la brièveté des saisons de croissance, des ruissellements importants en hiver et au printemps, ainsi que des risques croissants de sécheresse estivale liés au changement climatique. La Finlande, située à l'extrémité nord de la culture de plein champ à grande échelle, possède une longue tradition de drainage artificiel : environ 85% des terres agricoles nécessitent un drainage pour rester productives, le drainage souterrain couvrant, selon les estimations, 60 à 70% de la superficie cultivée.

Cet article présente et analyse un guide finlandais récemment publié sur le drainage contrôlé et l'irrigation souterraine, élaboré par l'Association de l'éducation sur la gestion de la nature « Luoko ry » en collaboration avec l'Association finlandaise sur le drainage des terres agricoles. Plutôt que de présenter de nouveaux résultats expérimentaux, cet article met l'accent sur le processus d'élaboration, la structure et le contenu du guide, ainsi que sur son rôle en tant qu'outil pratique d'aide à la décision à l'intention des agriculteurs, des concepteurs de systèmes de drainage, des conseillers et des décideurs politiques. Ce guide synthétise des décennies de recherche nationale et internationale, ainsi que l'expérience finlandaise menée sur le terrain concernant les sols minéraux, les sols tourbeux et les sols sulfatés acides — trois groupes de sols présentant un comportement hydrologique et une sensibilité environnementale distinctes.

Cet article — tout comme le guide lui-même — vise à traduire les connaissances scientifiques en recommandations pratiques, à intégrer les objectifs agronomiques et environnementaux, et à souligner l'importance des conditions spécifiques à chaque site dans la planification d'un drainage contrôlé. Une attention particulière est accordée à la régulation du niveau des eaux souterraines et du ruissellement afin de réduire les pertes en nutriments, d'atténuer les émissions de gaz à effet de serre provenant des sols tourbeux cultivés et d'améliorer la résistance face à l'excès d'eau et à la sécheresse. La pertinence du guide au-delà de la Finlande est également abordée, en mettant l'accent sur son applicabilité aux régions boréales et tempérées confrontées à des défis climatiques similaires. L'article conclut que les lignes directrices axées sur la pratique jouent un rôle essentiel pour combler l'écart entre la recherche et la mise en œuvre, et que le guide finlandais fournit un cadre transmissible pour une gestion de l'eau agricole résistante climatique.

Mots-clés : Drainage contrôlé; Irrigation souterraine; Agriculture boréale; Gestion de l'eau agricole; Adaptation au climat; Sols tourbeux; Sols sulfatés acides.

1. INTRODUCTION

Agricultural water management in boreal regions is characterised by pronounced seasonal contrasts. Excess water during autumn, winter and spring frequently limits field trafficability and soil aeration, while water deficits during summer can constrain crop growth during critical developmental stages. Climate change is expected to intensify both extremes, with increasing winter precipitation and more frequent summer droughts. These trends challenge conventional drainage systems that are designed primarily to remove excess water rather than to manage water dynamically.

CD modifies conventional subsurface drainage by allowing the drainage outflow level to be regulated, typically through adjustable control structures installed in collector drains. When combined with SI, the same infrastructure can be used to introduce water into the soil profile during dry periods (figure 1). Together, these practices enable seasonal regulation of groundwater levels according to crop demand and environmental objectives.

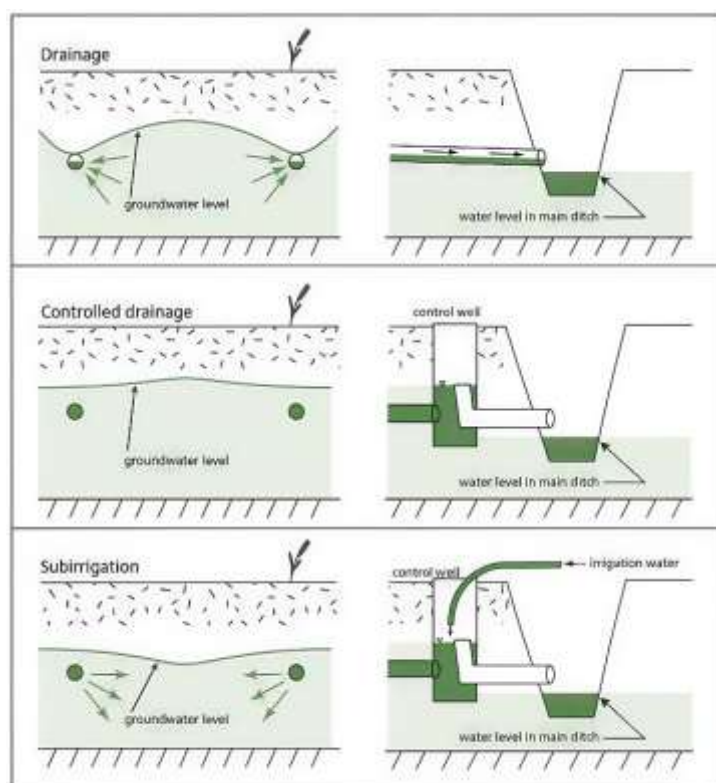


Figure 1. Conceptual illustration of the functioning of conventional drainage, controlled drainage, and subsurface irrigation.

Although the technical principles of controlled drainage have been known for decades, their adoption depends strongly on local conditions, farmer knowledge and the availability of practical guidance. In Finland, research on CD and SI has been conducted since the 1990s, yet implementation has remained limited compared to the estimated technical potential. This gap between research knowledge and practical uptake motivated the development of a comprehensive national guide on CD and SI. At the same time, the publication forms a thematic continuation of earlier outputs by the association, particularly the guides *Turvepeltojen moninaiset merkitykset* (The Multiple Roles of Cultivated Peatlands, Mäkelä et al. 2023) and *Kastelu peltoviljelyssä* (author's translation: Irrigation in Field Crop Production, Bergholm et al. 2023). Together, these publications complement and reinforce one another, contributing to the development of sustainable water management practices under Finnish conditions.

Controlled drainage is currently implemented on approximately 80,000 hectares of agricultural land in Finland (Luke 2023), and the area is steadily increasing. Based on topographic conditions, the method has been estimated to be potentially applicable on up to 700,000 hectares, corresponding to roughly 30% of the total cultivated area in Finland (Puustinen et al. 2019). Although not all of this area is suitable due to soil-related constraints, a substantial share of the technical potential for controlled drainage remains unutilised (Luke 2023; Paasonen-Kivekäs 2016).

The objective of this paper is to present the Finnish guide, focusing on (i) the rationale and process of its development, (ii) the structure and key content areas of the guide, and (iii) its intended role as an accessible information source and decision-support tool for farmers and other stakeholders. The paper does not aim to reproduce the guide's content in full, but rather to reflect on how scientific and practical knowledge were integrated into a coherent advisory publication addressing the multiple water-management challenges of boreal agriculture under a changing climate.

2. RATIONALE FOR DEVELOPING A NATIONAL GUIDE

- **Boreal context and need for guidance**

Finland represents one of the most drainage-dependent agricultural systems globally. A large proportion of agricultural land is located on flat or gently sloping landscapes, typically characterised by fine-textured mineral soils, organic soils, and acid sulfate soils.

Acid sulfate soils are sulfur-rich sediments, typically found in low-lying coastal areas, where sulfidic layers remain stable under waterlogged conditions. However, drainage—particularly initial subsurface drainage and land reclamation on previously undrained fields, as well as the deepening of existing drainage systems—can lower the groundwater level and expose these layers to oxygen. This triggers sulfide oxidation and the formation of sulfuric acid, leading to a sharp decline in soil pH and the release of harmful metals to ditches, streams, and downstream water bodies, posing significant environmental risks

Due to the climatological and geological constraints, artificial drainage is in most cases a prerequisite for cultivation. At the same time, increasing environmental pressures—such as nutrient loading of surface waters, greenhouse gas emissions from organic soils, and biodiversity—have intensified regulatory and societal demands for more sustainable water management practices.

CD, particularly when combined with SI, offers potential solutions to several of these challenges. From a water protection perspective, these practices can reduce nutrient losses—especially nitrogen—by decreasing drainage volumes and enhancing water retention in the soil, although the magnitude of these effects varies depending on soil type and site conditions. From a climate perspective, maintaining higher groundwater levels can reduce soil organic matter decomposition, particularly on organic soils, thereby lowering carbon dioxide emissions while also influencing other greenhouse gases.

From an agronomic perspective, controlled drainage enables more balanced management of excess and deficit water conditions across seasons. It improves drainage during wet periods, thereby enhancing trafficability and soil aeration, while allowing water to be retained or supplied during dry periods to support crop growth. The effectiveness of these benefits depends strongly on soil properties: coarse-textured soils generally respond well due to higher hydraulic conductivity, whereas fine-textured soils tend to exhibit slower responses but may still benefit under suitable conditions and careful management.

Overall, CD and SI can increase the resilience of agricultural systems by moderating hydrological extremes, improving yield stability, and enhancing resource efficiency. However, their performance is highly site-specific and depends on soil characteristics, topography, existing drainage infrastructure, and farm management practices. Without clear guidance, inappropriate implementation may lead to suboptimal performance or unintended negative effects, such as reduced trafficability, insufficient drainage during wet periods as well as soil compaction.

The need for a practical, science-based guide has therefore been recognised by practitioners, researchers, and advisory organisations. While international literature provides valuable insights, it often lacks adaptation to boreal conditions and Finnish soil types, highlighting the importance of nationally tailored guidance.

- **Objectives of the guide**

The primary objective of the Finnish guide is to support informed decision-making among farmers, drainage planners and officials. Rather than promoting controlled drainage universally, the guide aims to help users assess where and under what conditions CD and SI are suitable. Secondary objectives include improving environmental performance, increasing resilience to climate variability and enhancing the long-term functionality of drainage systems.

3. DEVELOPMENT PROCESS OF THE GUIDE

- **Collaborative approach**

The guide was developed through a broad, multi-stakeholder process reflecting both practical expertise and scientific knowledge. The main publisher, Association for Nature Management Education Luoko ry, is a non-profit organization aiming to promote education related to environmental, agricultural and water-related topics. The editorial board included representatives from Sitra; the Drainage Foundation sr; Sedu (Seinäjäki University of Applied Sciences); Österbottens Svenska Lantbrukssällskap (author's translation:

The Swedish Agricultural Society of Ostrobothnia); the Finnish Field Drainage Association; the University of Helsinki; and Association for Nature Management Education Luoko ry, ensuring coverage of research, advisory services, education, and practical drainage implementation. In addition, several Finnish drainage planners and contractors, as well as researchers with extensive experience in CD and SI on both mineral and peat soils, contributed to the preparation of the guide. Their contributions during the commenting process helped ensure that the guide reflects both the latest scientific understanding and practical field experience. Researchers provided up-to-date knowledge on soil hydrology, nutrient dynamics, and greenhouse gas emissions, while practitioners contributed insights into field-scale implementation and operational challenges.

- **Integration of research and practice**

A key principle in the development process was the translation of research results into operational recommendations. Rather than presenting experimental data in isolation, the guide synthesises findings across studies and links them to practical implications. For example, relationships between groundwater level and carbon dioxide emissions from peat soils are discussed in the context of feasible water-level targets under real farming conditions.

- **Structure and usability**

Considerable emphasis was placed on the structure and usability of the guide. The content was organised to follow a logical progression from basic principles to site-specific applications. At the same time, a key objective was to integrate environmental considerations—such as water protection and climate impacts—throughout the guide wherever possible, rather than treating them as separate topics. Visual elements, case examples and checklists were incorporated to facilitate understanding and practical use. Although the guide is grounded in science, the language and presentation were tailored to a non-academic audience.

4. CONTENT AND THEMATIC STRUCTURE OF THE GUIDE

- **Principles of soil water management**

The guide begins by outlining fundamental principles of soil properties, soil water balance, drainage and irrigation. Understanding the interaction between soil structure, pore size distribution and water movement is essential for evaluating the feasibility of controlled drainage. In particular, it is important to understand the relationships between water pressure potential, groundwater level and soil moisture, as these govern water availability for plants and the functioning of CD systems (Figure 2). These principles provide the foundation for later chapters that address specific practices.

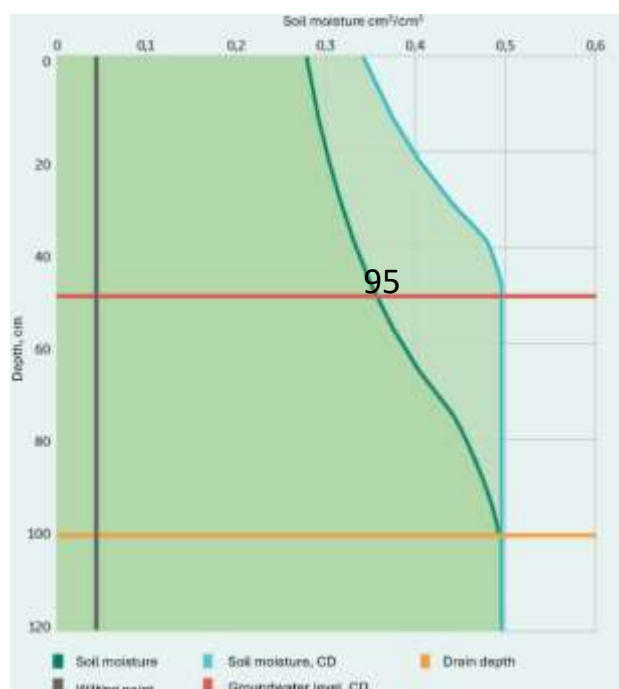


Figure 2. Conceptual diagram illustrating soil water balance under conventional and controlled drainage. In the CD scenario, soil water storage within the 0–100 cm soil layer is approximately 95 mm higher compared to conventional drainage. The diagram represents conditions in a coarse-textured mineral soil.

- **Suitability of controlled drainage under Finnish conditions**

One of the core contributions of the guide is its systematic assessment of suitability across different soil types. Coarse textured mineral soils with good hydraulic conductivity are generally well suited to both CD and SI. In contrast, fine textured clay soils pose challenges related to slow water movement, as their small pore sizes limit both infiltration and lateral flow. This makes it difficult to adjust the groundwater level in a timely and controllable manner. In addition, clay soils are structurally sensitive: prolonged periods of high moisture can weaken soil structure and increase the risk of compaction, while insufficient drying can hinder the formation and maintenance of stable aggregates. These factors may reduce trafficability, delay field operations, and limit the practical applicability of controlled drainage.

At the same time, it should be noted that certain clay soils with acid sulfate soil properties may develop a stable granular structure (known as *urpasavi* in Finnish and *grynlera* in Swedish). These soils are characterised by strong aggregate stability and exceptionally high hydraulic conductivity compared to typical clay soils, making them more favourable for controlled drainage. Cultivated peat soils and acid sulfate soils are treated as special cases due to their environmental sensitivity.

- **Environmental impacts**

The guide devotes substantial attention to environmental outcomes. Evidence from Finnish and international studies indicates that controlled drainage can reduce nutrient losses, particularly nitrogen, primarily by decreasing drainage volumes and prolonging water residence time in the soil, but also possibly through enhanced denitrification and plant uptake (e.g. Wesström et al. 2014). Reductions in phosphorus losses are more variable and site-specific but can occur through reduced erosion and particulate transport when peak flows are attenuated. In the case of acid sulfate soils, controlled drainage can help reduce environmental impacts by limiting the oxidation of sulfidic layers, although the benefits are typically more pronounced when combined with SI.

In addition, controlled drainage can mitigate hydrological extremes by reducing peak runoff following rainfall events and increasing water retention in the field, thereby contributing to more stable flow regimes in receiving water bodies.

On peat soils, maintaining a higher groundwater table can substantially reduce carbon dioxide emissions by limiting aerobic peat decomposition (figure 3), while at the same time potentially increasing methane emissions under very wet conditions. At typical CD groundwater levels (30–60 cm), the risk of increased methane emissions appears limited, as CH₄ fluxes are observed only intermittently under saturated conditions, and overall, the net climate impact remains generally favourable when groundwater levels are maintained sufficiently high during the growing season.

The guide discusses these benefits alongside potential trade-offs, such as reduced trafficability, delayed field operations in wet periods, and the need for careful management to avoid excessive saturation or unintended nutrient mobilisation under certain conditions.

On acid sulfate soils, CD limits sulfide oxidation by raising the groundwater table, reducing their environment impact. However, CD is often insufficient alone, as groundwater levels may drop during dry periods, requiring SI. It also has limited effects on N₂O emissions and nitrogen leaching and may increase liming needs due to capillary rise of acidity (Yli-Halla et al. 2020).

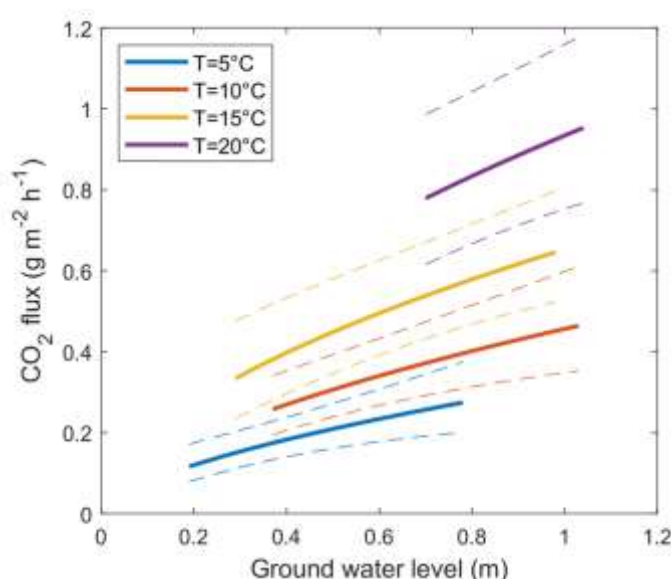


Figure 3. Relationship between groundwater level and CO₂ emissions on peat soils. Heikkinen et al. 2024.

- **Practical implementation and operation**

Practical guidance covers planning, design, construction and operation. Seasonal regulation strategies are emphasised, highlighting that controlled drainage is not a static system but requires adaptive management. Periodic opening of weirs during high-flow periods is recommended to maintain drainpipe function, particularly in iron-rich areas. Emerging technologies for remote and automated control are introduced, including solar-powered weir actuators with mobile-network data transmission that allow management without grid connection—an option of particular relevance in northern conditions where individual fields may lie far from infrastructure (figure 4). Current limitations of such systems, including investment cost and operational reliability, are also discussed.



Figure 4. Remotely controlled and automated drainage control wells have been piloted in Finland, and several prototype systems have been developed. These systems can be powered by solar panels and operated without a direct connection to the electricity grid, with data transmission via mobile networks. Photo: Jari Kolehmainen.

- **Case examples**

Selected Finnish case studies illustrate how CD and SI have been implemented under different conditions. These examples demonstrate both successful applications and limitations, reinforcing the importance of site-specific assessment.

5. ROLE OF THE GUIDE AS AN INFORMATION SOURCE

- **Target audiences**

The guide is intended for a broad audience, including farmers, drainage planners, advisors, environmental authorities and policymakers. Its layered structure allows readers with different backgrounds to access relevant information without requiring extensive prior knowledge.

- **Bridging research and implementation**

By synthesising research and field experience, the guide acts as an intermediary between science and practice. It does not replace site-specific planning or professional advice but provides a common knowledge base that supports dialogue among stakeholders.

- **Transferability beyond Finland**

Although developed for Finnish conditions, many principles presented in the guide are applicable in other boreal and temperate regions. Similar challenges related to climate variability, nutrient management and peat soil cultivation exist across northern Europe and parts of North America. The guide therefore offers a transferable framework rather than a location-specific manual.

6. DISCUSSION

The development of the Finnish controlled drainage guide highlights the importance of practice-oriented synthesis in addressing complex environmental challenges. While scientific research provides essential insights, its impact depends on effective communication and contextualisation as well as appropriate

implementation. Guidelines that integrate agronomic, environmental and economic perspectives can facilitate more informed and balanced decision making.

Particular attention is needed in the context of clay soils, which dominate many Finnish agricultural areas and present specific challenges for controlled drainage. Their low hydraulic conductivity and slow water movement limit the effectiveness and responsiveness of water level control, while structural sensitivity and risks related to compaction and poor trafficability constrain practical implementation. At the same time, significant spatial variability exists even within clay soils, and certain well-structured or organically enriched clays may exhibit more favourable hydraulic properties, highlighting the importance of site-specific assessment by drainage designers.

Despite these limitations, the overall technical potential of controlled drainage in Finland remains considerable. Current implementation levels of approximately 80,000 ha fall well below the technical potential of approximately 700,000 ha, suggesting that wider adoption could deliver tangible benefits in terms of improved water management, reduced nutrient losses and climate-change mitigation, particularly on organic soils. Realising this potential requires not only technical solutions, but also increased awareness, advisory support, and incentives that lower the threshold for adoption. In the current Common Agricultural Policy (CAP) period (2023–2027), investment support of 40 % of total costs is available for controlled drainage in Finland, while complementary environmental compensation is provided for peat soils and acid sulfate soils. The guide can be seen as one step towards bridging the gap between research knowledge and field-scale implementation, complementing these policy instruments.

The work also speaks directly to the theme of the 26th ICID Congress, Water and agricultural resilience in the face of climate change. In a boreal context, climate resilience does not primarily mean addressing chronic water scarcity but rather coping with growing hydrological variability—wetter autumns and winters combined with more frequent and severe summer droughts. CD and SI address both ends of this spectrum using a single infrastructure, making them particularly suited as climate-adaptation tools. At the same time, guidelines have inherent limitations. They cannot capture all local variability, nor can they substitute for field-level monitoring and adaptive management. Future updates of the guide will need to incorporate new research findings, technological developments and policy changes.

7. CONCLUSIONS

The Finnish guide on CD and SI represents a comprehensive effort to translate scientific knowledge into practical, site-specific guidance for boreal agriculture. By integrating agronomic, environmental and technical perspectives, the guide highlights the multifunctional role of controlled drainage as a tool for managing water excess and deficit, reducing nutrient losses, and mitigating climate impacts. At the same time, it emphasises that the effectiveness of these measures depends strongly on local conditions, including soil properties, topography and management practices.

The development process demonstrates the value of collaborative, practice-oriented approaches in bridging the gap between research and implementation. By combining scientific evidence with field-scale experience, the guide provides a shared knowledge base for farmers, planners and advisors, supporting more informed decision-making and reducing the risks associated with inappropriate implementation. Particular attention to soil-specific challenges—such as the slow hydrological response of clay soils or the environmental sensitivity of peat and acid sulfate soils—further strengthens the relevance and applicability of the guidance.

Despite the increasing interest in controlled drainage, a substantial share of its technical potential in Finland remains unutilised. Wider adoption, where conditions are suitable, could contribute to improved water management, enhanced yield stability and reduced environmental pressures. Realising this potential, however, requires continued advisory support, development of practical tools and incentives, and further integration of emerging technologies such as monitoring and automation.

More broadly, the guide provides a transferable framework for climate-resilient agricultural water management in boreal and temperate regions facing similar challenges of hydrological variability, environmental constraints and the need to balance productivity with sustainability. At the same time, it underlines that guidelines cannot replace site-specific planning and adaptive management and should be viewed as a foundation for continuous learning and development.

The experience gained from developing the guide suggests that similar approaches could be beneficial in other regions facing increasing climate variability and environmental constraints. Controlled drainage, when implemented under appropriate conditions and supported by clear guidance, can contribute to more resilient and sustainable agricultural systems.

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