

Integrating sustainability assessments to facilitate decision making in sustainable water management in agriculture

Tamara Avellán^a, Hanna Dencker^b, Jonas Nordström^c, Nóra Hatvani^{d,*} , Balázs Sándor Gál^e, Wiesław Fialkiewicz^f

^a University of Oulu, Water, Energy and Environmental Engineering, Pentti Kaiteran katu 1, Linnanmaa, Oulu, Finland

^b Uppsala University, Department of Earth Sciences, P.O. Box 256, Uppsala, SE-751 05, Sweden

^c Lund University, School of Economics and Management, Agrifood Economics Centre and Swedish University of Agricultural Science, Department of Economics, P.O. Box 7080, Lund, 220 07, Sweden

^d Bay Zoltán Nonprofit Ltd, Division of Biotechnology, Department of Biomass Production and Valorisation, Derkovits fasor 2, Szeged, 6726, Hungary

^e Bay Zoltán Nonprofit Ltd, Engineering Division, Department of System Design, Iglói út 2, Miskolc, 3519, Hungary

^f Wrocław University of Environmental and Life Sciences, Institute of Environmental Engineering, pl. Grunwaldzki 24, Wrocław, 50-363, Poland

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ABSTRACT

Agricultural production necessitates sustainable practices to ensure long-term and sustained food security. Water is a key ingredient for food production. Ensuring sustainable water management in agriculture is thus essential for global wellbeing. But how do we make sure that our practices are sustainable? A large variety of sustainability assessments abound. Their results may even show conflicting results. In this study, we demonstrate the application of three sustainability assessment methods – Water Footprint Assessment, Cost-Benefit Analysis and Life Cycle Assessment – for the use of a water retainer product on different soil types, crops and growing seasons in a farm in Poland. In addition, we aggregate the results of these assessments through a Multi-Criteria Decision Analysis (PROMETHEE) to facilitate decision making. Our findings suggest that yields of all crops, on all soils in both growing seasons increased. However, yield gain was insufficient in most cases to offset the increased costs of using the water retainer product. The Multi-Criteria Decision Analysis showed that soil type and crops used had a larger effect on rank than the application of the water retainer. Overall, the conclusion from the various methods is to not recommend the use of the water retainer as an efficient water saving technology for the specific case. Our analysis showed the effects on the economic and environmental dimension of sustainability but does not include the social dimension due to the lack of data, leaving an incomplete picture of sustainability.

1. Introduction

The agricultural sector plays a vital role in feeding a growing global population and supporting the livelihoods of those engaged in farming. However, pressing challenges such as adapting to climate change, reducing pollution, and fostering healthy ecosystems demand innovative approaches. Agriculture is both a critical economic driver and a fundamental societal necessity. It is essential for meeting the needs of a growing population, mitigating climate change, and conserving biodiversity (Velten et al., 2015; Streimikis and Baležentis, 2020). With agriculture occupying a significant portion of the Earth's land (Rockström et al., 2009), its practices can lead to varying environmental

impacts, including land depletion, soil degradation, water pollution and biodiversity loss. Conversely, sustainable practices can offer benefits such as carbon sequestration and flood mitigation (Streimikis and Baležentis, 2020). To sustainably feed the global population, agriculture must innovate across its systems and supply chains, including farming practices and land management (Streimikis and Baležentis, 2020).

Agriculture also consumes a large proportion of freshwater resources (Rockström et al., 2009), and within the European Union, agricultural pollution contributes to river basin degradation. Water retention in soils is a central pillar of sustainable agricultural water management. By increasing the soil's capacity to store water, retention measures help buffer crops against precipitation variability, reduce irrigation demand,

* Corresponding author.

E-mail addresses: tamara.avellan@oulu.fi (T. Avellán), Denckerhanna@gmail.com (H. Dencker), jonas.nordstrom@agrifood.lu.se (J. Nordström), nora.hatvani@bayzoltan.hu (N. Hatvani), balazs.gal@bayzoltan.hu (B.S. Gál), wieslaw.fialkiewicz@upwr.edu.pl (W. Fialkiewicz).

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and stabilize yields, particularly under conditions of drought or erratic rainfall (Abdallah et al., 1681; CoLab [Internet]). Long-term experiments show that management-induced increases in soil organic carbon can influence soil-water retention properties, though the effects may be subtle depending on soil depth and texture (Panagea et al., 2021). Techniques such as conservation agriculture—with minimum tillage, crop residue retention, and mulching—can improve water-holding capacity by enhancing organic matter and modifying pore structure (Antón et al., 2021).

Technological solutions to increase the soil water retention capacity help retain water in the soil profile and to the plants' root zones. These solutions either support a reduction of water infiltration into the sub-soil or one of evaporation into the atmosphere (e.g. (Keiblinger and Kral, 2018; Mohawesh and Durner, 2019; Seddik et al., 2019)). Amendments used to increase soil water retention capacity can be classified into different groups, based on their origin or composition: inorganic and organic amendments formed as a result of natural processes (e.g. zeolite and unprocessed wood waste, respectively) and materials of anthropogenic origin (e.g. biochar, super-absorbent polymers, geotextiles, geocomposites) (Śpitalniak et al., 2021). An example of a type of amendment formed from materials of anthropogenic origin, is a commercially available product, the Water Retainer product (WR). According to the manufacturer's claims, WR is designed to mitigate water vapor loss by capturing a portion of the humidity that evaporates through the soil capillary system, as well as air humidity, and converting it into small droplets. This process helps maintain soil moisture levels and ensures water availability for plants (Water & Soil Ltd., n.d.b).

More broadly, the academic and policy debate reveals that “sustainability” in agricultural water management is not monolithic: different stakeholders emphasize environmental, economic, and social dimensions in different ways. Dahal et al. (2023), for example, used a Delphi survey among experts to define a context-sensitive concept of sustainability in agricultural water management that explicitly integrates climate change, stakeholder participation, incentives, and farmer needs (Dahal et al., 2023).

A broad array of assessment methods has been developed to evaluate technical and policy options for agricultural water management, each targeting different dimensions of sustainability and producing complementary, and sometimes conflicting, evidence for decision-making. On the environmental side, life cycle assessment (LCA), water-footprint accounting and biophysical performance indicators (e.g., irrigation efficiency, soil-water balance, biodiversity and nutrient-loss metrics) are commonly used to quantify resource use and environmental externalities of alternatives. Economists frequently apply cost–benefit analysis, cost-effectiveness analysis, farm-level profitability metrics (net present value, benefit–cost ratios) and wider input–output or ecosystem-service valuation methods to capture economic viability and distributional impacts. For social dimensions, social life cycle assessment (sLCA), indicator-based sustainability frameworks, participatory appraisal (surveys, focus groups, livelihood-capital approaches) and governance/acceptance metrics are increasingly recommended to address labour, health & safety, equity and community resilience — though applications in agricultural water studies remain fewer and methodologically diverse (Huertas-Valdivia et al., 2020). Recognising this diversity, recent reviews emphasize the proliferation of performance metrics and MCDA tools precisely because no single method captures all relevant trade-offs; yet the multiplicity of valid but disparate results can create confusion for practitioners and policy-makers who must weigh economic returns against environmental limits and social outcomes (Psomas et al., 2021; Ciccìu et al., 2022).

1 This research therefore addresses a critical gap: how to integrate disparate assessment outcomes into a coherent decision framework. We propose and test the use of multi-criteria decision analysis (MCDA), specifically the PROMETHEE method, to synthesize results from a cost–benefit analysis (CBA), an LCA, and a water footprint assessment (WFA). This study presents the results of a study conducted in the EU

H2020 WATERAGRI project, on the use of the WR described above at a case study site in Poland in the growing seasons of 2021 and 2022 and its effect on crop yields of wheat, barley and oats. This article explores how individual and integrated sustainability assessments can help address economic and environmental dimensions of sustainability in relation to water scarcity situations in European agriculture, and thus support on site decision-making.

2. Methods

2.1. Overview of the assessment process

The intention of this work was to assess the sustainability of the WR product in European agriculture, and to understand the role that soil and crop type may play in the decision to use the WR. To assess this, three types of commonly used assessments were applied, namely: the Water Footprint Assessment, the Cost-Benefit Analysis and the Life Cycle Assessment. These methods were selected based on the expertise of the consortium members and intended to show a variety of assessments, as well as their respective strengths and possible weaknesses. Through these the environmental and economic dimensions of sustainability were assessed. However, as these individual assessments may present conflicting findings or may be hard to interpret individually by the target audience – i.e., farmers and advisory services – a combination of the key results was further investigated. Fig. 1 shows an overview of the process, from the various scenarios to the assessment methods, and the integration of the results.

Footprint tools evaluate the environmental impacts of resource consumption and emissions, serving as a robust metaphor for the physical effects of human activities on water, carbon, and nitrogen systems (Lewis et al., 2022). The concept of the water footprint was introduced by Hoekstra in 2002 and initially applied on a national scale. Over time, the methodology was refined to accommodate various scales and is now standardized in the *Water Footprint standard* (ISO 14046:2014) (Aldaya et al., 2012; ISO [Internet]).

CBA is a tool for evaluating projects with shorter or longer time horizons (García-Herrero et al., 2022) and has its theoretical roots in neoclassical welfare economics (OECD, 2006). CBAs rely on calculating a net present value (NPV) through discounting of costs and benefits in monetary terms (Hoogmartens et al.). Projects with a positive NPV indicate enhanced social welfare, warranting implementation. In cases where financial resources are limited or only one technology can be adopted, the project with the highest NPV should typically be prioritized. The value of changes in environmental factors (such as reduced eutrophication or improved water quality) can be included in the analysis. However, valuing ecosystem services can be challenging and is sometimes seen as a limitation of the method.

A key advantage of using life cycle tools is the holistic perspective they provide, considering the entire life cycle of a product or process. This approach allows for the identification of shifts in environmental burdens, the analysis of the entire supply chain, and the comparison of various scenarios and practices (De Luca et al., 2017). Life cycle approaches, rooted in systems thinking, offer a long-term viewpoint that spans from cradle to cradle or cradle to grave (Rivela et al., 2022). These methods are unified in their focus on evaluating the entire life cycle, from raw material extraction to final disposal. The primary goal of an LCA is to quantify all environmental impacts of an activity based on physical energy and material flows (Fauzi et al., 2019).

Multi-Criteria Decision Analysis is a term used for methods that can incorporate multiple conflicting criteria and provide results that are rational, justifiable, and explainable (De Luca et al., 2017; Talukder et al., 2018). A well-developed MCDA can establish a strong basis for identifying the most optimal outcome (Yang et al., 2021). MCDA is widely used by researchers due to its holistic nature and its ability to balance and integrate various perspectives, even in complex scenarios. This method is particularly useful for understanding the intricate

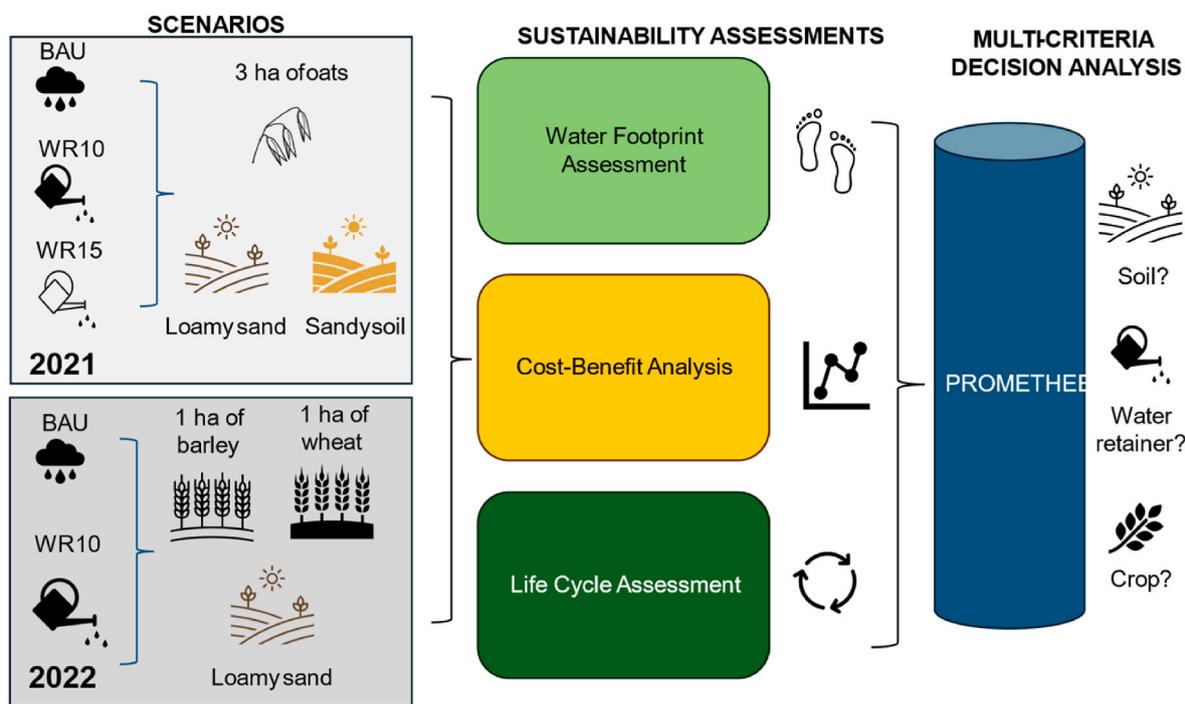


Fig. 1. Overview of the assessment process, from the scenarios (BAU – Business As Usual, WR – Water Retainer application with 10 meaning a dosage of 10L/ha and 15 meaning 15L/ha), to the three different sustainability assessments, and the integration of the results through the Multi-Criteria Decision Analysis.

relationship between society and nature, and it combines both qualitative and quantitative aspects to interpret conflicting decision criteria (De Luca et al., 2017). Using MCDA, all relevant alternatives can be ranked, and the most optimal solution can be identified (Lbianca et al., 2022).

Two main types of scenarios (Fig. 1) provided the basic approach for the assessments: Business as usual (BAU) scenarios and Water Retainer (WR) scenarios. The BAU scenarios represent conventional farming practices without the application of any water retention agent, while WR scenarios include the application of the WR product. Within these two main types, nine different scenarios were analysed, according to the two soil types (loamy sand and sandy soil), the different crops (oats, barley, wheat) and the two growing seasons the field tests took place in (2021, 2022). Throughout the manuscript a common code was developed for the scenario descriptions which can be found in Table 1.

2.2. Context, site description and intervention

The assessments were carried out with data resulting from a case

Table 1
Overview of the different soils, crops, and the Water Retainer applications in the two growing seasons and scenario names used for all assessments (in italics).

Growing season	Crop	Water Retainer application	Soil Type	
			Sandy Soil	Loamy Sand
2021	Oats	none (BAU)	<i>2021-SS-O-BAU</i>	<i>2021-LS-O-BAU</i>
		10 L/ha	<i>2021-SS-O-WR10</i>	<i>2021-LS-O-WR10</i>
		15 L/ha	–	<i>2021-LS-O-WR15</i>
2022	Barley	none (BAU)	–	<i>2022-LS-B-BAU</i>
		10 L/ha	–	<i>2022-LS-B-WR10</i>
	Wheat	none (BAU)	–	<i>2022-LS-W-BAU</i>
		10 L/ha	–	<i>2022-LS-W-WR10</i>

study in Poland as part of the WATERAGRI research project. WATERAGRI, short for “Water Retention and Nutrient Recycling in Soils and Streams for Improved Agricultural Production,” is an EU Horizon 2020-funded initiative that ran from 2020 to 2024 (www.wateragri.eu).

The case study site was located within the continental zone of southern Poland, specifically in the lowlands of Lower Silesia (51°15'36.2"N, 16°54'21.5"E). Field experiments were carried out in Śleganina catchment (17 km²) at a farm which specializes in cereal production and spans more than 500 ha (Fig. 2).

Meteorological parameters (shortwave solar radiation, longwave solar radiation, air temperature, relative humidity, wind speed and precipitation) were measured in the field at 10-min intervals since November 2020. Monthly precipitation values were aggregated, while potential evapotranspiration was calculated according to the Food and Agriculture Organization of the United Nations (FAO) Penman-Monteith equation (Fig. 3). The annual precipitation in 2021 and 2022 was 553 mm and 494 mm, respectively. The year 2021 can be considered as close to normal in terms of the mean annual precipitation of the study area, measured over the period 1991–2020, which is 541 mm. Although the annual rainfall in 2022 was only 10 % less than in 2021, a 51 % decrease in rainfall during the growing season was observed. Thus, in 2022, when persistent lack of precipitation affected large areas of Europe from winter to summer, drought had a serious impact on the yield of the case study site.

In this case study location, a commercially available water retainer product was used as a method to enhance soil water retention and thus support yield during low rainfall events. The WR product, manufactured by the Hungarian company Water & Soil Ltd. is a liquid, organic, biodegradable soil conditioner suitable for both conventional and organic farming, and most suitable for high-value crops such as fruits and vegetables, not necessarily for the crops used here. According to the manufacturer's claims, when applied to the soil surface, it enhances the plants' ability to absorb water and reduces evaporation, mitigating drought and dehydration risks. The product, applied through spraying, fully biodegrades within three months. It is reported by the manufacturer to have additional beneficial effects: optimizing water balance, minimizing irrigation requirements, and supporting rainfed agriculture

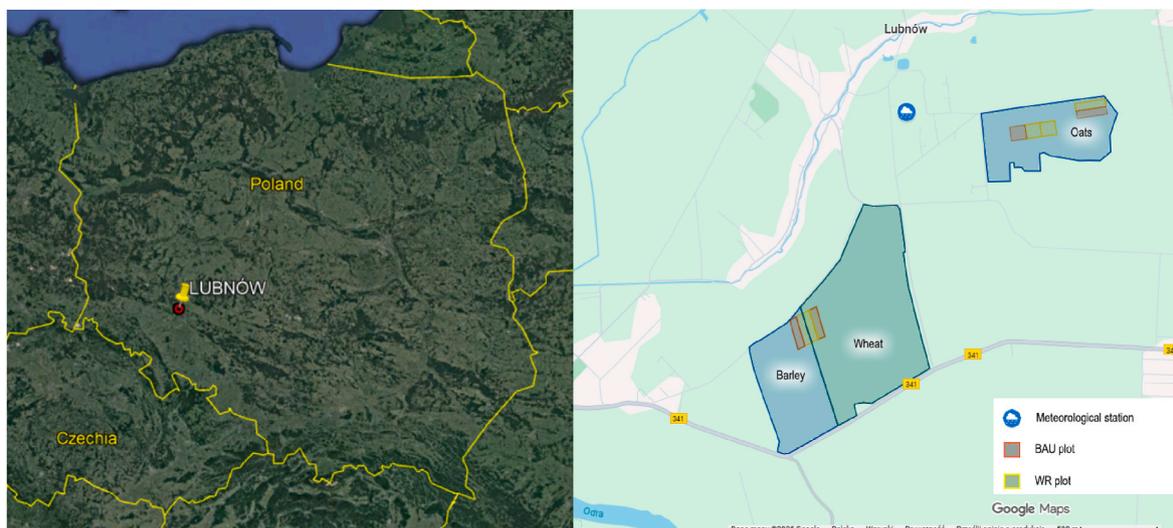


Fig. 2. The location of case study site (left) and experimental plots (right).

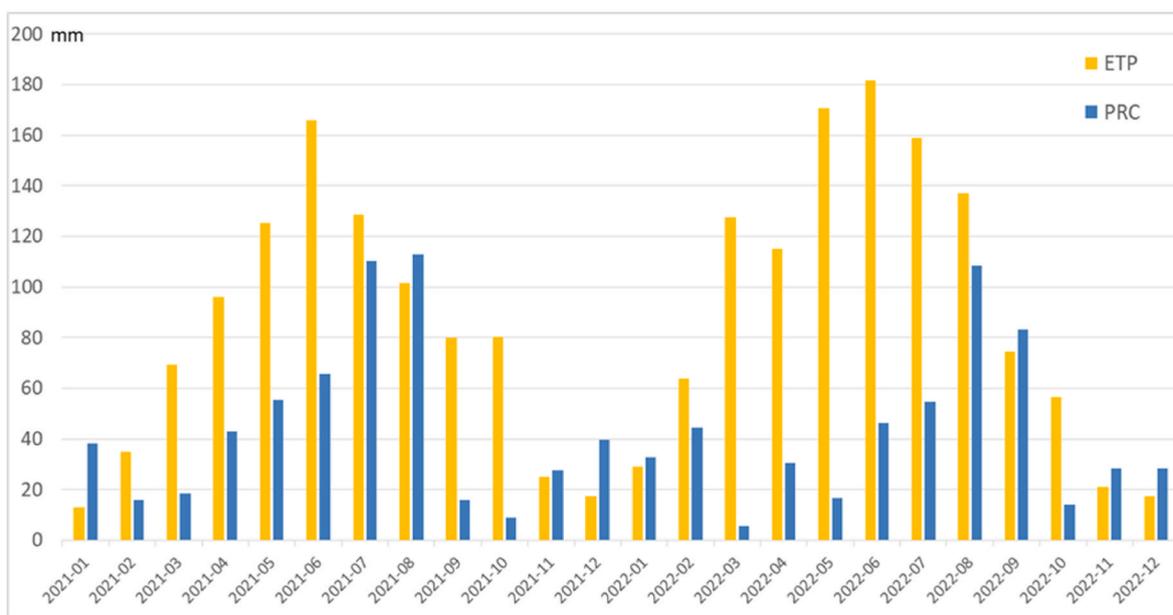


Fig. 3. Monthly precipitation (PRC) and potential evapotranspiration (ETP) in Śleganina catchment.

under low rainfall conditions. This intends to lead to healthier soils, reduced salinity, and higher yields with lower water demand (Water & Soil Limited, n.d.a). The composition of the WR product and the exact mechanism of its action is considered confidential and was not shared with researchers of the WATERGARI consortium for the protection of industrial property.

The WR product was tested during the 2021 and 2022 growing seasons, both on rainfed agricultural land. In 2021, WR was applied across 3 ha of oat crops. Two soil profiles—sandy soil and loamy sand—were identified at the site, and soil moisture was monitored throughout the growing season. The site comprised four plots, with the WR product applied at varying dosages across three plots. For the 2022 growing season, new locations at the farm were selected for study. One hectare each of barley and wheat was investigated, and soil moisture monitoring continued as in the previous year. The application rate of 10 L per hectare was evaluated for all crops and soil types, with an additional test of 15 L per hectare for oats in 2021 (Table 1).

During the cultivation of crops different fertilizers were applied at

the farm. Their total load was converted into the rate of nitrogen applied for individual crops, namely 79.7 kg/ha for oats and 85.4 kg/ha for barley and wheat. The permissible concentration value of total nitrogen concentrations in lowland streams is 4.9 mg/l (as per the Regulation of the Minister of Infrastructure of June 25, 2021 on the Classification of Ecological Status, Ecological Potential and Chemical Status, and the Method of Classification of the State of Surface Water Bodies, as well as Environmental Quality Standards for Priority Substances (Journal of Laws, 2021; Item 1475)).

2.3. The water footprint assessment

The WFA builds upon the notion of virtual water, which refers to the water required to produce a product or deliver a service. It measures the environmental burden associated with a product or service, emphasizing the finite nature of water as a resource (De Benedetto and Klemes, 2009). Defined in *The Water Footprint Assessment Manual* (Mekonnen and Hoekstra, 2011), WFA quantifies freshwater usage (in $m^3/year$) by

considering both direct and indirect water use.

In agriculture, the crop water footprint (WF_{crop}) is typically expressed as the water volume required per tonne of crop yield ($m^3/tonne$) and determined by dividing the total annual water usage by the total crop yield for the same period. In this context, blue water originates from irrigation, green water from rain, and grey water from polluted freshwater resulting from agricultural processes (Shrestha et al., 2013).

The total WF_{crop} combines the three water components, blue, green and grey, as per:

$$WF_{crop} = WF_{crop, blue} + WF_{crop, green} + WF_{crop, grey} \quad (1)$$

The **Crop Blue Water Footprint** ($WF_{crop, blue}$) represents the consumption of surface and groundwater resources, accounting for water lost to evaporation, incorporation into products, or discharge to different catchments or the sea. In practice it represents the volume of irrigation water use (CWU_{blue} , m^3/ha) per unit of crop yield (Y , tonne/ha):

$$WF_{crop, blue} = CWU_{blue} / Y \quad (2)$$

As the crops were not irrigated during the cultivation period at the case study site, $WF_{crop, blue} = 0$.

The **Crop Green Water Footprint** ($WF_{crop, green}$) involves the consumption of rainwater that does not become runoff and is calculated as the green component of crop water use (CWU_{green} , m^3/ha) divided by crop yield (Y , tonne/ha):

$$WF_{crop, green} = CWU_{green} / Y \quad (3)$$

CWU_{green} was calculated as minimum daily value of P_{eff} and ET_c and summed up over the growing period., where P_{eff} is effective precipitation and ET_c is crop evapotranspiration.

Lastly, the **Crop Grey Water Footprint** ($WF_{crop, grey}$) indicates pollution, defined as the volume of water required to dilute pollutants to meet water quality standards. Evaluated based on the pollutant load applied to the field (AR , kg/ha), leaching-runoff fraction (α), and water quality standards:

$$WF_{crop, grey} = ((\alpha * AR) / (C_{max} - C_{nat})) / Y \quad (4)$$

C_{max} is the maximum acceptable concentration and C_{nat} is the natural concentration of a pollutant in the receiving water body, expressed in kg/m^3 . When natural concentration is unknown, for simplicity one may assume $C_{nat} = 0$.

The meteorological data mentioned in section 2.2 were used to calculate daily sum of precipitation while the crop evapotranspiration was calculated following the FAO Penman-Monteith equation at a daily interval (Allen, 1998). Nitrogen was chosen as the predominant pollutant to calculate $WF_{crop, grey}$. Because no measurement of real nitrogen load entering the water body was available, a fixed value of α equal to 10 per cent of nitrogen fertilizers applied in the field was assumed (Mekonnen and Hoekstra, 2011).

2.4. The Cost-Benefit Analysis

The CBA aimed to assess the overall costs and potential monetary benefits of using the WR product. Net values were used in the analysis, with social security fees included to account for their contribution to labour costs. However, value-added tax (VAT) was excluded, as it is deductible for farmers.

The analysis incorporated various physical flows, including yield (tonnes per hectare), WR application rate (L/ha), fieldwork duration, fuel consumption (L/ha) for activities such as fertilization, spraying, sowing, harvesting, and soil preparation, as well as input material usage per hectare (seed, fertilizer, urea, ammonium nitrate, and the herbicide Mustang Forte). Yield and WR application rates are presented in Table 4 in the results section, while details on fieldwork duration, fuel consumption, and input material use are available in Appendix 1. The

corresponding monetary values assigned to these physical flows are provided in Table 2, with further details on calculation methodologies outlined in Appendix 1. Table 2 also summarizes the input variables used in the CBA, as provided by the farmer who carried out the tests.

Since this study does not require discounting future costs and benefits as the WR product fully biodegrades within three months, net (the difference between benefits and costs) serves as the primary policy-relevant measure in the CBA. In this context, net profit and net present value are equivalent. To evaluate the financial benefits of the farmer of using the WR, we calculated and compared the difference in net profit between the BAU scenario and the corresponding WR scenario.

The WR product is applied together with fertilizer and, if used, pesticides. Therefore, there is no additional cost from fuels and machines to apply the WR product (costs excluded from this CBA). The minimal extra workload to add the WR product to the other chemicals being applied on the land, and labour costs for applying the WR product were also excluded.

2.5. The life cycle assessment

LCA is a widely accepted method for environmental impact assessment that can be applied in numerous areas. LCA can assess environmental impacts at both micro and macro levels, allowing modelling and comparison of different scenarios. In the case of the WATERAGRI project, LCA was used to assess the environmental footprint of the proposed solutions for the different concepts/systems to model material and energy flows and to determine their impacts. These categories represent the potential environmental impacts, providing an estimate of what could occur if emissions follow the defined trajectory under certain environmental conditions. However, LCA results are relative rather than predictive, meaning that they indicate the likelihood of environmental impacts.

The impact assessment focuses on categories being most relevant to the objectives of this study. These categories were selected from the Environmental Footprint reference package 3.0, provided by the European Commission's 'European Platform on LCA'. Detailed descriptions of the methodology's impact categories are provided in the International

Table 2

Description of input variables (see the full explanation of input variables in Appendix 1).

Input variables	Values used		
	2021	2022	
	oats	spring wheat	spring barley
Private benefits			
Yield (tonne/ha)	(see Table 4 for values)		
Market value yield (EUR/tonne) in Poland, VAT excluded	143	240	206
Private costs			
Market price of Water Retainer (EUR/l), VAT excluded ^a	8.86	11.81	11.81
Fuel cost of agro-technical procedures (EUR/ha), VAT excluded	28.50	35.77	35.77
Input material cost (for seeds and fertilizer) (EUR/ha), VAT excluded	82	295	289
Labour cost of agro-technical procedures (EUR/ha) ^b	7.09	5.27	5.27
Net profit of using WR (difference between benefits and costs)	(see Table 6 for values)		

Notes.

^a The WR product was bought in Hungary, where the market price for 20 L was 225 EUR in 2021 and 300 EUR in 2022 (including 27 % VAT).

^b Labour costs consist of the total amount of hours of labour carried out to cultivate the crop: one field with 33 ha of oat (2021) and another field with 22 ha of wheat and 30 ha of barley (2022).

Reference Life Cycle Data System (Institute for Environment and Sustainability (Joint Research Centre), 2010) guidelines and the Intergovernmental Panel on Climate Change, Fifth Assessment Report (IPCC et al., 2014). By evaluating the impact categories, the LCA helps guide decision-making and improve the environmental performance of the systems assessed.

The system boundaries were set first, and the scenarios were defined. The system boundary for the LCA follows a "cradle to gate" approach, covering all phases from seed supply to cultivation, including fertilizer and pesticide use, soil cultivation and waste management. The system boundary was set at harvest, excluding transport and processing of produce in downstream phases, and the end-of-life stage (Fig. 4). The producer of the WR product, Water & Soil Ltd., considers the exact composition and production technology to be confidential in order to protect its industrial property. As a result, researchers were not provided with the detailed information required to model the production process in the LCA, and the manufacturing stage of the WR product was therefore excluded from the analysis. Nevertheless, the environmental impacts associated with transporting the WR product from Hungary to the case study site in Poland were included in the assessment.

The functional unit of the study is defined as one tonne of harvested crop produce from the test fields. Yield is influenced by soil type and the application of WR product, while tillage and crop protection treatments remained equal across all scenarios.

As defined in section 2.1 for the overall set up, two main types of scenarios (Fig. 5) provided the basic approach for the LCA: BAU scenarios and WR scenarios.

The LCA was conducted using GaBi Professional 10.6 software, utilizing two databases for modelling: the ecoinvent database (version 3.8) from 2022 and the Thinkstep database (ts-GaBi) from 2022. No country-specific processes were necessary for the analysis, such as those for energy mix or natural gas consumption, as they were not crucial for the environmental assessment (the full inventory can be found in Appendix 2).

The LCA input data was provided by the Wroclaw University of

Environmental and Life Sciences, Institute of Environmental Engineering, who was the contact point with the farmer. It encompassed key aspects of agricultural operations, including the quantity of seeds used for sowing, details on agricultural preparations such as herbicides and fertilizers—covering their composition, weight, and transport distances—and the machinery utilized for cultivation. Additionally, the dataset includes information on crop yield from the fields at the case study site, along with the application of the WR. Waste management data was also collected, detailing waste quantity, quality, transport distances, and disposal methods. All measurements were recorded on-site by the farmers, ensuring accuracy and relevance for the study.

In accordance with LCA standards, material and energy flows that could not be modelled due to insufficient information were deemed negligible if they contributed less than a few percent to the total impact, following the "cut-off" rule. For the 2021 season, the proportion of excluded substances was 2.6 % for scenarios involving 10 L/ha of WR and 3.8 % for scenarios involving 15 L/ha of WR. Similarly, for the 2022 season, the percentage of excluded materials remained below 3 %, ensuring compliance with LCA standards. To ensure accurate comparisons, emissions from WR transportation were excluded from the 2022 data, as this parameter was not considered in the 2021 season either.

Following ISO 14040 standards, allocation involves distributing input and output flows across a product system. In this study, allocation was necessary for the 2021 season, where material and energy flows were based on a sample area of 33 ha. Each scenario considered 1/33 of the total input flows. Yield data was based on measurements from 1 ha plots during harvest. In 2022, allocation was not required as more accurate data was obtained.

The scenarios were compared based on the following key impact categories (as per https://green-business.ec.europa.eu/environmental-footprint-methods/life-cycle-assessment-ef-methods_en).

- **Acidification** [mol H⁺ eq.]: Acidification occurs when sulphur dioxide and nitrogen oxides react with water vapor, forming acid rain that damages ecosystems and hinders plant growth. This indicator

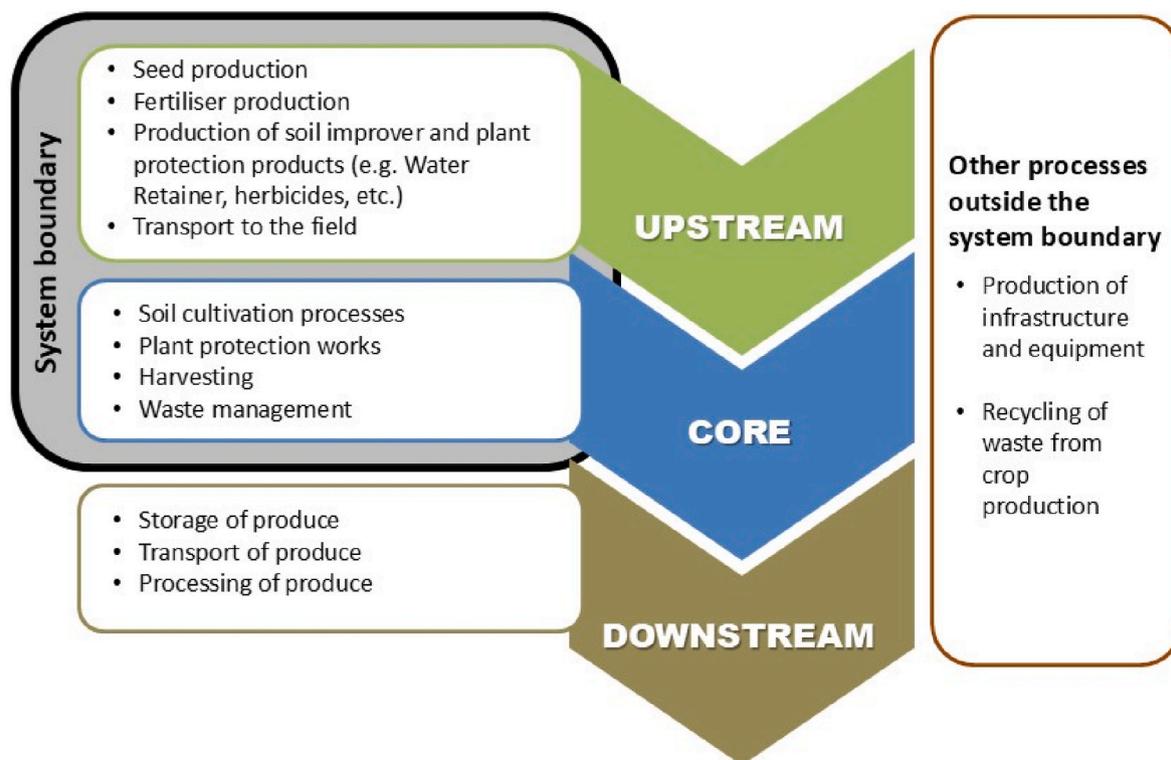


Fig. 4. System boundary of Life Cycle Assessment.

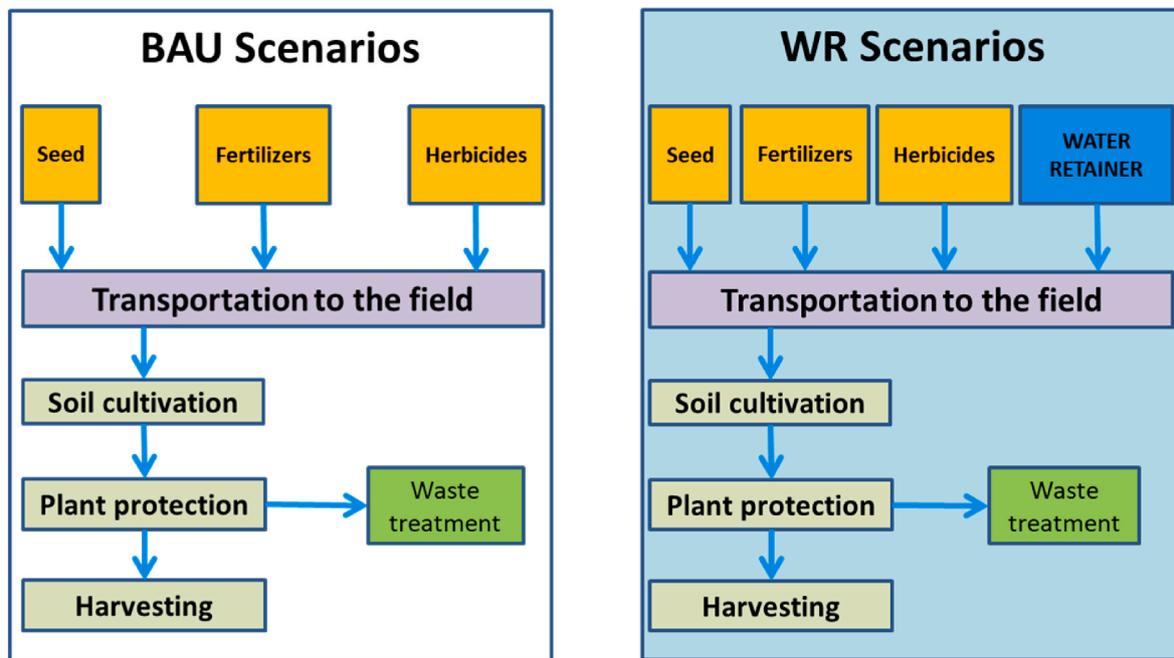


Fig. 5. “Business As Usual” scenarios (left) versus Water Retainer (right) scenarios as they were used for the LCA.

refers to the potential impact of substances originating from processes such as combustion in electricity, heat production and transport, converted to the equivalent of moles of H^+ ion.

- **Climate change, total** [kg CO₂ eq.]: Climate change results from increased greenhouse gas (GHG) emissions warming the atmosphere. Main gases include carbon dioxide, methane, nitrous oxides, and fluorinated compounds. This indicator refers to the global warming potential of all GHG emissions compared to the amount of the global warming potential of 1 kg of CO₂.
- **Eutrophication, freshwater** [kg P eq.]: Substances such as fertilisers promote growth of algae or specific plants which can lead to aquatic biomass overgrowth, biodiversity loss and fish kills, due to phosphorus and nitrogen overflow into freshwater. The potential impact of substances contributing to freshwater eutrophication is converted to the equivalent of kilograms of phosphorus.
- **Land use** [Pt]: Land use refers to land occupation and transformation by activities such as agriculture, forestry, construction, and mining. The impacts include loss of species, of the organic matter content of soil, or erosion. This composite indicator measures impacts on four soil properties (biotic production, erosion resistance, groundwater regeneration and mechanical filtration), expressed in points.
- **Resource use, fossils** [MJ]: Resource use covers depletion of non-renewable resources like fossil fuels, metal ores and minerals, highlighting the decline rate of these materials and the possibility of the non-availability of fossil fuels for future generations. The amount of materials contributing to this indicator is converted into MJ.

The calculation of environmental performance for the scenarios analysed provided an overview of the impact changes due to WR use, comparing it against the BAU scenarios. The analysis focused on comparing the key impact categories across all the scenarios.

2.6. The Multi-Criteria Decision Analysis (PROMETHEE)

There is no straightforward rule for selecting the best MCDA method (Wątróbski et al., 2019). For this study, the main types of MCDA methods were evaluated based on the research objectives. Since the alternatives are predefined, a multi-attribute method was chosen. A strong sustainability perspective was prioritized, so a method with a low

degree of compensation was preferred. Both ELECTRE and PROMETHEE offer low compensation, with PROMETHEE having a slightly higher degree compared to ELECTRE (Cinelli et al., 2014). Previous research has demonstrated that PROMETHEE is an effective and transparent method for assessing agricultural sustainability (Talukder et al., 2018) employing an outranking approach to rank alternatives (Nautiyal et al., 2021). Developed in 1982 by J.P. Brans (Brans and Vincke, 1985; Behzadian et al., 2010a), PROMETHEE includes two primary versions: PROMETHEE I, which provides partial rankings, and PROMETHEE II, an extension that offers complete rankings from the most to least feasible alternatives (Talukder et al., 2018; Behzadian et al., 2010a).

The PROMETHEE method relies on pairwise comparisons of alternatives for each criterion. To generate rankings using PROMETHEE, additional data is required: weights and a preference function (Behzadian et al., 2010a). While the method does not prescribe how weights should be determined, it assumes that this step can be managed by the user (Talukder et al., 2018). The weights are used to mathematically express the relative importance of each criterion. As stipulated by Brans and De Smet (Brans et al., 2016a), the sum of all weights must equal one, as shown in Equation (1). This article adopts the equal weights approach.

$$\sum_{j=1}^k w_j = 1 \quad (5)$$

For each criterion, the preference function converts the preference difference between two alternatives into a value ranging from zero to one (Behzadian et al., 2010a). There are six different suggested preference functions: usual criterion, quasi-criterion, criterion with linear preference, level-criterion, criterion with linear preference and indifference area and Gaussian criteria (Brans and Vincke, 1985). The usual criterion was deemed to be most suitable in this case. The primary aim of PROMETHEE is to evaluate a finite set of alternatives denoted as $A = a_1, a_2, \dots, a_i, \dots, a_n$ (Brans et al., 2016a). In this study, the alternatives represent the nine scenarios assessed across the three SAs (see Table 1).

The criteria are represented as $g, \{g_1(\cdot), g_2(\cdot), \dots, g_j(\cdot), \dots, g_k(\cdot)\}$, corresponding to selected parameters from each SA (Brans and De Smet, 2016). To streamline calculations, the decision matrix is normalized using techniques designed to maximize beneficial criteria (Equation (6))

and minimize non-beneficial criteria (Equation (7)). This normalization process employs the min-max formula (Palczewski and Salabun, 2019; Goswami, 2020).

$$R_{ij} = \frac{[x_{ij} - \min(x_{ij})]}{[\max(x_{ij}) - \min(x_{ij})]} \tag{6}$$

$$R_{ij} = \frac{[\max(x_{ij}) - x_{ij}]}{[\max(x_{ij}) - \min(x_{ij})]} \tag{7}$$

Once the weights, preference function, evaluation table, and normalization technique are defined, the PROMETHEE procedure begins (Brans et al., 2016a). The preference model outlines the data used for PROMETHEE, their units, and their treatment as either beneficial or non-beneficial criteria. The following key results from each of the assessments were used in the PROMETHEE assessment.

- From the LCA, ‘climate change total’ impact was included.
- From the WFA, the ‘crop water footprint WF_{crop} ’ was used.
- From the CBA, ‘net profit’ was included.

The ‘climate change total’ impact category was selected to represent the cultivation process’s contribution to global warming. WF_{crop} was chosen as it encompasses all crop growth components (green, blue and grey) thereby accounting for the crop’s total water usage and nitrogen leakage. Lastly, ‘net profit’ was incorporated to reflect increased costs associated with WR use, which proved unprofitable when isolated within the CBA.

A total of nine scenarios results from the different combinations and these were the basis for the analyses done in the MCDA (Table 1). Initially, all nine scenarios were included in the PROMETHEE analysis. Subsequent rounds of analysis separated scenarios by growing season to account for reduced precipitation in 2022 and assess the sensitivity of rankings to the inclusion of specific scenarios. The same preference model (Table 3) was applied across all three PROMETHEE analyses, with only the included scenarios varying. The procedure and input data otherwise remained consistent.

The computation of the PROMETHEE method is carried out in five steps (their detailed description can be found in Appendix 3). The PROMETHEE calculations were carried out in three runs. In the first run, all nine scenarios were included. In the second and third rounds of calculations, the scenarios were separated by growing season, to identify potential changes depending on crop type and the sensitivity of the final ranking based on included scenarios.

3. Results

3.1. Yields for the different scenarios

The application of the WR product had an overall positive effect on yields in 2021 and 2022 (Table 4) (see full results in Appendix 4). However, the extent of the yield increase varied depending on crop type, soil type and the WR application rate.

In 2021, applying the WR product at 10 L/ha increased oat yields by 7.4 % in sandy soil (2021-SS-O-WR10) compared to the untreated plot

(2021-SS-O-BAU). The same WR rate in loamy sand (2021-LS-O-WR10) resulted in a higher yield gain of 12.9 %. Increasing the WR application to 15 L/ha (2021-LS-O-WR15) further enhanced oat yields in loamy sand: the yield was 38.6 % and 22.8 % higher compared to the untreated plot (2021-LS-O-BAU) and the 10 L/ha WR application (2021-LS-O-WR10), respectively.

A similar trend was observed in 2022, where wheat grown in loamy sand with WR at 10 L/ha dosage (2022-LS-W-WR10) showed a 10.6 % yield increase compared to the untreated plot (2022-LS-W-BAU). The most pronounced yield improvement was seen for barley in loamy sand, where WR application at 10 L/ha (2022-LS-B-WR10) increased yield by 35.8 %, compared to the untreated plot (2022-LS-B-BAU).

A comparison of oat yields in 2021 across three conditions, i.e. BAU, WR10, WR15 revealed that increasing the WR rate from 10 L/ha to 15 L/ha resulted in a threefold increase in yield improvement, rising from 12.9 % to 38.6 % (Table 4). These findings suggest the need for further research to determine the optimal WR dosage, balancing yield benefits against economic feasibility.

3.2. The water footprint assessment

Water footprint calculations performed for the crops grown during 2021 and 2022 show that in 2021, oats grown on sandy soil with WR product showed an 8 % reduction in total WF (WF_{crop}) (Table 5). On loamy sand, WR applications of 10 L/ha and 15 L/ha reduced WF by 11 % and 15 %, respectively. Although the area experienced serious drought in 2022, the application of the WR with the rate of 10 L/ha for wheat and barley production resulted in 10 and 26 % reduction of WF, respectively. The WF parameters, including green and grey water footprints, showed significant improvements in water use efficiency in plots where WR was applied.

The blue water footprint for the farm is zero, as it relies entirely on rainfed crops with no irrigation. The use of WR altered the green water footprint by storing precipitation in the soil, making it fully available to plants and thereby increasing yields. Since evapotranspiration exceeded effective precipitation, plants utilized all available water, causing green water scarcity to reach 100 %. Rainfall data further indicated that average annual precipitation was insufficient to meet crop water requirements, highlighting persistent water scarcity for the crops assessed. WR application reduced the water footprint in all scenarios, enabling more efficient use of rainwater and contributing to increased yields. However, these yield gains remain below optimal levels due to ongoing water scarcity, especially in 2022, which prevented plants from fully thriving.

3.3. The Cost-Benefit Analysis

The CBA indicates that the farmer’s profit from cultivation is determined by the difference between private benefits and private costs. The final row of Table 6 presents the net profit difference between WR and BAU scenarios. A positive net profit difference would suggest that using WR is economically beneficial from the farmer’s perspective. However, the net profit difference is negative for all tested crops at the study site.

Three primary factors influence these results: yield variation, WR costs and market prices. The relatively low yield increases for oats on

Table 3
Preference model, explaining the included criteria and how they will be treated.

Criterion, g	Assessment	Applied SA measure	Unit of measurement	Weight of criterion, W^a	Preference direction	Preference function
g_1	LCA	Climate change total	kg CO ₂ eq.	0,33	Min	Usual criterion
g_2	WFA	WF_{crop}	m ³ /tonne	0,33	Min	Usual criterion
g_3	CBA	Net profit	EUR	0,33	Max	Usual criterion

^a W = equal.

Table 4

Overview of yields for the different scenarios.

Scenario	2021-SS-O-BAU	2021-SS-O-WR10	2021-LS-O-BAU	2021-LS-O-WR10	2021-LS-O-WR15	2022-LS-W-BAU	2022-LS-W-WR10	2022-LS-B-BAU	2022-LS-B-WR10
Yield (kg/ha)	680	730	1400	1580	1940	2550	2820	1480	2010
Yield increase compared to relevant BAU scenario (kg/ha)	–	50	–	180	540	–	270	–	530
Yield increase compared to relevant BAU scenario (%)	–	7.4 %	–	12.9 %	38.6 %	–	10.6 %	–	35.8 %

Note: The average yield from the test site is lower than the general average from Poland.

Table 5Water Footprint (m³/tonne) of crops cultivated at the case study site. Decrease in WF_{crop} is calculated compared to the relevant BAU scenario.

Scenario	2021-SS-O-BAU	2021-SS-O-WR10	2021-LS-O-BAU	2021-LS-O-WR10	2021-LS-O-WR15	2022-LS-W-BAU	2022-LS-W-WR10	2022-LS-B-BAU	2022-LS-B-WR10
WF _{crop} , green	4265	3919	2071	1835	1495	565	511	973	716
WF _{crop} , blue	0	0	0	0	0	0	0	0	0
WF _{crop} , grey	2392	2198	1162	1029	838	683	618	1178	867
WF _{crop}	6657	6117	3233	2865	2333	1248	1129	2151	1584
Decrease in WF _{crop}	–	8 %	–	11 %	15 %	–	10 %	–	26 %

Table 6

Results of the cost-benefit analysis.

Scenario	2021-SS-O-BAU	2021-SS-O-WR10	2021-LS-O-BAU	2021-LS-O-WR10	2021-LS-O-WR15	2022-LS-W-BAU	2022-LS-W-WR10	2022-LS-B-BAU	2022-LS-B-WR10
Yield (kg/ha)	680	730	1400	1580	1940	2550	2820	1480	2010
Private benefit: Market value yield (EUR/ha)	97	104	200	226	278	612	676	304	413
Private costs (EUR/ha)									
Water Retainer cost	0	89	0	89	133	0	118	0	118
Labour cost of agro-technical procedures	7.1	7.1	7.1	7.1	7.1	5.3	5.3	5.3	5.3
Fuel cost of agro-technical procedures, excluding VAT	28.5	28.5	28.5	28.5	28.5	35.8	35.8	35.8	35.8
Input material cost, excluding VAT	82	82	82	82	82	295	295	289	289
Net profit of using WR	–20.6	–102.6	82.4	19.4	27.4	276	222	–26	–35
Difference net profit	n.i.	–81	n.i.	–63	–56	n.i.	–53	n.i.	–9

Note: Yield in tonne per hectare is based on information from the farmer. Labour cost of agro-technical procedures consists of the direct labour costs that are associated with the cultivation of the crop. The cost is based on the reported time used for the work on the field. Fuel cost of agro-technical procedures consist of fuel costs related to fertilisation, spraying, sowing, combine and disc harrow. Input material cost consists of costs for seed and fertiliser. See SM1 for additional information and input data for the CBA. (n.i.: not interpretable).

sandy soil (7.4 %), combined with a lower market price for oats compared to wheat and barley results in the most substantial negative impact on profitability. Despite spring barley having a lower market price than wheat, it exhibited the most promising response to WR application, with a yield increase of 35.8 %. In contrast, although applying 15 L/ha WR to oats instead of 10 L/ha resulted in a significant additional yield increase (+22.8 %, yield in 2021-LS-O-WR15 scenario compared to the yield in 2021-LS-O-WR10 scenario), this improvement was not reflected proportionally in net profits. While the financial loss associated with applying 15 L/ha WR was lower for oats, than that of applying 10 L/ha WR, the reduction in loss was not big enough to make a positive profit.

3.4. The life cycle assessment

3.4.1. Findings of the 2021 season

To analyse the environmental impact changes originating from using WR, the model evaluation data were divided into groups according to the scenarios defined in Table 1, because average yields vary significantly between different crops and soil types, even without applying WR. The BAU scenario on loamy sand (2021-LS-O-BAU) had the highest environmental impact for one tonne of oat produce. Environmental impact reductions were observed with the WR application at 10 L/ha dose, for oat cultivation on both soil types (2021-SS-O-WR10, 2021-LS-

O-WR10), compared to the relevant BAU scenarios (2021-SS-O-BAU, 2021-LS-O-BAU, respectively), for all five key impact categories (Table 7). On loamy sand, treatment with WR at 10 L/ha and 15 L/ha dose (2021-LS-O-WR10, 2021-LS-O-WR15) resulted in an average reduction of 11 % and 28 %, respectively, across the evaluated key impact categories. On sandy soil, treatment with WR at 10 L/ha dose (2021-SS-O-WR10) resulted in an average reduction of 6 % across the assessed key impact categories, compared to the BAU scenario (2021-SS-O-BAU).

3.4.2. Findings of the 2022 season

WR treatments led to increased yields for wheat and barley (Table 4), attributed solely to WR, as other cultivation and weather conditions remained constant. In parallel to this gain, the results in Table 8 present that three out of five key environmental impact categories showed reductions in impact for the WR scenario with wheat (2022-LS-W-WR10), with an average decrease of 7 % within these three categories, compared to the BAU scenario (2022-LS-W-BAU). For barley (2022-LS-B-WR10), all key environmental impact categories showed reductions in impact compared to the BAU scenario (2022-LS-B-BAU), with a remarkable (30 %) reduction in eutrophication, freshwater category, and an average reduction of 20 %, taking into account all five key impact categories.

The LCA models for BAU and WR scenarios differ only in the WR transport and the yields. The transport related to the WR delivery is

Table 7

Impacts in the key impact categories of LCA, for oat production in 2021. Impact changes are calculated as a percentage of the impact in the relevant BAU scenario. The functional unit of the study is defined as one tonne of harvested crop produce from the test fields.

Scenario	2021-SS-O-BAU	2021-SS-O-WR10	2021-LS-O-BAU	2021-LS-O-WR10	2021-LS-O-WR15
EF 3.0 Acidification [mol H ⁺ eq.]	8.26	7.72	4.01	3.57	2.90
EF 3.0 Acidification, impact change	n.i.	-7 %	n.i.	-11 %	-28 %
EF 3.0 Climate change, total [kg CO ₂ eq.]	1179.17	1101.04	572.74	508.71	414.31
EF 3.0 Climate change, total, impact change	n.i.	-7 %	n.i.	-11 %	-28 %
EF 3.0 Eutrophication, freshwater [kg P eq.]	0.20	0.19	0.10	0.09	0.07
EF 3.0 Eutrophication, freshwater, impact change	n.i.	-5 %	n.i.	-10 %	-30 %
EF 3.0 Land use [Pt]	13740.43	12943.07	6673.93	5980.02	4870.33
EF 3.0 Land use, impact change	n.i.	-6 %	n.i.	-10 %	-27 %
EF 3.0 Resource use, fossils [MJ]	17204.05	16059.3	8356.25	7419.8	6042.93
EF 3.0 Resource use, fossils, impact change	n.i.	-7 %	n.i.	-11 %	-28 %

(n.i.: not interpretable).

Table 8

Impacts in the key impact categories of LCA, for the wheat and barley production in 2022. Impact changes are calculated as a percentage of the impact in the relevant BAU scenario. The functional unit of the study is defined as one tonne of harvested crop produce from the test fields.

Scenario	2022-LS-W-BAU	2022-LS-W-WR10	2022-LS-B-BAU	2022-LS-B-WR10
EF 3.0 Acidification [mol H ⁺ eq.]	2.78	2.69	3.95	3.15
EF 3.0 Acidification, impact change	n.i.	-3 %	n.i.	-20 %
EF 3.0 Climate change, total [kg CO ₂ eq.]	343.54	369.90	557.12	493.36
EF 3.0 Climate change, total, impact change	n.i.	8 %	n.i.	-11 %
EF 3.0 Eutrophication, freshwater [kg P eq.]	0.084	0.076	0.10	0.07
EF 3.0 Eutrophication, freshwater, impact change	n.i.	-10 %	n.i.	-30 %
EF 3.0 Land use [Pt]	11909.74	11003.42	13580.83	10328.09
EF 3.0 Land use, impact change	n.i.	-8 %	n.i.	-24 %
EF 3.0 Resource use, fossils [MJ]	4876.17	5163.81	8211.21	7104.64
EF 3.0 Resource use, fossils, impact change	n.i.	6 %	n.i.	-13 %

(n.i.: not interpretable).

visible in the impacts of all WR scenarios but is largely offset by the increased average yield. Due to the need to transport the WR (i.e. to the field), the contribution of transport to the 'climate change, total' and 'resource use, fossils' impact categories is highly increased in both 2022-LS-B-WR10 and 2022-LS-W-WR10 scenarios, but an overall increase in the effect is observed only for 2022-LS-W-WR10 (Table 8). The reason behind this result is that the global warming potential (GWP) is 0.55 for barley and 0.78 for wheat (data from ecoinvent database, version 3.8), meaning that production of wheat seeds used for sowing causes a higher environmental pressure than that of the barley seeds. Due to this difference, the reduction in environmental impact originating from increased yields cannot compensate the increase of environmental impact caused by WR transport in the case of wheat, while it can in the case of barley.

3.5. The Multi-Criteria Decision Analysis (PROMETHEE)

Following the 5-step process, the final result is the interpretation of the ranking table of the scenarios (results of the intermediate steps can be found in Appendix 5). Table 9 presents the PROMETHEE II results based on Equation (10) (see Appendix 3). The highest-ranked scenario is wheat, grown in loamy sand in 2022 without the WR (2022-LS-W-BAU), followed closely by the same scenario with the WR (2022-LS-W-WR10),

Table 9

PROMETHEE II final ranking interpretation.

	Net outranking flow, PROMETHEE II, step 5, all scenarios			
	Positive OF (φ+)	Negative OF (φ-)	Net OF (φ = φ+ - φ-)	Ranking PII
2021-SS-O-BAU	0,011	0,576	-0,566	8
2021-SS-O-WR10	0,008	0,583	-0,575	9
2021-LS-O-BAU	0,171	0,141	0,030	5
2021-LS-O-WR10	0,150	0,129	0,020	6
2021-LS-O-WR15	0,193	0,088	0,104	3
2022-LS-W-BAU	0,460	0,002	0,457	1
2022-LS-W-WR10	0,432	0,006	0,426	2
2022-LS-B-BAU	0,145	0,139	0,006	7
2022-LS-B-WR10	0,202	0,103	0,098	4

showing a net flow difference of only 0.031. Scenarios ranked 3 to 6 have relatively small net flow differences, indicating low preference variation. The bottom four scenarios all involve oats, with the lowest two grown in sandy soil.

In the second round of calculations, scenarios are divided by growing season and adhere to the same preference model. This approach mirrors the procedure of the first attempt, beginning with annual evaluation tables that outline the input values for each criterion.

When scenarios are evaluated by growing season, the results are consistent with those from the full dataset (Table 10). In 2021, only oats were sown, with a clear preference for loamy sand. The top-ranked scenario includes the WR and a significant preference is evident for loamy sand over sandy soil. In 2022, the top-ranked scenarios are both wheat, while barley ranks lowest, particularly the scenario without the WR, which shows a large negative preference.

When all scenarios are compared, four scenarios stand out: 2021-SS-O-BAU and 2021-SS-O-WR10 exhibit high negative outranking flows, while 2022-LS-W-BAU and 2022-LS-W-WR10 show high positive outranking flows. When analysed by growing season, the results become more distinct. In 2021, loamy sand is clearly preferred over sandy soils, while in 2022, wheat is strongly favoured over barley. The results highlight that soil type and crop choice have a more significant impact on preference than the distinction between business-as-usual and WR usage.

Table 10
PROMETHEE II final ranking interpretation when assessing the individual growing seasons separately.

Net outranking flow, PROMETHEE II, step 5				
	Positive OF (Leaving - φ+)	Negative OF (Entering - φ-)	Net OF (φ = φ+ - φ-)	Ranking PII
2021				
2021-SS-O-BAU	0,037	0,550	-0,513	4
2021-SS-O-WR10	0,019	0,621	-0,602	5
2021-LS-O-BAU	0,429	0,049	0,380	2
2021-LS-O-WR10	0,360	0,052	0,308	3
2021-LS-O-WR15	0,452	0,025	0,427	1
2022				
2022-LS-W-BAU	0,500	0,028	0,473	2
2022-LS-W-WR10	0,525	0,019	0,505	1
2022-LS-B-BAU	0,003	0,741	-0,738	4
2022-LS-B-WR10	0,128	0,368	-0,240	3

4. Discussion

4.1. Results gained using different sustainability assessments

The commercially available Water Retainer product was assessed in the Polish case study targeting the environmental sustainability dimension through the WFA and LCA and the economic dimension via a CBA. Table 11 summarizes the differences of the main parameters assessed in each of the assessment types comparing the BAU with the respective WR scenario values. From a perspective of environmental sustainability, findings indicate that the WR product improved grain yields (wheat, barley and oats) during the 2021 and 2022 growing seasons, with modest positive impacts on Crop Water Footprint, Climate change, total and Land use, Acidification, Eutrophication, freshwater and generally also Resource use, fossils (Table 11). The 2021 oat (10 L/ha; sandy soil, 2021-SS-O-WR10) scenario exhibited the highest environmental burdens across all impact categories. In contrast, the 2022 wheat scenario showed the lowest impacts for Acidification, Climate change, total, and Resource use, fossils, while the 2021 oat (15 L/ha; loamy sand, 2021-LS-O-WR15) scenario performed best in Eutrophication, freshwater and Land use categories. The 2022 results identified Climate change, total and Acidification as the most significant impact categories. Overall, the assessments of environmental sustainability

indicate a positive outcome for the application and use of the WR for the kinds of conditions studied. However, these environmental benefits must be interpreted cautiously, as the production process of the WR product was excluded from the LCA due to limited data, potentially negating the observed positive effects. Because of confidentiality, the exact composition of WR and the details of its production technology are not disclosed. What is known is that the raw material is a plant-based food-industry by-product with a high organic content and no hazardous substances. On this basis, we consider that the application of WR can be reasonably treated in the LCA as a primary raw material use with negligible production impacts. Therefore, excluding the production process from the analysis is not expected to influence the results in a way that would compromise scientific reliability or the validity of the evaluation.

The assessments of the economic dimension of sustainability stood in stark contrast to the environmental one. The CBA revealed that increased yields could not offset the WR's purchase and application costs for the relatively cheap food products that the WR was applied to in this case study. This result should be complemented with the note that the product is not specifically recommended by the manufacturer for cereal crops, but rather for crops that produce much higher profit per unit area than cereals, such as berries, vegetables, or other horticultural crops. The result of the CBA also need to be considered with caution, as it did not account for potential external benefits of WR in terms of reduced CO₂ emissions, as more food can be produced on the same land. One reason was the lack of data of the climate impact of producing WR.

In summary, while the application of the WR product demonstrates yield benefits and environmental advantages, it poses challenges for economic sustainability. The results reveal a clear trade-off: while the water retainer delivers modest but consistent environmental benefits in terms of yields and impact indicators, these gains are insufficient to compensate for its purchase and application costs under current cereal production and respective market prices, rendering the technology environmentally promising but economically unviable in the studied context. Therefore, its overall sustainability remains uncertain, and its application cannot currently be recommended for similar sites and crops. Further research on WR production and social impacts is needed to clarify its sustainability.

The PROMETHEE method was selected for its ability to support strong sustainability concepts due to its low degree of compensation (Cinelli et al., 2014). This proved useful as using the WR was economically unprofitable in all scenarios according to the CBA, while it improved environmental outcomes in the LCA and WFA. The identified rank reversal (see Appendix 6) indicates that the method has a low degree of compensation but is not fully non-compensatory (Verly and Smet, 2013a).

The results show minor differences between BAU scenarios and those

Table 11
Comparison of the WR scenarios with BAU scenario (shaded in grey) for individual sustainability assessments. Cells in green show the highest value for the respective row.

Scenario	2021-SS-O-BAU	2021-SS-O-WR10	2021-LS-O-BAU	2021-LS-O-WR10	2021-LS-O-WR15	2022-LS-W-BAU	2022-LS-W-WR10	2022-LS-B-BAU	2022-LS-B-WR10
	YIELD	680	730	1400	1580	1940	2550	2820	1480
Yield increase compared to relevant BAU scenario (kg/ha)	-	50	-	180	540	-	270	-	530
Yield increase compared to relevant BAU scenario (%)	-	7.4%	-	12.9%	38.6%	-	10.6%	-	35.8%
WFA									
Decrease in WF _{crop}	-	8%	-	11%	15%	-	10%	-	26%
CBA									
Net profit of using WR	-	-102.6	-	19,40	27,40	-	222	-	-35
Difference net profit	-	-81	-	-63	-56	-	-53	-	-9
LCA									
Difference in Acidification (mol H ⁺ eq.)	-	-0,54	-	-0,44	-1,11	-	-0,80	-	-0,09
Difference in Climate change, total (kg CO ₂ eq.)	-	-78,13%	-	-64,03%	-158,43%	-	-63,77%	-	-26,36%
Difference in Eutrophication, freshwater (kg P eq.)	-	-0,01	-	-0,01	-0,03	-	-0,03	-	-0,004
Difference in Land use (Pt)	-	-797,36%	-	-693,91%	-1803,60%	-	-3252,74%	-	-906,32%
Difference in Resource use, fossils (MJ)	-	-1144,75	-	-936,45	-2313,32	-	-1106,57	-	-287,64

using the WR, with both 2021 and 2022 favouring WR use in the top-ranked scenarios (Table 12). When all scenarios are compared, three of the top four include the WR. Comparing PROMETHEE and LCA results, the top-ranked and bottom two scenarios are consistent but differ slightly when net profit is considered. The lowest impact value in ‘Climate change, total’ category is observed in 2022-LS-W-WR10, followed by 2022-LS-W-BAU, which emits 32.22 kg CO₂ eq. more. The highest emissions are from 2021-SS-O-BAU, with 2021-SS-O-WR10 emitting 78.13 kg CO₂ eq. less per hectare. The WFA results align with LCA and PROMETHEE rankings, with consistent top and bottom scenarios across methods. For oats in sandy soil, the CBA confirms low profitability, with net profits of –21 EUR/ha for BAU and –103 EUR/ha with WR. Similarly, for barley in 2022, BAU net profits were –26 EUR/ha, dropping to –35 EUR/ha with WR. Reduced impact values in ‘Climate change, total’ category and WF_{crop} do not offset negative profits due to normalization and equal weighting. However, for 2022-LS-W-BAU, stronger economic performance compensates for weaker results in other parameters, making it the top-ranked scenario overall.

The study demonstrates that the PROMETHEE method is effective for evaluating agricultural scenarios and integrating results from multiple sustainability assessments. WR use improves sustainability in environmental terms, though uncertainties remain due to the exclusion of WR production from the analysis. Increased sustainability does not imply overall production sustainability. As noted in the LCA, the assessments are bound by focusing on the production phase and upstream activities. However, isolating variables like soil type and crop type is challenging, especially when weather conditions, such as the 51 % lower rainfall in 2022 compared to the long-term average, impact results. PROMETHEE’s results are heavily dependent on input data, including the identified alternatives and the criteria used.

4.2. Methodological questions

While all assessments allow for the provision of recommendations, they may highlight different elements of the use and usefulness of the application of the WR. Table 13 provides an overview of the strengths and weaknesses of the different assessment methods applied. The WFA is not only simple to calculate but it can also be understood relatively easily by non-scientists, making it a great tool for the communication with users, such as farmers. However, it is limited to the biophysical, environmental aspects of the use of the product and gives no information about its economic or social costs. In contrast, the CBA concentrates on the economic value of the product in terms of the costs for the user, e.g. the farmer but also society at large, thus potentially taking social costs and benefits into account. However, actually estimating the value of non-marketable goods such as improved water quality can be very challenging and often expensive to carry out. The LCA is based on standardized databases which can help in the comparability across cases, when the same system boundaries and functional units are used. It

Table 13
Overview of strengths and weaknesses of the different assessments.

	Pros/strengths	Cons/weaknesses
WFA	<ul style="list-style-type: none"> Enables combining quantitative (blue and green WF) and qualitative (grey WF) aspects of water use. Simple to calculate. Easy to understand. 	<ul style="list-style-type: none"> Highly variable in place and time. Difficult to account the social or economic aspect of water use.
CBA	<ul style="list-style-type: none"> Compare the value of physical flows in one common unit (EUR, USD, etc). Can include both private costs and benefits as well as external (social) costs and benefits. The outcome variable, "Net Present Value," which reflects the project's impact on social welfare, is easily interpretable and effectively communicates its benefits to policy and decision-makers. 	<ul style="list-style-type: none"> Estimating the monetary value of non-market goods, such as improved water quality and reduced eutrophication, can be difficult. Studies that aim to estimate the value of non-market goods and services can be expensive to carry out.
LCA	<ul style="list-style-type: none"> LCA is an increasingly recognized and adopted methodology worldwide. It considers multiple environmental impacts, not just carbon footprint. The application of LCA can be a decision support tool. Implementing LCA can provide a competitive advantage. 	<ul style="list-style-type: none"> The precision of the analysis depends on the input data. Time-consuming assessment. The comparability of LCA results are limited, due to the fact that the determination of the system boundary and the functional unit are often based on subjective criteria.
PROMETHEE	<ul style="list-style-type: none"> Integrates findings Ranks individual scenarios Allows differentiation of effects, i.e. soil, crop, season in the actual case 	<ul style="list-style-type: none"> Complicated method Not easy to explain to stakeholders

considers a number of different environmental impacts including the carbon footprint, however its precision is dependent on the quality of the input data. The assessment itself is time consuming to set up and the results need expert support for their interpretation. Lastly, the MCDA used supports the integration of the findings across the different assessments and can help discover parameters that are influencing the ranking of the scenarios. However, it is complex to apply and not intuitive to explain to stakeholders.

In addition, to the benefits and risks showed above one major issue when applying multiple assessment types is the risk of comparing ‘apples with oranges’. As such the functional unit, or the base unit of assessment needs to be consistent or at least comparable to be able to draw any meaningful overarching conclusions. In this particular case, the WFA and LCA use crop yield in **tonne** as the functional unit, whereas the CBA uses per **hectare** as the functional unit. However, for this analysis, such discrepancies did not influence the outcomes, as the CBA could equally be expressed in relation to yield—i.e., costs and benefits per tonne per hectare—without altering the underlying economic rationale or policy-relevant conclusions. Since a negative or positive net profit calculated for the total yield per hectare remains negative or positive when normalized to yield per tonne per hectare, the decision rule concerning the economic viability of implementing WR strategies remains unaffected by the choice of functional unit. Moreover, environmental impact indicators generally exhibit an inverse relationship with yield; for instance, as crop yields increase, eutrophication per tonne tends to decrease, thereby reinforcing the environmental benefits of productivity gains.

An additional dimension relevant to the interpretation of the results concerns thus the scope of the benefits considered within each assessment framework, contrasting individual costs and benefits (i.e. to the

Table 12
Comparison of final rankings. The top scenarios are in green, and the bottom ones are in orange.

	Rank comparison	
	All scenarios	Per year
2021-SS-O-BAU	8	4
2021-SS-O-WR10	9	5
2021-LS-O-BAU	5	2
2021-LS-O-WR10	6	3
2021-LS-O-WR15	3	1
2022-LS- W-BAU	1	2
2022-LS-W-WR10	2	1
2022-LS-B-BAU	7	4
2022-LS-B-WR10	4	3

farmer) with societal costs and benefits (i.e. nutrients and eutrophication, and GHG emissions and climate change). The CBA focuses exclusively on private costs and benefits accruing to the farmer, while externalities—such as the societal benefits associated with reduced eutrophication—are not included due to the absence of site-specific data on nutrient runoff. These environmental effects are instead incorporated through model assumptions in the WFA and LCA. Moreover, the spatial context of eutrophication reduction significantly influences the magnitude of associated social benefits, implying that such benefits are likely to vary across different cultivation areas. In this analysis, equal weighting was applied to the WFA, LCA, and CBA within the PROMETHEE method to avoid privileging any single assessment approach. However, in contexts where eutrophication constitutes a severe regional concern and reliable estimates of its monetized benefits are lacking, it may be appropriate to adjust the weights and assign greater importance to the WFA or LCA to more accurately reflect relevant environmental externalities.

When considering the external benefits associated with reduced CO₂ emissions from cultivation, it is also necessary to account for the negative emissions resulting from the production of the initial quantities of oats, spring wheat, and spring barley. Incorporating the social cost of these emissions would result in a substantially negative social net benefit for the cultivation of these cereals, potentially leading to the conclusion that their production is not socially desirable. In addition, while the social dimension of sustainability was initially intended to be included in the assessment, the lack of sufficient stakeholder engagement prevented the implementation of a social Life Cycle Assessment (sLCA). The integration of social parameters would have contributed to a more comprehensive sustainability evaluation by capturing potential benefits for local communities and enhancing the understanding of interactions among environmental, social, and economic dimensions.

Existing research allows outlining plausible social impacts associated with the use of water-retention technologies. Evidence shows that adoption of water-saving measures is strongly shaped by social interaction and peer networks, which significantly influence farmers' technology uptake (Wang and Xu, 2024). Furthermore, social capital has been shown to enhance farmers' resilience to water scarcity, suggesting that stabilising water availability through retention products may indirectly strengthen livelihood security (Aguilar et al., 2022). Economic studies similarly demonstrate that water-saving technologies can improve production efficiency and income stability, although initial investment costs may create adoption barriers, particularly for smallholders (Tai et al., 2024; Lei and Yang, 2024). Social acceptance is also closely tied to participatory processes, as collaborative governance mechanisms have been found to foster trust, reduce conflict, and support long-term sustainability in water management. Applying a social lens can thus highlight additional considerations around health, safety, and labour conditions, where both reduced drought-related stress and potential new maintenance burdens require attention. In Avellán et al. (2025) we show what a difference the addition of the social dimension of sustainability can make when analysing farm constructed wetlands as a water and nutrient retention solution in Northern Italy (Avellán et al., 2025). Here, we were able to demonstrate that while the economic dimension proved negative and the environmental one slightly positive, it is the social dimension that pushes the technology towards a positive score. The current lack of a social sustainability assessment thus significantly hampers holistic decision-making capacity for farmers. Systematically assessing social sustainability alongside economic and environmental criteria could make the difference between rejecting or adopting water-retention technologies, as it reveals impacts on livelihood security, social acceptance, and resilience that directly shape real-world feasibility and long-term uptake.

A further limitation of this study is that the multi-assessment and MCDA framework was applied to only one water retention technology, the commercial WR product, even though multiple WATERAGRI solutions were implemented across the 10 project sites. While we also

conducted a set of LCA, LCC, and sLCA assessments for farm constructed wetlands (CWs) at the Italian case study site (Avellán et al., 2025), these analyses relied on the life-cycle family of methods only and did not generate a comparable multi-assessment dataset suitable for integration into the PROMETHEE framework. A broader comparison across WR, CWs, and other nature-based or technological alternatives would certainly have strengthened the generalizability of our findings; however, several methodological and practical constraints limited the feasibility of such an approach. Many solutions were at early development stages or lacked field-scale implementation, preventing the collection of consistent environmental, economic, and social data. In other cases, farmers or technology providers were unable or unwilling to share the socio-economic information required for CBA, LCC, or sLCA. Additionally, extreme drought conditions during the 2022 growing season caused yield failures at several sites, further restricting the availability of valid datasets. As a result, the Polish WR case was the only site for which a relatively coherent set of multi-family assessments (WFA, CBA, LCA) could be completed and meaningfully integrated through MCDA. Our intention, therefore, was not to present the WR as inherently preferable to other water retention strategies, but to demonstrate the methodological value of combining multiple sustainability assessments in a single decision-support framework under real-world data constraints. This proof-of-concept highlights the potential of integrated assessment approaches while underscoring the need for future research to extend the framework to a wider range of solutions and contexts.

5. Conclusion

The aim of this article was to evaluate how individual and integrated sustainability assessment approaches can inform on-site decision-making by addressing the economic and environmental dimensions of sustainability under conditions of water scarcity in European agriculture. We showed that, at the Polish study site, the application of WR measures resulted in yield increases for all tested crops and soil types across both seasons, including during the extreme drought conditions of 2022. Despite a positive green water footprint (WF_{green}), crop water requirements consistently exceeded average annual precipitation. The LCA indicated minimal environmental impacts, with only slight increases observed in 2022 for wheat in the categories of 'Climate change, total' and 'Resource use, fossils', while reductions were noted in all other key impact categories across both seasons. The CBA demonstrated that, under current conditions, increased yields were insufficient to compensate for the costs associated with WR implementation for the relatively low-value food crops examined. Thus, overall, while the environmental assessment showed a positive effect of the use of the WR, the economic assessment exhibited a rather unfavourable result. The research team could therefore not recommend the wide-spread use of the WR for the types of crops and soils assessed.

However, these findings should be interpreted with caution due to data limitations related to WR production, on nutrient runoff and GHG emissions. While the CBA accounts for private costs and benefits from the farmer's perspective, it does not consider externalities such as the societal benefits of reduced eutrophication and climate change potential. These are instead captured in the other assessments and the multi-criteria analysis. In cases where such external benefits and costs can be reliably identified and monetized, their inclusion in the CBA is strongly recommended to provide a more comprehensive assessment of the societal implications of environmental interventions. In addition, a sensitivity analysis suggests that economic feasibility could improve under scenarios involving either a 40 % increase in grain prices or a 40 % reduction in WR costs, with positive outcomes observed for barley on sandy soil (data not shown in the results but in Appendix 7).

Reliable methods are thus crucial for tracking progress and supporting decision-making. To advance in this field, it is essential to expand the perspective beyond traditional focuses and include all

dimensions of sustainability in decision-making, including the social perspective. A broad approach is necessary to identify conflicts, synergies, and trade-offs, helping to avoid silo effects (Rivela et al., 2022). As such, assessing sustainability in agriculture presents challenges due to its connections with various policy areas, such as sustainable development, rural development, environmental protection, and climate change (Streimikis and Baležentis, 2020). When policy areas overlap, inconsistencies can arise. The WFA results show that the WF_{grey} exceeds the nitrogen leakage limits set by the Water Framework Directive (Directive EWF, 2019) (Directive, 2000/60/EC of the European Parliament and of the Council establishing a framework for Community action in the field of water policy), yet the applied fertilizer amount complies with the Nitrates Directive (Council Directive 91/676/EEC concerning the protection of waters against pollution caused by nitrates from agricultural sources). This inconsistency underscores the difficulty of farmers to abide to (inconsistent) policies and the complexity of addressing diffuse pollution in agriculture. This highlights the need for further exploration of these inconsistencies, particularly regarding the Green Deal and EU's common agricultural policy (CAP) in the European context.

In conclusion, this study demonstrates that individual and integrated sustainability assessments can offer valuable insights into the economic and environmental implications of water retention measures under conditions of water scarcity in European agriculture. The analysis showcases the challenges for interpreting and integrating the results of the assessment and highlights the need for improved data collection and availability to better contrast individual versus societal benefits and losses. To support coherent and informed on-site decision-making, future assessments should adopt a comprehensive sustainability perspective, including the social dimension, and account for policy interactions and inconsistencies.

CRedit authorship contribution statement

Tamara Avellán: Writing – review & editing, Writing – original

7 Appendix

Appendix 1. Data and calculations for the Cost-Benefit Analysis

This material provides information about the data and the calculations for each of the variables that are included in the CBA.

Yield in tonne per hectare – based on information from the farmer.

Compared to the average yield/ha in Poland the yield at the test site is lower. According to Statistics Poland office report for 2021 the average yield for oats was 3.14 tonne/ha, 3.96 tonne/ha for wheat and 3.78 tonne/ha for barley.

Market value yield (net of value added tax, VAT) - The Polish market price for.

Oats in 2021	143 EUR/tonne, net of VAT,
Spring wheat in 2022	240 EUR/tonne, net of VAT,
Spring barley in 2022	206 EUR/tonne, net of VAT.

Cost of Water Retainer product (net of VAT) – Market price in EUR for 20 L in Hungary including VAT (EUR 225 in 2021 and EUR 300 in 2022). Price per liter net of VAT (EUR 8.86 in 2021 and EUR 11.81 in 2022). The application of WR can be done together with the application of fertilisers and/or pesticides. Costs for e.g., diesel or machinery has therefore not been added to the application of WR. The labour cost for applying WR together with fertilisers or pesticides is negligible. For that reason, labour costs for applying WR have not been added as a cost for WR.

Labour cost of agro-technical procedures.

The labour cost consists of the direct cost that was associated with the cultivation of the crop. The cost was based on the reported time use (in hours) for the work on the field. The field was 55 ha (22 ha wheat + 30 ha barley) and 33 ha for oats.

draft, Visualization, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization. **Hanna Dencker:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis. **Jonas Nordström:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Nóra Hatvani:** Writing – review & editing, Writing – original draft, Visualization. **Balázs Sándor Gál:** Writing – review & editing, Formal analysis. **Wiesław Fialkiewicz:** Writing – original draft, Resources, Methodology, Investigation, Formal analysis, 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.

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Table A 1

Total time use for cultivations of spring wheat and spring barley (field size 55 ha):

Activity	Time (hour)
Sowing	24
Fertilisation 1.5 h of work - two times in the season	3
Spraying of WR, once a season	1.5
Disc harrow	24
Harvest	20
Total	72.5

Table A 2

Total time use for cultivations of oats (field size 33 ha)

Activity	Time (hour)
Sowing	18
Fertilisation 1.5 h of work - two times in the season	3
Spraying of WR, once a season	1.5
Disc harrow	16
Harvest	20
Total	58.5

The labour cost per hectare is calculated as total time use on the field for cultivation of the crops divided by the field size and multiplied by the hourly wage rate (including social fees).

Labour cost for wheat and barley:	$(72.5 \text{ h}/55 \text{ ha}) * 4 \text{ EUR}/\text{hour} = 5.27 \text{ EUR}/\text{ha}$.
Labour cost for oats:	$(58.5 \text{ h}/33 \text{ ha}) * 4 \text{ EUR}/\text{hour} = 7.09 \text{ EUR}/\text{ha}$.

During the time of the field study, the lowest national monthly wage level was PLN 3010 (EUR 643) including social fees.

Fuel costs for agro-technical procedures and input material costs, seed and fertilizer are given in the table below. The cost/total field values calculated are rounded to a whole number, except for the total cost. Costs are shown gross except where it is indicated that the amount is exclusive of VAT.

Table A 3

Fuel costs for agro-technical procedures and input material costs

Data concerning fuel cost of agro-technical procedures:	2021	2022
Fuel price	PLN 5.5/L = EUR 1.18/L	PLN 7.0/L = EUR 1.47/L
Field size	33 ha	55 ha (22 ha wheat + 30 ha barley)
Disc machine, fuel consumption and cost of fuel	300 L/total field; 300 L/total field * 1.18 EUR/L = 354 EUR/total field	500 L/total field; 500 L/total field * 1.47 EUR/L = 735 EUR/total field
Fertilization, fuel consumption and cost of fuel	30 L/total field * 2 times per season = 60 L/total field; 60 L/total field * 1.18 EUR/L = 71 EUR/total field	50 L/total field * 2 times per season = 100 L/total field; 100 L/total field * 1.47 EUR/L = 147 EUR/total field
Spraying of WR, fuel consumption and cost of fuel	20 L/total field * 1 per season = 20 L/total field; 20 L/total field * 1.18 EUR/L = 24 EUR/total field	35 L/total field * 1 per season = 35 L/total field; 35 L/total field * 1.47 EUR/L = 52 EUR/total field
Combine harvester, fuel consumption and cost of fuel	360 L/total field; 360 L/total field * 1.18 EUR/L = 425 EUR/total field	600 L/total field; 600 L/total field * 1.47 EUR/L = 882 EUR/total field
Sowing, fuel consumption and cost of fuel	240 L/total field; 240 L/total field * 1.18 EUR/L = 283 EUR/total field	400 L/total field; 400 L/total field * 1.47 EUR/L = 588 EUR/total field
Total cost	1157 EUR/total field, 35.05 EUR/ha gross, 28.50 EUR/ha excluding VAT	2404 EUR/total field; 43.71 EUR/ha gross, 35.77 EUR/ha excluding VAT
Data concerning input material cost		
Seed	Quantity needed: 0.16 t oats/ha Price: 500 PLN/t * 0.16 t/ha = PLN 80/ha = 17.2 EUR/ha	Wheat: PLN 900/tonne (0.18 t/ha) = 900 * 0.18 = PLN 162/ha/4.75 = EUR 34/ha Barley PLN 800/tonne (0.16 t/ha) = 800 * 0.16 = PLN 128/ha/4.75 = EUR 27/ha
Fertilizers	Urea: 80 kg/ha * EUR 0.387/kg = 30.96 EUR/ha Ammonium nitrate: 130 kg/ha * EUR 0.301/kg = 39.13 EUR/ha Mustang Forte (herbicide): 0.8 L/ha * EUR 17.2/L = 13.76 EUR/ha Total fertiliser cost: 84 EUR/ha	Polifoska (multicomponent fertilizer) 150 kg/ha * EUR 0.947/kg = 142.05 EUR/ha Urea: 80 kg/ha * EUR 0.863/kg = 69 EUR/ha Ammonium nitrate: 120 kg/ha * EUR 0.8/kg = 96 EUR/ha Mattera (herbicide for dicotyledonous weeds) 1 L/ha * EUR 22/L = 22 EUR/ha Total fertiliser cost: 329 EUR/ha
Total cost	101 EUR/ha, 82 EUR/ha excluding VAT	Wheat: 363 EUR/ha, 295 EUR/ha excluding VAT Barley: 356 EUR/ha, 289 EUR/ha excluding VAT

Net profit of using Water Retainer corresponds to the difference in the profit for the farmer without the use of WR and with the application of WR.

Appendix 2. Inventory for LCA assessments

For the LCA, cumulative input material and energy data were applied for 1 ha of the experimental areas. The inventory data for 2021 assessments is presented in the following two tables.

Table B 1
Input flows of 2021 scenarios

Name	Quantity	Unit	Transport distance (km)	Type of transport
Crops (seeds)	160	kg	75	Truck; 24 t
Urea	80	kg	370	Truck; 24 t
Ammonium nitrate	130	l		
Herbicide (Mustang forte)	0,8	l		
Water Retainer	10 or 15*	l	888	Passenger car**
Cultivation (soil cultivation)	1	Application per season	(not relevant)	(not relevant)
Cultivation (sowing)	1			
Cultivation (fertilizer, broadcast spreader)	2			
Cultivation (fertilizer, sprayer)	1 (2)*			
Cultivation (Water Retainer, sprayer) optional	1			
Cultivation (crop protection)	1			
Cultivation (harvester)	1			

*(in case of WR scenarios).

** Only a small lot needed for the field tests in the WATERAGRI project was transported to Poland from Hungary.

Table B 2
Output flows of 2021 scenarios

Name	Scenario	Quantity	Unit	Transport distance (km)	Type of transport
Crop yield	2021-LS-O-BAU	1400	kg	(not relevant)	(not relevant)
	2021-LS-O-WR10	1580	kg		
	2021-LS-O-WR15	1940	kg		
	2021-SS-O-BAU	680	kg		
	2021-SS-O-WR10	730	kg		
Polypropylene (waste, recycling)	All	0,91	kg	53	Truck; 9,3 t
Polyethylene (waste, landfill)	All	0,61	kg	9	Truck; 9,3 t

The inventory data for 2022 assessments is presented in the following two tables.

Table B 3
Input flows of 2022 wheat scenarios

Name	Quantity	Unit	Transport distance (km)	Type of transport
Crops (seeds)	180	kg	75	Truck; 24 t
Urea	80	kg	370	Truck; 24 t
Ammonium nitrate	130	l		
Herbicide (Mustang forte)	0,8	l		
Water Retainer	10*	l	888	Passenger car**
Cultivation (soil cultivation)	1	Time per season	(not relevant)	(not relevant)
Cultivation (sowing)	1			
Cultivation (fertilizer, broadcast spreader)	2			
Cultivation (fertilizer, sprayer)	1			
Cultivation (Water Retainer, sprayer) optional	1*			
Cultivation (mulching)	1			
Cultivation (crop protection)	1			
Cultivation (harvester)	1			

*(in case of WA scenario).

** Only a small lot needed for the field tests in the WATERAGRI project was transported to Poland from Hungary.

Table B 4
Output flows of 2022 wheat scenarios

Name	Scenario	Quantity	Unit	Transport distance (km)	Type of transport
Crop yield	2022-LS-W-BAU	2550	kg	(not relevant)	(not relevant)
	2022-LS-W-WR10	2820	kg		
Polypropylene (waste, recycling)	All	25	kg	53	Truck; 24 t
Polyethylene (waste, landfill)	All	2,5	kg	9	Truck; 24 t

Table B 5
Energy and material incoming flows of 2022 barley scenario (1 ha)

Name	Quantity	Unit	Transport distance (km)	Type of transport
Crops (seeds)	160	kg	75	Truck; 24 t
Urea	80	kg	370	Truck; 24 t
Ammonium nitrate	130	L/ha		
Herbicide (Mustang forte)	0,8	L/ha		
Water Retainer	10*	L/ha	888	Passenger car
Cultivation (soil cultivation)	1	Time per season	(not relevant)	(not relevant)
Cultivation (sowing)	1			
Cultivation (fertilizer, broadcast spreader)	2			
Cultivation (fertilizer, sprayer)	1			
Cultivation (mulching)	1			
Cultivation (Water Retainer, sprayer) optional	1*			
Cultivation (crop protection)	1			
Cultivation (harvesting)	1			

*(in case of WA scenario).

Table B 6
Output flows of 2022 barley scenarios (1ha)

Name	Scenario	Quantity	Unit	Transport distance (km)	Type of transport
Crop yield	2022-LS-B-BAU	1480	kg	(not relevant)	(not relevant)
	2022-LS-B-WR10	2010	kg		
Polypropylene (waste, recycling)	All	25	kg	53	Truck; 24 t
Polyethylene (waste, landfill)	All	2,5	kg	9	Truck; 24 t

Appendix 3. PROMETHEE stepwise calculation process

The computation of the PROMETHEE method is carried out in five steps.

Step 1: The first step is the determination of deviations, which is based on pair-wise comparisons. The relationship is stated according to Equation (1). The difference between the evaluations of alternatives *a* and *b* for each criterion (*g*) is denoted as $d_j(a, b)$ (Behzadian et al., 2010b).

$$d_j(a, b) = g_j(a) - g_j(b) \tag{Equation 1}$$

Step 2: The second step is calculating the preference function, $P_j(a, b)$, which states the preference of alternative *a* with consideration of *b* expressed in a function of $d_j(a, b)$ (Behzadian et al., 2010b). Values closer to 1 indicate a larger preference, and small values closer to 0 indicate indifference. For the usual criterion preference function the relation is defined by Equation (2) (Brans et al., 2016b).

$$P(d) = \begin{cases} 0 & d < 0 \\ 1 & d > 0 \end{cases} \tag{Equation 2}$$

Step 3: The third step consists of the calculation of the overall preference index following Equation (3). Here $\pi(a, b)$, defines the preference of *a* with regards to *b* individually for each criterion, in a range from 0 to 1 and is defined as the weighted sum $p(a, b)$ for each criterion. The weight is denoted w_j for the *j*th criteria (62).

$$\forall a, b \in A, \pi(a, b) = \sum_{j=1}^k P_j(a, b)w_j \tag{Equation 3}$$

Step 4: The fourth step is to calculate the outranking flows, which gives the partial ranking equal to the results of PROMETHEE I. For each alternative, the positive outranking flow, denoted by Equation (4), and the negative outranking flow, denoted by Equation (5), should be calculated respectively for each alternative (Behzadian et al., 2010b; Goswami, 2020).

$$\phi^+(a) = \frac{1}{n-1} \sum_{x \in A} \pi(a, x) \tag{Equation 4}$$

$$\phi^-(a) = \frac{1}{n-1} \sum_{x \in A} \pi(x, a) \tag{Equation 5}$$

Step 5: The fifth and final step is to calculate the net outranking flow to obtain a complete ranking, equal to the results of PROMETHEE II. The net outranking flow for every alternative is denoted $\phi(a)$, according to Equation (6) (Behzadian et al., 2010b).

$$\phi(a) = \phi^+(a) - \phi^-(a) \tag{Equation 6}$$

To further illustrate the partial ranking based on the positive and negative outranking flows, the results can be presented in a matrix disclosing the preference (P), indifference (I) or incomparability (R). The relation for P, I and, R are stated in Equation (7) (Brans et al., 2016b).

$$aP^Ib \text{ iff } \begin{cases} \phi^+(a) > \phi^+(b) \text{ and } \phi^-(a) < \phi^-(b), \text{ or} \\ \phi^+(a) = \phi^+(b) \text{ and } \phi^-(a) < \phi^-(b), \text{ or} \\ \phi^+(a) > \phi^+(b) \text{ and } \phi^-(a) = \phi^-(b) \end{cases} \tag{Equation 7}$$

$$aI^Ib \text{ iff } \phi^+(a) = \phi^+(b) \text{ and } \phi^-(a) = \phi^-(b)$$

$$aR^Ib \text{ iff } \begin{cases} \phi^+(a) > \phi^-(a) > \phi^-(b), \text{ or} \\ \phi^+(a) < \phi^+(b) \text{ and } \phi^-(a) < \phi^-(b) \end{cases}$$

When a is preferred over b, aP^Ib a higher positive outranking flow and a lower negative outranking flow is seen for a, in regard to b. When a and b are indifferent, aI^Ib , both their positive and negative outranking flows are equal. If a comparison is incomparable, the flows are not consistent and a clear preference cannot be decided between those two alternatives (Brans et al., 2016b).

Outranking methods based on pair-wise comparisons can get affected by rank reversal. The problem with rank reversal comes in if the relative position of two alternatives gets influenced by a third alternative. (Brans et al., 2016b). The problem of rank reversal can occur if the difference in net flow between two indicators is small (Verly and Smet, 2013b). The scientific debate about rank reversal is still active. It has been proven that if the relationship stated in Equation (8) for PROMETHEE II and 9 and 10 for PROMETHEE I is true, no rank reversal can occur (Brans et al., 2016b).

$$|\phi(a) - \phi(b)| > \frac{2}{n - 1} \tag{Equation 8}$$

$$|\phi^+(a) - \phi^+(b)| > \frac{1}{n - 1} \tag{Equation 9}$$

$$|\phi^-(a) - \phi^-(b)| > \frac{1}{n - 1} \tag{Equation 10}$$

The PROMETHEE calculations were carried out in three rounds. In the first run, all nine scenarios are included. In the second and third rounds of calculations, the scenarios are separated by growing season, to identify potential changes depending on crop type and the sensitivity of the final ranking based on included scenarios.

Appendix 4. Water footprint accounting for the growing seasons in 2021 and 2022

Table D 1
Growing season 2021

Parameter	Unit	2021-SS-O-BAU	2021-SS-O-WR10	2021-LS-O-BAU	2021-LS-O-WR10	2021-LS-O-WR15
P _{eff}	mm	290	290	290	290	290
ET _c	mm	649	649	649	649	649
CWU _{green}	m ³ /ha	2900	2900	2900	2900	2900
AR	kg/ha	79,7	79,7	79,7	79,7	79,7
α	–	0,1	0,1	0,1	0,1	0,1
C _{max}	kg/m ³	0,0049	0,0049	0,0049	0,0049	0,0049
C _{nat}	kg/m ³	0	0	0	0	0
(α × AR)/(C _{max} - C _{nat})	m ³ /ha	1627	1627	1627	1627	1627
Y	tonne/ha	0,68	0,73	1,4	1,58	1,94
WF _{crop, green}	m ³ /tonne	4265	3919	2071	1835	1495
WF _{crop, blue}	m ³ /tonne	0	0	0	0	0
WF _{crop, grey}	m ³ /tonne	2392	2198	1162	1029	838
WF _{crop}	m ³ /tonne	6657	6117	3233	2865	2333

Table D 2
Growing Season 2022

Parameter	Unit	2022-LS-W-BAU	2022-LS-W-WR10	2022-LS-B-BAU	2022-LS-B-WR10
P _{eff}	mm	144	144	144	144
ET _c	mm	714	714	714	714
CWU _{green}	m ³ /ha	1440	1440	1440	1440
AR	kg/ha	85,4	85,4	85,4	85,4
α	–	0,1	0,1	0,1	0,1
C _{max}	kg/m ³	0,0049	0,0049	0,0049	0,0049

(continued on next page)

Table D 2 (continued)

Parameter	Unit	2022-LS-W-BAU	2022-LS-W-WR10	2022-LS-B-BAU	2022-LS-B-WR10
C_{nat}	kg/m ³	0	0	0	0
$(\alpha \times AR)/(C_{max} - C_{nat})$	m ³ /ha	1743	1743	1743	1743
Y	tonne/ha	2,55	2,82	1,48	2,01
WF _{crop, green}	m ³ /tonne	565	511	973	716
WF _{crop, blue}	m ³ /tonne	0	0	0	0
WF _{crop, grey}	m ³ /tonne	683	618	1178	867
WF_{crop}	m³/tonne	1248	1129	2151	1584

Appendix 5. PROMETHEE I result

Outranking flow, stating the aggregated preference matrix, which gives the preference of one scenario compared to another, based on equations (4) and (5).

Table E 1

Outranking flow of PROMETHEE I, step 4 all scenarios

	2021-SS-O-BAU	2021-SS-O-WR10	2021-LS-O-BAU	2021-LS-O-WR10	2021-LS-O-WR15	2022-LS-W-BAU	2022-LS-W-WR10	2022-LS-B-BAU	2022-LS-B-WR10	Positive OF (Leaving - $\varphi+$)
2021-SS-O-BAU	–	0,071	0	0	0	0	0	0,003	0,011	0,011
2021-SS-O-WR10	0,063	–	0	0	0	0	0	0	0	0,008
2021-LS-O-BAU	0,53	0,538	–	0,055	0,049	0	0	0,093	0,101	0,171
2021-LS-O-WR10	0,521	0,53	0,047	–	0	0	0	0,056	0,046	0,15
2021-LS-O-WR15	0,596	0,604	0,115	0,074	–	0	0	0,099	0,052	0,193
2022-LS-W-BAU	0,909	0,918	0,38	0,388	0,314	–	0,047	0,401	0,319	0,46
2022-LS-W-WR10	0,882	0,89	0,352	0,36	0,286	0,02	–	0,374	0,291	0,432
2022-LS-B-BAU	0,511	0,516	0,071	0,043	0,011	0	0	–	0,008	0,145
2022-LS-B-WR10	0,601	0,599	0,161	0,115	0,046	0	0	0,09	–	0,202
Negative OF (Entering - $\varphi-$)	0,576	0,583	0,141	0,129	0,088	0,002	0,006	0,139	0,103	

PROMETHEE I results are presented below, where preferences are indicated as P (a1 preferred over a2), NP (a2 preferred over a1), or R (alternatives incomparable). Incomparability occurs when P or NP conditions are unmet due to inconsistent flow differences. Notably, oats in sandy soil with the WR (2021-SS-O-WR10) are not preferred in any comparison, while wheat in loamy sand without the WR (2022-LS-W-BAU) is consistently preferred.

Table E 2

PROMETHEE I final ranking interpretation.

a2		2021-SS-O-BAU	2021-SS-O-WR10	2021-LS-O-BAU	2021-LS-O-WR10	2021-LS-O-WR15	2022-LS-W-BAU	2022-LS-W-WR10	2022-LS-B-BAU	2022-LS-B-WR10
a1	2021-SS-O-BAU	–	P	NP	NP	NP	NP	NP	NP	NP
	2021-SS-O-WR10	NP	–	NP	NP	NP	NP	NP	NP	NP
	2021-LS-O-BAU	P	P	–	R	NP	NP	NP	R	NP
	2021-LS-O-WR10	P	P	R	–	NP	NP	NP	P	NP
	2021-LS-O-WR15	P	P	P	P	–	NP	NP	P	R
	2022-LS-W-BAU	P	P	P	P	P	–	P	P	P
	2022-LS-W-WR10	P	P	P	P	P	NP	–	P	P
	2022-LS-B-BAU	P	P	R	NP	NP	NP	NP	–	NP
	2022-LS-B-WR10	P	P	P	P	R	NP	NP	P	–
				P	Clear preference of a1					
			R	Incomparability						
			NP	The second alternative (a2) is preferred over this one (a1).						

When PROMETHEE I is performed for each growing season separately, all scenarios are comparable. For 2021, oats in loamy sand with a higher WR dose (2021-LS-O-WR15) is preferred over all others, whereas oats in sandy soil with the WR (2021-SS-O-WR10) are not preferred in any comparison. Regarding the outcomes of 2022, wheat in loamy sand with the WR (2022-LS-W-WR10) is preferred over all other scenarios, while barley in loamy sand without WR (2022-LS-B-BAU) is not preferred over any scenario.

Table E 3
 PROMETHEE I final ranking interpretation when assessing the individual growing seasons separately.

2021		a2				
a1	2021-SS-O-BAU	2021-SS-O-BAU	2021-SS-O-WR10	2021-LS-O-BAU	2021-LS-O-WR10	2021-LS-O-WR15
	2021-SS-O-WR10	NP	P	NP	NP	NP
	2021-LS-O-BAU	P	P	NP	P	NP
	2021-LS-O-WR10	P	P	NP		NP
	2021-LS-O-WR15	P	P	P	P	
2022		a2				
a1	2022-LS- W-BAU	2022-LS- W-BAU	2022-LS-W-WR10	2022-LS-B-BAU	2022-LS-B-WR10	
	2022-LS-W-WR10	P	NP	P	P	
	2022-LS-B-BAU	NP	NP	P	NP	
	2022-LS-B-WR10	NP	NP	P		
		P				
	R					
	NP					

Clear preference of a1
Incomparability
The second alternative (a2) is preferred over this one (a1).

Appendix 6. Rank reversal

When looking at the rankings (see tables in Appendix 5), there is an inconsistency between the top two ranked scenarios. When all scenarios are compared in round one, wheat in loamy sand and without WR scores highest and with WR second. But in round three, when separated per year wheat in loamy sand with WR scores a little bit above the business-as-usual scenario. This circumstance requires a test for potential rank reversal according to Equations (11)–(13).

$$|\phi(a) - \phi(b)| > \frac{2}{n - 1} \tag{Equation 11}$$

$$|\phi^+(a) - \phi^+(b)| > \frac{1}{n - 1} \tag{Equation 12}$$

$$|\phi^-(a) - \phi^-(b)| > \frac{1}{n - 1} \tag{Equation 13}$$

Table F 1
 Test for potential rank reversal PROMETHEE I.

Potential rank reversal all scenarios, PROMETHEE I				
	Positive OF (Leaving - ϕ^+)	$ \phi^+(a) - \phi^+(b) $		$\frac{1}{n - 1}$
2022-LS-W-BAU	0,460	0,028	<	0,125
2022-LS-W-WR10	0,432	0,028	<	0,125
Negative OF (Leaving - ϕ^-)				
	$ \phi^-(a) - \phi^-(b) $			$\frac{1}{n - 1}$
2022-LS-W-BAU	0,002	0,003	<	0,125
2022-LS-W-WR10	0,006	0,003	<	0,125
Potential rank reversal 2022, PROMETHEE I				
	Positive OF (Leaving - ϕ^+)	$ \phi^+(a) - \phi^+(b) $		$\frac{1}{n - 1}$
2022-LS-W-BAU	0,500	0,025	<	0,333
2022-LS-W-WR10	0,525	0,025	<	0,333
Negative OF (Leaving - ϕ^-)				
	$ \phi^-(a) - \phi^-(b) $			$\frac{1}{n - 1}$
2022-LS-W-BAU	0,028	0,008	<	0,333
2022-LS-W-WR10	0,019	0,008	<	0,333

Below the rank reversal test for PROMETHEE I is applied to the two scenarios of concern. The calculations show that the relation in Equations (12) and (13) are not met, the differences in both positive and negative outranking flow are smaller than $\frac{1}{n-1}$ and therefore, a rank reversal can occur.

Table F 2
Test for potential rank reversal PROMETHEE II.

Potential rank reversal all scenarios, PROMETHEE II				$\frac{1}{n-1}$
	Net OF ($\varphi = \varphi+ - \varphi-$)	$ \phi(a) - \phi(b) $		
2022-LS-W-BAU	0,457	0,031	<	0,25
2022-LS-W-WR10	0,426	0,031	<	0,25
Potential rank reversal 2022, PROMETHEE II				$\frac{1}{n-1}$
	Net OF ($\varphi = \varphi+ - \varphi-$)	$ \phi(a) - \phi(b) $		
2022-LS-W-BAU	0,473	0,033	<	0,667
2022-LS-W-WR10	0,505	0,033	<	0,667

Also, the relation is not met when assessing the potential rank reversal for PROMETHEE II according to Equation (11). The small differences in net outranking flow make it possible for rank reversal. Mathematically, this rank reversal occurs because when all nine scenarios are compared, the net outranking flow of 2022-LS-W-BAU is higher than 2022-LS-W-WR10 ($a_6 > a_7$). In this case, the net outranking flow of 2022-LS-W-BAU is around 7 % higher. The opposite occurs in 2022 where the net outranking flow of LS-W-WR10 is higher than 2022-LS-W-BAU ($a_7 > a_6$). In this case, the net outranking flow of LS-W-WR10 is around 7 % higher than 2022-LS-W-BAU. In both cases, 2022-LS-W-BAU and 2022-LS-W-WR10 are preferred over all the other alternatives, which means they are the two most preferred scenarios and outranked all the others. Looking at the input data, both alternatives have similar values for the three criteria, looking closer, the values for g_1 and g_2 are more favourable for 2022-LS-W-WR10. Since these criteria are set to be minimised and $a_7 < a_6$ for both evaluations (a_6 values are 10–11 % greater than a_7). That would indicate that 2022-LS-W-WR10 should be preferred over 2022-LS-W-BAU, but 2022-LS-W-BAU has a higher net profit (the g_3 value of a_6 is 24 % greater than a_7). This plays a decisive role when compared with all nine scenarios, resulting in 2022-LS-W-BAU having a greater net outranking flow than 2022-LS-W-WR10. But with only four alternatives in 2022, the differences across alternatives are not large enough to increase the net outranking flow of 2022-LS-W-BAU over 2022-LS-W-WR10.

Appendix 7. Sensitivity analysis of the CBA

To figure out how sensitive our results are to variations in costs and revenues (benefits), we carried out a robustness check. As the difference in profit of using WR is negative in the calculations (see Table 6 in the results), we focus on changes that reduce the loss. In the analysis we thus assumed that (a) the market price for the crops increases by 40 % and that (b) the market price for WR decreases by 40 %. Evidently, reduced costs for energy, labour and input material would also have a positive effect on the profit. From an analytical perspective an increase in the market price for the crops or a corresponding decrease in energy, labour or input material costs will show the same general pattern on the profit. For that reason, we only show the results for an increase in the market price for the crops/yield. The results are shown below.

Table G 1
Difference in private profit for the farmer EUR/hectare with 40 % changes in (a) crop prices or (b) product costs

Scenario	Market prices of crops and WR for the respective years	Increase in market price of the crop with 40 %	Decrease in market price of Water Retainer with 40 %
2021-SS-O-WR10	–82 EUR/ha	–79 EUR/ha	–56 EUR/ha
2021-LS-O-WR10	–63 EUR/ha	–53 EUR/ha	–38 EUR/ha
2021-LS-O-WR15	–55 EUR/ha	–25 EUR/ha	–18 EUR/ha
2022-LS-B-WR10	–9 EUR/ha	35 EUR/ha	25 EUR/ha
2022-LS-W-WR10	–53 EUR/ha	–27 EUR/ha	–20 EUR/ha

Although the financial loss of using the WR is reduced due to the increase in the market price for the crops or the decrease in the price for WR, the general pattern still suggest that it is unprofitable to apply the WR for cultivation of oats and spring wheat for farmers with the same or similar production conditions as the test site. Application of WR for cultivation of spring barley becomes on the other hand profitable. More specifically, an increase in the market price of spring barley by 8.4 % together with the use of WR would give the farmer the same profit level with and without the use of WR (difference in private net benefit = 0). A decrease in the market price of WR by 8.4 % would also result in the same profit level for the farmer if he/she applies WR or not.

Data availability

Data will be made available on request.

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