

DO WE KNOW WHETHER DECISION SUPPORT SYSTEMS FOR IRRIGATION ARE USEFUL?

SAVONS-NOUS SI LES SYSTÈMES D'AIDE À LA DÉCISION POUR L'IRRIGATION SONT UTILES?

Claire Richert¹, Frédéric Grelot², Sophie Martin³, Hélène Tribouillois⁴

ABSTRACT

Irrigation Decision Support Systems (IDSS) are precision agriculture tools designed to help farmers schedule irrigation. They are promoted by public policies, for example in France. This article presents a first overview of the current state of knowledge regarding their usefulness. More specifically, this study aims to identify the main purpose of IDSS and evaluate the extent to which the existing literature provides information on the ability of IDSS to meet this purpose. First, studies that claim to evaluate an IDSS were identified. They all provided a list of purposes for IDSS in their introduction. The most frequently mentioned purpose was that they should improve water productivity. The studies presenting a suitable methodology for carrying out a meta-analysis of the effect of IDSS on water productivity and its 2 components (yield and irrigation volume) were subsequently selected. The ability of IDSS to improve water productivity as a function of the type of crops, climate, and type of IDSS was also examined. Using an IDSS improved water productivity for 57% of the cases taken into account, generally because the irrigation volume was lower, with no negative impact on yield. This value fell to 48% for market gardening crops. No significant effect of the climate and the type of IDSS were found. Given the low number of data points by study, these results are probably affected by a publication bias and should be considered as an upper limit of the effect of IDSS on water productivity.

Keywords: Decision support systems; Precision agriculture tools; Yield and irrigation volume; Market gardening crops; Water productivity.

RÉSUMÉ

Les systèmes d'aide à la décision pour l'irrigation (IDSS) sont des outils d'agriculture de précision conçus pour aider les agriculteurs à programmer l'irrigation. Ils sont encouragés par les politiques publiques, notamment en France. Cet article présente un premier aperçu de l'état actuel des connaissances concernant leur utilité. Plus précisément, cette étude vise à déterminer l'objectif principal des IDSS et à évaluer dans quelle mesure la littérature existante renseigne sur leur capacité à atteindre cet objectif. Dans un premier temps, les études affirmant évaluer un IDSS ont été recensées. Elles présentaient toutes, dans leur introduction, une liste des objectifs des IDSS. L'objectif le plus fréquemment cité était l'amélioration de la productivité de l'eau. Les études présentant une méthodologie adaptée à la réalisation d'une méta-analyse de l'effet des IDSS sur la productivité de l'eau et sur ses deux composantes — le rendement et le volume d'irrigation — ont ensuite été sélectionnées. La capacité des IDSS à améliorer la productivité de l'eau en fonction du type de culture, du climat et du type d'IDSS a également été examinée. L'utilisation d'un IDSS a amélioré la productivité de l'eau dans 57 % des cas pris en compte, généralement parce que le volume d'irrigation était plus faible, sans effet négatif sur le rendement. Cette proportion est tombée à 48 % pour les cultures maraîchères. Aucun effet significatif du climat ni du type d'IDSS n'a été observé. Compte tenu du faible nombre de points de données par étude, ces résultats sont

1 UMR MIA Paris-Saclay, Université Paris-Saclay, AgroParisTech, INRAE, Palaiseau, 91120, France Email: richert.claire@gmail.com

2 G-EAU, Univ. Montpellier, AgroParisTech, BRGM, CIRAD, INRAE, Institut Agro, IRD, Montpellier, France

3 UMR MIA Paris-Saclay, Université Paris-Saclay, AgroParisTech, INRAE, Palaiseau, 91120, France

4 Terres inovia, 110 chemin de la Côte Vieille, 31450 Baziège, France

probablement affectés par un biais de publication et doivent être considérés comme une limite supérieure de l'effet des IDSS sur la productivité de l'eau.

Mots clés : Systèmes d'aide à la décision; Outils d'agriculture de précision; Rendement et volume d'irrigation; Cultures maraîchères; Productivité de l'eau.

Introduction

Water management is a major field of application of precision agriculture, which is defined as “[...] a management strategy that gathers, processes and analyzes temporal, spatial and individual plant and animal data and combines it with other information to support management decisions according to estimated variability for improved resource use efficiency, productivity, quality, profitability and sustainability of agricultural production.” (International Society of Precision Agriculture 2024). Indeed, among 67 articles reviewed by Bhakta, Phadikar, and Majumder (2019) to describe the present status of precision agriculture, 26 deal specifically with this topic.

Precision agriculture tools in the domain of water management are generally Irrigation Decision Support Systems (IDSS), which are presented in the review of Zhang et al. (2021). They aim to facilitate irrigation scheduling by linking data describing a specific agricultural plot and its evolution to irrigation-triggering rules. The latter are generally based on soil moisture and/or plant conditions (plant water conditions or canopy temperature), and determine the timing and/or amount of irrigation events. Soil moisture and plant conditions can be measured directly by in situ sensors or estimated using mechanistic or machine learning models. Input data to feed these models can come from a number of technologies, in addition to in situ sensors: weather stations, satellites, airborne sensors, unmanned aerial vehicles, or databases that provide gridded weather or soil data.

Public policies have been implemented to foster the development of digital tools in the field of precision agriculture. Lajoie-O'Malley et al. (2020) analyzed policy documents from 3 major international organizations: the United Nations Food and Agriculture Organization, the Organization for Economic Cooperation and Development, and the World Bank. Their analysis reveals that these organizations present digital and precision agriculture as a promising solution to feed a growing population while alleviating pressure on ecosystems.

However, evidence to support these hopes in the potential of digital agriculture to benefit both farmers and the environment remains insufficient. Ingram et al. (2022) asked stakeholders of the digital agriculture sector in the UK (mainly researchers and representatives of the Agritech industry) to define the questions that should be a priority for research in this field. They listed 7 themes to explore. One of them was to understand the benefits and uptake of data and technologies.

The participants highlighted the need to better demonstrate the economic, environmental, and social benefits of digital agriculture.

This article presents the first overview of existing evidence regarding the usefulness of IDSS, defined here as their ability to fulfill their purpose. Articles that claim to evaluate an IDSS were systematically reviewed to identify the purpose that is the most often attributed to these tools and to assess the extent to which they fulfill it. In Section 3, the process used to identify articles that claim to evaluate an IDSS is explained. Next, the steps followed to identify the main purpose of IDSS and the outcome of this process are described. Finally, the methodology used in the meta-analysis is presented. The results of the meta-analysis are detailed in Section 4 and discussed in Section 5.

Materials and methods

Method overview

Articles that claimed to evaluate an IDSS were systematically searched for. All authors justified their work on IDSS in the introductory section of their articles by listing the purposes of IDSS. The analysis focused on the one most cited. Not all pre-selected articles presented a methodology suitable for assessing whether an IDSS met this particular purpose: for the meta-analysis, only studies that reported the data necessary to evaluate the performance of an IDSS in relation to this purpose were considered. All their results were analyzed together to assess the performance of IDSS in general and as a function of type of crop, climate, and type of IDSS.

Article identification and selection

The process implemented to select the articles considered in this review is described in **Figure 1**. The literature search was conducted in Web of Science and Scopus in December 2025 and the final database included 71 articles.

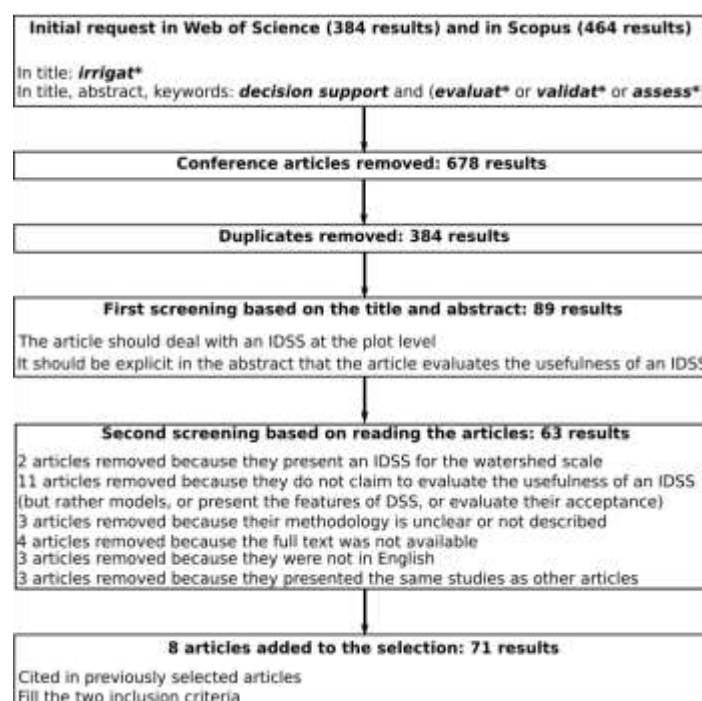


Figure 1. Process implemented to select the articles included in the review

Identification of the purposes of IDSS

In all the articles included in the corpus, the authors justified their work on IDSS in the introductory section by explaining the usefulness of IDSS. These introductions were thus analyzed to identify all the purposes of IDSS they mentioned. The aim of this analysis was to select the most frequently cited purpose in the corpus to study the extent to which IDSS met it.

Fourteen purposes for IDSS were mentioned (cf. **Figure 2**). The most frequently cited (61% of the articles) was that IDSS should help improve water productivity. This label includes claims that IDSS could be useful to “use water more efficiently” (for instance in Flores Cayuela et al. (2022) and Ale et al. (2023)), or increase “water use efficiency” (for instance in Adeyemi et al. (2018), Mirás-Avalos et al.

(2019) and Car et al. (2012)) or “water productivity” (for instance in Sui et al. (2020), Teshome et al. (2023), and Mendes et al. (2024)). The common idea between these different terminologies is that IDSS should help produce more per unit of irrigation water.

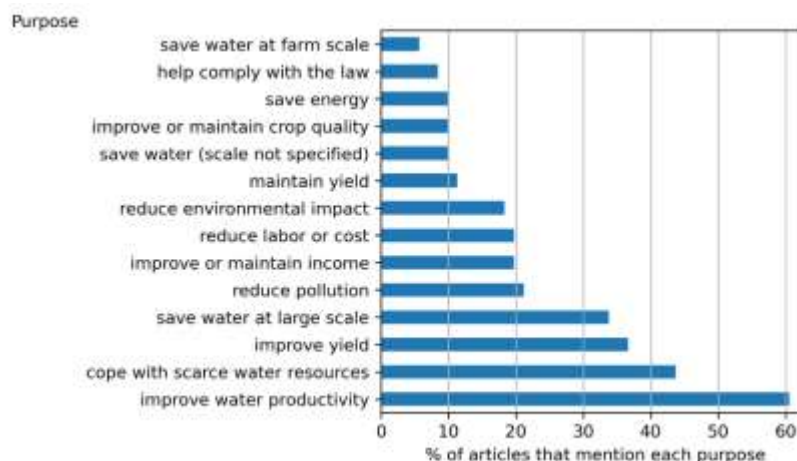


Figure 2. Purposes of IDSS identified in the introductions of the 60 articles selected associated to the percentage of articles that mentioned each one of them

Selection of the articles included in the meta-analysis

In the 71 articles included in the corpus, the authors stated to have evaluated the usefulness of an IDSS (or to have demonstrated that an IDSS was useful). However, not all studies focused on water productivity. To assess the ability of an IDSS to improve water productivity, it is necessary to compare the water productivity achieved with and without the IDSS. This requires having access to measures or estimates of yield and irrigation water volume with and without the IDSS. This was the case for 21 out of the 71 articles selected. Two of them were excluded because they explicitly defined standard irrigation doses as a multiple of the doses recommended by the IDSS. Consequently, it did not represent farmers' practices.

The articles taken into account in further analyses are the 19 remaining articles that compared both the yield and irrigation water volumes obtained using an IDSS or using traditional practices. Among these articles, 17 considered only observed values and 2 (Malik and Dechmi 2019; Roy et al. 2021) combined observed and estimated values. In these 2 articles, observed irrigation volumes applied by the farmers were compared to optimal irrigation volumes recommended by the IDSS evaluated. Yields were then simulated using both scenarios of irrigation.

Data included in the meta-analysis

A data point is made up of the 4 pieces of information needed to assess the effect of an IDSS on water productivity: the yield obtained without the IDSS, the yield obtained with the IDSS, the irrigation water volume applied without using the IDSS, the irrigation water volume applied using the IDSS.

These values were provided at the site scale in 17 articles. A site here is an area with a pedoclimatic context described as homogeneous. In the 2 remaining articles (Malik and Dechmi (2019) and Domínguez et al. (2023)), data points were provided at a larger scale. Malik and Dechmi (2019) classified the 13 soil types they studied into 2 groups: shallow and/or high permeability, and low permeability soils. Data points from their study were available at the level of these groups. Domínguez et al. (2023) presented values of yield and irrigation water volumes aggregated at country level. A spatial unit was therefore a group of soil type in Malik and Dechmi (2019), a country in Domínguez et

al. (2023), and a site in all the other articles.

Each data point was associated to a crop, growing season, IDSS, and spatial unit. In total, the 19 articles provided 97 data points. The number of data points by article is detailed in **Figure 3**. For each article, the crops studied and the countries considered are presented in **Table 1**.

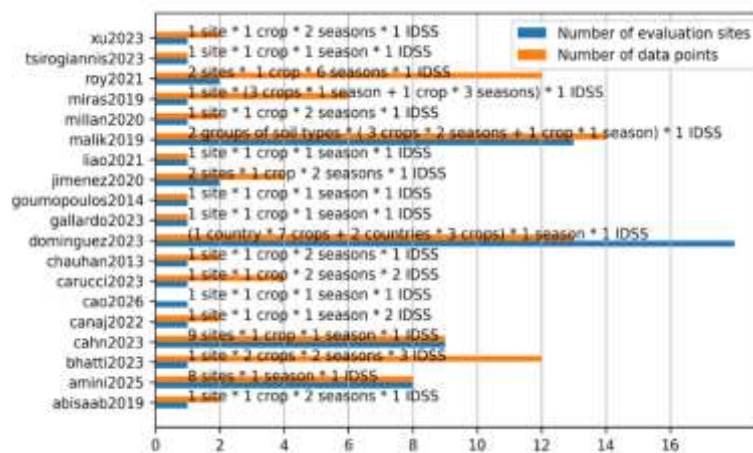


Figure 3. Number of sites and data points studied by article

Table 1. Description of the articles selected to examine the effect of IDSS on water productivity

Reference	Crop	Country
Abi Saab et al. (2019)	wheat	Lebanon
Amini, Emami, and Dehghanisanij (2025)	sugarbeet, apple, alfalfa, wheat	Iran
Bhatti et al. (2023)	maize, soybean	USA
Cahn, Smith, and Melton (2023)	broccoli, lettuce	USA
Canaj et al. (2021)	zucchini	Italy
Cao et al. (2026)	maize	China
Carucci et al. (2023)	tomato	Italy
Chauhan et al. (2013)	peanut	Australia
Domínguez et al. (2023)	onion, alfalfa, barley, garlic, maize, oats, potato, wheat	Spain, Lebanon, Tunisia
Gallardo et al. (2023)	tomato	Spain
Goumopoulos, O'Flynn, and Kameas (2014)	strawberry	Ireland
Jimenez et al. (2021)	maize	USA
Liao et al. (2021)	tomato	China
Malik and Dechmi (2019)	barley, wheat, maize, sunflower, alfalfa	Spain
Millán et al. (2020)	olive	Spain
Mirás-Avalos et al. (2019)	endive, lettuce, muskmelon, potato	Spain
Roy et al. (2021)	grapes	India
Tsirogiannis, Malamos, and Baltzoi (2023)	grapes	Greece
Xu et al. (2023)	pakchoi	China

Data analysis

Categories of IDSS effects

The majority of studies included in this analysis did not provide information regarding the uncertainty of the effect of the IDSS on irrigation water volume and yield.

This uncertainty was at least affected by measurement inaccuracy. Irrigation volumes were generally measured using flow meters (for example in Abi Saab et al. (2019), Carucci et al. (2023), Domínguez

et al. (2023)) or water meters (for example in Millán et al. (2020), Mirás-Avalos et al. (2019), Tsirogiannis, Malamos, and Baltzoi (2023)). The accuracy of these sensors is not perfect: Liao et al. (2021) reported a 1% accuracy for the ultrasonic flow meter used in their experiment. This accuracy was likely the one indicated by the constructor and obtained in laboratory conditions, for a new flow meter, and for the flow rates specified by legal standards. But accuracy is typically not the same in field conditions and decreases with the flow or water meter age: Arregui et al. (2018) found that the average error between actual water consumption volumes and volumes indicated by new water meters for domestic use was actually -4% because their performance is limited at low flow rates. This average error was between -6 and -9% for water meters that were 6 years old.

Authors who provided information on yield measurement often indicated that it was carried out on a sample of the entire experimental field (Abi Saab et al. (2019), Carucci et al. (2023), Gallardo et al. (2023), Millán et al. (2020)). Abi Saab et al. (2019) measured yield on a 1m² surface out of 300m² in each one of their 3 replicates by treatment. They found a relative standard deviation of yield between 4 and 8% by treatment. Xu et al. (2023) reported relative standard deviation of yield by treatment between 9 and 10%.

Given the probably low precision of the data extracted from the corpus, numerical values were not directly analyzed. Instead, data points were grouped into 3 categories to study the effect of IDSS on irrigation volume, yield, or water productivity: “lower for IDSS”, “no difference”, and “higher for IDSS”. Irrigation water volume or yield was considered higher (or lower) with the IDSS if it was at least 10% higher (or lower) than with the farmer's rules. The underlying assumption was that the actual value of irrigation water volume or yield could lie anywhere between minus 5% and plus 5% around the measured value. Consequently, if the difference between 2 measured values was lower than 10%, the sign of this difference was not necessarily the same as the sign of the difference between the 2 actual values. In other words, it was assumed that a difference of yield or irrigation water volume lower than 10% could not be identified given the inaccuracy of measurement.

The relative inaccuracy of measurement of irrigation water volume and yield had to be added to obtain the relative inaccuracy of water productivity (Taylor 1997). Therefore, a relative inaccuracy of 10% for water productivity was used, which implied that 2 values of water productivity were considered different if their difference was at least 20% of the water productivity obtained without using an IDSS.

Analysis of IDSS effects

Sankey diagrams were used to visualize how the effects of IDSS on yield, irrigation volume, and water productivity were related in general.

Then, each data point was associated to a type of crop (field crop, market gardening, or orchards and grapevine), a climate, and a type of IDSS (with or without sensors). The Köppen-Geiger climate classification maps produced by Rubel and Kottek (2010) were used to associate a climate to each data point. The relationship between each of these variables and the effect of IDSS on water productivity were analyzed using chi-square tests for independence.

Results

Effect of IDSS on irrigation water volume, yield, and water productivity

Using an IDSS generally did not negatively affect yield (cf. **Figure 4. a**), which increased for 31% and remained approximately the same for 66% of the data points. It decreased irrigation water volume for 59% of the data points, did not affect this variable for 25% of the data points, and increased it for 16% of them. Using an IDSS rarely resulted in both a higher yield and a lower irrigation water volume (approximately 9% of the data points). It was associated to both a lower irrigation water volume and no difference in yield for 46% of the data points.

Water productivity rarely decreased when using an IDSS (for 3% of the data points), and it increased for 57% of the data points (cf. **Figure 4. b**).

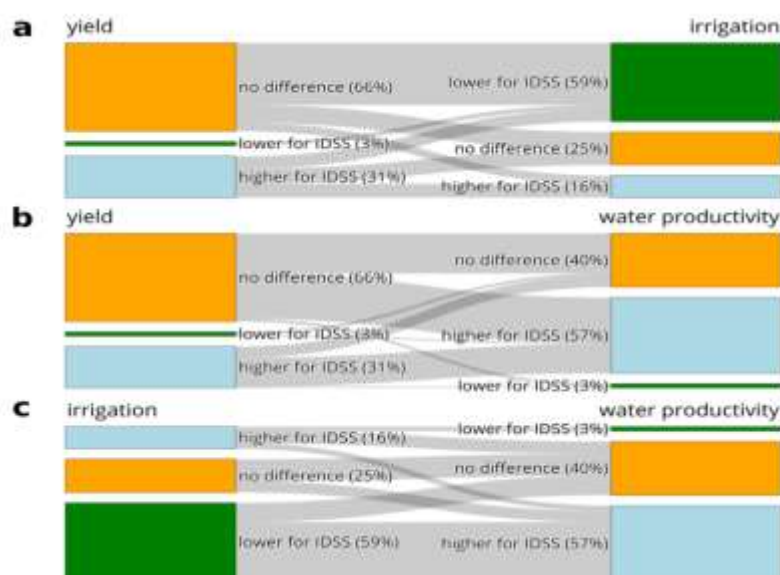


Figure 4. Sankey diagrams showing the way the repartition of the data points in the 3 categories (lower with an IDSS, no difference, higher with an IDSS) is related between (a) yield and irrigation water volume, (b) yield and water productivity, (c) irrigation water volume and water productivity (N = 97). Irrigation water volume and yield were considered lower (or higher) when using an IDSS if they decreased (or increased) by at least 10%. Water productivity was considered lower (or higher) when using an IDSS if it decreased (increased) by at least 20%.

Effect of the type of crop, of IDSS evaluated, and climate on IDSS performance

Crops were categorized into market gardening crops, field crops, or orchards and grapevines. Similarly, climates were simplified into 3 categories: dry, temperate, and continental climate. Besides, data points that related to an IDSS that relied on sensors were distinguished from those that concerned an IDSS that was not associated to sensors.

The category of crops was the only tested variable for which the p-value of the chi-square test of independence was below 0.05. The hypothesis that the effect of IDSS on water productivity was the same for all crop categories could therefore be rejected. For 48% of the data points that concerned market gardening crops, using an IDSS improved water productivity. For field crops and orchards and vineyards, the water productivity obtained when using an IDSS was higher than when usual rules were applied for 62% and 56% of the data points, respectively.

Discussion

Key findings on IDSS performance from the meta-analysis

According to the data analyzed, IDSS rarely induced a lower yield compared to traditional practices, but did not generally help increase it either. They led to an increase in water productivity in 57% of the cases studied. This increase was generally due to a decrease in the volume of irrigation.

Using an IDSS rarely led to both a higher yield and a lower irrigation volume. However, for half of the data points, using an IDSS was associated to a lower volume of irrigation while yield remained stable. In these cases, the plots managed according to traditional practices were probably over-irrigated and the IDSS helped reduce runoff and drainage.

The data analyzed covered a wide range of crops, and all climates except from tropical and polar, for which IDSS may not be relevant. They also represented all 4 types of irrigation scheduling methods identified by Gu et al. (2020) in a review, which are methods based on evapotranspiration and water

balance, on soil moisture or soil matric potential sensors, on plant-water-status-related indices, or on simulated results from process-based models.

The link between these factors and the effect of IDSS on water productivity could therefore be investigated. However, given the small number of data points available, the data were grouped into broad categories to perform statistical analyses. No significant relationship was found between the effect of IDSS on water productivity and the type of climate or whether or not the IDSS included sensors, but IDSS improved water productivity more often for field crops than for market gardening crops.

This could be explained by the fact that market gardeners were already more involved in precision irrigation practices than farmers growing field crops, and thus had less room for improvement. Indeed, market gardening crops included in our analysis were all irrigated with drippers or micro-sprinkle irrigation systems whereas field's crops were generally irrigated with sprinklers. Drip irrigation is associated on average to a higher application efficiency than sprinklers: by analyzing the results of field trials carried out at 25 experimental sites in France, Wittling, Molle, and Cheviron (2023) found that switching from sprinkler to drip irrigation resulted in water savings of between 5 and 35%.

Since less attention has been devoted to market gardening crops than field crops in the crop modelling domain (Silva and Giller 2020), another assumption is that crop models could be less performant for the former than for the latter.

Key learnings for future research on IDSS evaluation

Potential biases in the studies taken into account

The data analyzed came from a small number of studies (19), which each provided a small number of data points. They were thus likely subject to publication bias.

In addition, in 15 out of the 19 articles of our corpus, at least one of the authors was also involved in the development of the IDSS, and in 11 out of 17 studies based only on measured data, the IDSS treatments were conducted by the researchers themselves. In these cases, IDSS could have been used in conditions more favorable to improving water productivity than when used in real-life situations. Indeed, as explained by Cahn, Smith, and Melton (2023), following precisely an IDSS recommendations is not always possible in real-life conditions because workforce may not always be available to operate the irrigation system exactly when advised by the IDSS. Furthermore, improving water productivity is not necessarily the goal of farmers, as illustrated by the study of Benouniche et al. (2014).

Given all these potential biases, the results of the meta-analysis should be treated as an upper limit of the effect of IDSS on water productivity. These observations also highlight the need for independent and large-scale on-farm experiments that aim at testing whether IDSS actually help improve water productivity.

Remaining knowledge gaps

IDSS encompass various technologies and irrigation scheduling rules, and can be used in various pedoclimatic contexts. Given the small number of data points, only a rough analysis of the link between these factors and the effect of IDSS on water productivity was conducted.

Current knowledge is thus insufficient to characterize the situations in which adopting an IDSS is likely to lead to an increase in water productivity. More comparisons between the yield obtained and irrigation volume applied with or without an IDSS in studies that include several sites are needed to finely understand the factors that make these tools able to improve water productivity compared to traditional irrigation practices.

Besides, in most of the articles included in the corpus, 2 types of information on experimental conditions are missing to interpret the results. First, estimates of yield and irrigation volume measurement uncertainty are needed to understand whether differences are attributable to anything other than measurement error. Secondly, farmers who do not use an IDSS yet can follow different irrigation strategies. The effect of adopting an IDSS on water productivity depends on their current irrigation scheduling method. In this meta-analysis, the relationship between this factor and the effect of IDSS on water productivity could not be analyzed because traditional irrigation practices were defined in only 9 studies, and with different levels of precision.

Future research should report yield and irrigation water volume measurement inaccuracy and thoroughly describe the pedoclimatic context and farmers' usual practices to enable better identification of the situations in which the use of an IDSS can lead to greater water productivity.

Limitations of the meta-analysis

The results obtained depend on the studies included in the meta-analysis. Yet, some relevant articles may have been missed because they could not be identified with the criteria used during the literature search. Moreover, technical institutes and private companies may have performed comparisons between the yield obtained and irrigation water volume applied with and without using an IDSS, without publishing the results in peer-reviewed journals.

Conclusion

The most cited purpose of IDSS in the articles reviewed is to increase water productivity. Out of the 71 articles that claimed to evaluate an IDSS, 19 could be included in a meta-analysis to examine the effect of IDSS on water productivity.

Water productivity was higher when an IDSS was used in 57% of the cases studied, generally because irrigation volume was reduced while yield remained stable. In market gardening crops, this proportion fell below 50%.

Two main gaps were identified in the existing literature and should be addressed in future IDSS evaluations to enable the translation of their findings into practical advice to farmers. First, measurement inaccuracy of yield and irrigation water volume should be reported. Secondly, traditional irrigation scheduling rules should be well described.

References

- Abi Saab, Marie Therese, Ihab Jomaa, Sleiman Skaf, Salim Fahed, and Mladen Todorovic. 2019. "Assessment of a Smartphone Application for Real-Time Irrigation Scheduling in Mediterranean Environments." *Water* 11 (2): 252. <https://doi.org/10.3390/w11020252.X>
- Adeyemi, Olutobi, Ivan Grove, Sven Peets, Yuvraj Domun, and Tomas Norton. 2018. "Dynamic Neural Network Modelling of Soil Moisture Content for Predictive Irrigation Scheduling." *Sensors* 18 (10): 3408. <https://doi.org/10.3390/s18103408.X>
- Ale, Srinivasulu, Qiong Su, Jasdeep Singh, Sushil Himanshu, Yubing Fan, Blake Stoker, Eric Gonzalez, et al. 2023. "Development and Evaluation of a Decision Support Mobile Application for Cotton Irrigation Management." *Smart Agricultural Technology* 5 (October): 100270. <https://doi.org/10.1016/j.atech.2023.100270.X>
- Amini, Abdollah, Somayeh Emami, and Hossein Dehghanisanij. 2025. "Participatory Evaluation of an Irrigation Decision Support System for Water-Saving and Productivity Gains in Lake Urmia Basin." *Scientific Reports* 15 (1): 42480. <https://doi.org/10.1038/s41598-025-26567-z.X>
- Arregui, Francisco J., Francesc J. Gavara, Javier Soriano, and Laura Pastor-Jabaloyes. 2018. "Performance Analysis of Ageing Single-Jet Water Meters for Measuring Residential Water Consumption." *Water* 10 (5): 612. <https://doi.org/10.3390/w10050612.X>

- Benouniche, Maya, Marcel Kuper, Ali Hammani, and Harm Boesveld. 2014. "Making the User Visible: Analysing Irrigation Practices and Farmers' Logic to Explain Actual Drip Irrigation Performance." *Irrigation Science* 32 (6): 405–20. <https://doi.org/10.1007/s00271-014-0438-0>.X
- Bhakta, Ishita, Santanu Phadikar, and Koushik Majumder. 2019. "State-of-the-art Technologies in Precision Agriculture: A Systematic Review." *Journal of the Science of Food and Agriculture* 99 (11): 4878–88. <https://doi.org/10.1002/jsfa.9693>.X
- Bhatti, Sandeep, Derek M. Heeren, Susan A. O'Shaughnessy, Christopher M. U. Neale, Jacob LaRue, Steve Melvin, Eric Wilkening, and Geng Bai. 2023. "Toward Automated Irrigation Management with Integrated Crop Water Stress Index and Spatial Soil Water Balance." *Precision Agriculture* 24 (6): 2223–47. <https://doi.org/10.1007/s11119-023-10038-4>.X
- Cahn, Michael, Richard Smith, and Forrest Melton. 2023. "Field Evaluations of the CropManage Decision Support Tool for Improving Irrigation and Nutrient Use of Cool Season Vegetables in California." *Agricultural Water Management* 287 (September): 108401. <https://doi.org/10.1016/j.agwat.2023.108401>.X
- Canaj, Kledja, Angelo Parente, Massimiliano D'Imperio, Francesca Boari, Vito Buono, Michele Toriello, Andi Mehmeti, and Francesco Fabiano Montesano. 2021. "Can Precise Irrigation Support the Sustainability of Protected Cultivation? A Life-Cycle Assessment and Life-Cycle Cost Analysis." *Water* 14 (1): 6. <https://doi.org/10.3390/w14010006>.X
- Cao, Yingjian, Ming Zhan, Hang Xiong, Lin Chen, William D. Batchelor, Bowen Yang, Bo Chen, and Lijun Li. 2026. "Model Based Decision Making for Efficient Drip Irrigation Strategy of Maize in Arid Northwestern China-A Case Study in Bayannur District." *Field Crops Research* 336 (February): 110107. <https://doi.org/10.1016/j.fcr.2025.110107>.X
- Car, Nicholas J., Evan W. Christen, John W. Hornbuckle, and Graham A. Moore. 2012. "Using a Mobile Phone Short Messaging Service (SMS) for Irrigation Scheduling in Australia – Farmers' Participation and Utility Evaluation." *Computers and Electronics in Agriculture* 84 (June): 132–43. <https://doi.org/10.1016/j.compag.2012.03.003>.X
- Carucci, Federica, Anna Gagliardi, Marcella Michela Giuliani, and Giuseppe Gatta. 2023. "Irrigation Scheduling in Processing Tomato to Save Water: A Smart Approach Combining Plant and Soil Monitoring." *Applied Sciences* 13 (13): 7625. <https://doi.org/10.3390/app13137625>.X
- Chauhan, Yashvir S., Graeme C. Wright, Dean Holzworth, Rao C. N. Rachaputi, and José O. Payero. 2013. "AQUAMAN: A Web-Based Decision Support System for Irrigation Scheduling in Peanuts." *Irrigation Science* 31 (3): 271–83. <https://doi.org/10.1007/s00271-011-0296-y>.X
- Domínguez, Alfonso, José Antonio Martínez-López, Hacib Amami, Radhouan Nsiri, Fadi Karam, and Maroua Oueslati. 2023. "Adaptation of a Scientific Decision Support System to the Productive Sector—A Case Study: MOPECO Irrigation Scheduling Model for Annual Crops." *Water* 15 (9): 1691. <https://doi.org/10.3390/w15091691>.X
- Flores Cayuela, Carmen M., Rafael González Perea, Emilio Camacho Poyato, and Pilar Montesinos. 2022. "An ICT-Based Decision Support System for Precision Irrigation Management in Outdoor Orange and Greenhouse Tomato Crops." *Agricultural Water Management* 269 (July): 107686. <https://doi.org/10.1016/j.agwat.2022.107686>.X
- Gallardo, Marisa, M Teresa Peña-Fleitas, Francisco M Padilla, Juan Cedeño, and Rodney B Thompson. 2023. "Prescriptive-Corrective Irrigation and Macronutrient Management in Greenhouse Soil-Grown Tomato Using the VegSyst-DSS V2 Decision Support Tool." *Horticulturae* 9 (1128). <https://doi.org/Prescriptive-Corrective-Irrigation-and-Macronutrient-Management-in-Greenhouse-Soil-Grown-Tomato-Using-the-VegSyst-DSS-v2-Decision-Support-Tool>.X
- Goumopoulos, Christos, Brendan O'Flynn, and Achilles Kameas. 2014. "Automated Zone-Specific Irrigation with Wireless Sensor/Actuator Network and Adaptable Decision Support." *Computers and Electronics in Agriculture* 105 (July): 20–33. <https://doi.org/10.1016/j.compag.2014.03.012>.X
- Gu, Zhe, Zhiming Qi, Rasika Burghate, Shouqi Yuan, Xiyun Jiao, and Junzeng Xu. 2020. "Irrigation Scheduling Approaches and Applications: A Review." *Journal of Irrigation and Drainage Engineering* 146 (6): 04020007. [https://doi.org/10.1061/\(ASCE\)IR.1943-4774.0001464](https://doi.org/10.1061/(ASCE)IR.1943-4774.0001464).X
- Ingram, Julie, Damian Maye, Clive Bailye, Andrew Barnes, Christopher Bear, Matthew Bell, David Cutress, et al. 2022. "What Are the Priority Research Questions for Digital Agriculture?" *Land Use Policy* 114 (March): 105962. <https://doi.org/10.1016/j.landusepol.2021.105962>.X
- International Society of Precision Agriculture. 2024. "Precision Ag Definition." <https://www.ispag.org/about/definition>.X

- Jimenez, Andres-F., Brenda V. Ortiz, Luca Bondesan, Guilherme Morata, and Damianos Damianidis. 2021. "Long Short-Term Memory Neural Network for Irrigation Management: A Case Study from Southern Alabama, USA." *Precision Agriculture* 22 (2): 475–92. <https://doi.org/10.1007/s11119-020-09753-z>.X
- Lajoie-O'Malley, Alana, Kelly Bronson, Simone Van Der Burg, and Laurens Klerkx. 2020. "The Future(s) of Digital Agriculture and Sustainable Food Systems: An Analysis of High-Level Policy Documents." *Ecosystem Services* 45 (October): 101183. <https://doi.org/10.1016/j.ecoser.2020.101183>.X
- Liao, Renkuan, Shirui Zhang, Xin Zhang, Mingfei Wang, Huarui Wu, and Lili Zhangzhong. 2021. "Development of Smart Irrigation Systems Based on Real-Time Soil Moisture Data in a Greenhouse: Proof of Concept." *Agricultural Water Management* 245 (February): 106632. <https://doi.org/10.1016/j.agwat.2020.106632>.X
- Malik, Wafa, and Farida Dechmi. 2019. "DSSAT Modelling for Best Irrigation Management Practices Assessment Under Mediterranean Conditions." *Agricultural Water Management* 216 (May): 27–43. <https://doi.org/10.1016/j.agwat.2019.01.017>.X
- Mendes, Willians Ribeiro, Arthur Moraes E Videira, Salah Er-Raki, Derek M. Heeren, Ritaban Dutta, and Fábio M. U. Araújo. 2024. "Development of a Fuzzy Variable Rate Irrigation Control System Based on Remote Sensing Data to Fully Automate Center Pivots." *IEEE Transactions on Automation Science and Engineering* 21 (4): 6109–25. <https://doi.org/10.1109/TASE.2023.3322120>.X
- Millán, Sandra, Carlos Campillo, Jaume Casadesús, Juan Manuel Pérez-Rodríguez, and Maria Henar Prieto. 2020. "Automatic Irrigation Scheduling on a Hedgerow Olive Orchard Using an Algorithm of Water Balance Readjusted with Soil Moisture Sensors." *Sensors* 20 (9): 2526. <https://doi.org/10.3390/s20092526>.X
- Mirás-Avalos, José, José Rubio-Asensio, Juan Ramírez-Cuesta, José Maestre-Valero, and Diego Intrigliolo. 2019. "Irrigation-Advisor—A Decision Support System for Irrigation of Vegetable Crops." *Water* 11 (11): 2245. <https://doi.org/10.3390/w11112245>.X
- Roy, Adrija, Parag Narvekar, Raghu Murtugudde, Vilas Shinde, and Subimal Ghosh. 2021. "Short and Medium Range Irrigation Scheduling Using Stochastic Simulation-Optimization Framework With Farm-Scale Ecohydrological Model and Weather Forecasts." *Water Resources Research* 57 (5): e2020WR029004. <https://doi.org/10.1029/2020WR029004>.X
- Rubel, Franz, and Markus Kottek. 2010. "Observed and Projected Climate Shifts 1901-2100 Depicted by World Maps of the Köppen-Geiger Climate Classification." *Meteorologische Zeitschrift* 19 (2): 135–41. <https://doi.org/10.1127/0941-2948/2010/0430>.X
- Silva, João Vasco, and Ken E. Giller. 2020. "Grand Challenges for the 21st Century: What Crop Models Can and Can't (yet) Do." *The Journal of Agricultural Science* 158 (10): 794–805. <https://doi.org/10.1017/S0021859621000150>.X
- Sui, Ruixiu, Susan A. O'Shaughnessy, Steven R. Evett, Alejandro Andrade-Rodriguez, and Jonnie Baggard. 2020. "Evaluation of a Decision Support System for Variable-Rate Irrigation in a Humid Region." *Transactions of the ASABE* 63 (5): 1207–15. <https://doi.org/10.13031/trans.13904>.X
- Taylor, John R. 1997. "Propagation of Uncertainties." In *An Introduction to Error Analysis*, 2nd ed., 51–53. Univ. Science Books, Sausalito, California.
- Teshome, Fitsum T., Haimanote K. Bayabil, Bruce Schaffer, Yiannis Ampatzidis, Gerrit Hoogenboom, and Aditya Singh. 2023. "Exploring Deficit Irrigation as a Water Conservation Strategy: Insights from Field Experiments and Model Simulation." *Agricultural Water Management* 289 (November): 108490. <https://doi.org/10.1016/j.agwat.2023.108490>.X
- Tsirogiannis, Ioannis L., Nikolaos Malamos, and Penelope Baltzoi. 2023. "Application of a Generic Participatory Decision Support System for Irrigation Management for the Case of a Wine Grapevine at Epirus, Northwest Greece." *Horticulturae* 9 (2): 267. <https://doi.org/10.3390/horticulturae9020267>.X
- Wittling, Claire, Bruno Molle, and Bruno Cheviron. 2023. "What Is the Real Potential for Irrigation Water Savings at the Plot Level Resulting from Modernization of Irrigation Systems?" In *25th International Congress on Irrigation and Drainage*.
- Xu, Xiangying, Chao Wang, Hongjiang Wang, Yonglong Zhang, Zhuangzhuang Cao, Zhiping Zhang, Haibo Dai, and Minmin Miao. 2023. "Development and Performance Evaluation of an APP for Vegetable Fertilization and Irrigation Management Originated from EU-Rotate_n." *Agricultural Water Management* 289 (November): 108520. <https://doi.org/10.1016/j.agwat.2023.108520>.X
- Zhang, Jingwen, Kaiyu Guan, Bin Peng, Chongya Jiang, Wang Zhou, Yi Yang, Ming Pan, et al. 2021. "Challenges and Opportunities in Precision Irrigation Decision-Support Systems for Center Pivots." *Environmental Research Letters* 16 (5): 053003. <https://doi.org/10.1088/1748-9326/abe436>.X