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The potential of variable-rate technology for sustainable intensification of European arable farming

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ABSTRACT

Sustainable intensification of agriculture calls for reducing inputs while increasing yields. Variable-rate technology (VRT) enables the application of the right amount of resources at the right time and place to meet crop requirements. VRT remains relatively underutilized in European arable farming compared to Americas and Australia. Facilitating VRT adoption and other precision agricultural technologies in European arable farming requires understanding the pressing needs of farmers and proposing location-specific solutions to their problems. To address this gap, we conducted online surveys of experts in agricultural research, service, and primary production across seven European arable farming regions. Experts were asked to estimate the current and future adoption of VRT and to assess the role of relevant factors for adopting VRT in their regions. Furthermore, we asked about the challenges of fertilization, weed/pest control, and water management. Our results show a higher current and future VRT application for fertilization compared to weed/pest control and irrigation across all regions. The biggest barriers against VRT adoption in arable farming are cost, government regulations, and technology complexity. Moreover, our results show that VRT can more efficiently address the challenges of fertilizer application and weed/pest control, but has limited potential in addressing water management challenges, which need to be tackled by crop breeding, irrigation infrastructure, and water withdrawal rights. Our findings suggest that the low adoption of VRT in Europe is related to high cost and complexity of VRT, the substitute measures of VRT, and the limitation of VRT in addressing agroecological and policy-related challenges. Sustainable intensification thus requires a portfolio of technological, social, behavioral, and policy innovations.

1. Introduction

Rising food demand and the adverse environmental impacts of farming have led scientists and international organizations to endorse the concept of sustainable intensification in agriculture (FAO, 2011; Tilman et al., 2011; Godfray and Garnett, 2014; Finger et al., 2019; Cassman and Grassini, 2020; Helfenstein et al., 2020, Jones-Garcia and Krishna, 2021; Jain et al., 2023). Concerns about water scarcity,

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greenhouse gas emission, biodiversity loss, and climate change have increased the urgency of reducing the use of fertilizers, pesticides, and irrigation water in agriculture (Sutton et al., 2011b; Vanham et al., 2013; Storck et al., 2017; Möhring et al., 2020). Technological innovations are one strategy for improving resource management to maintain or increase agricultural productivity on existing agricultural land, while simultaneously reducing input use. In this regard, the development and deployment of precision agricultural technologies can support the operationalization of sustainable intensification.

As one of the precision agricultural technologies for resource management, variable-rate technology (VRT) is an effective measure to support sustainable intensification in agricultural production, by reducing resource inputs without loss of crop yield (Gebbers and Adamchuk, 2010; Basso and Antle, 2020; Späti et al., 2021; Gabriel and Gandorfer, 2023). Based on sensor or satellite mapping (Griffin and Lowenberg-DeBoer, 2005), VRT can support farmers in adjusting inputs of mineral fertilizer (Robertson et al., 2012; Colaço and Molin, 2017; Nawar et al., 2017), manure (Zhang et al., 2021), pesticides (Dammer, 2016; da Costa Lima and Mendes, 2020), water (Dukes and Perry, 2006; O'Shaughnessy et al., 2019), seeds (Virk et al., 2020), and lime (Mills et al., 2020) according to the crop requirements in specific locations on the field. The adoption of VRT to save pesticides, fertilizer, and water use has been shown to not only increase profitability but also benefit the environment and meet government regulations (Kempenaar et al., 2017; Fabiani et al., 2020).

VRTs have been commercialized since 1995 (McFadden et al., 2023),

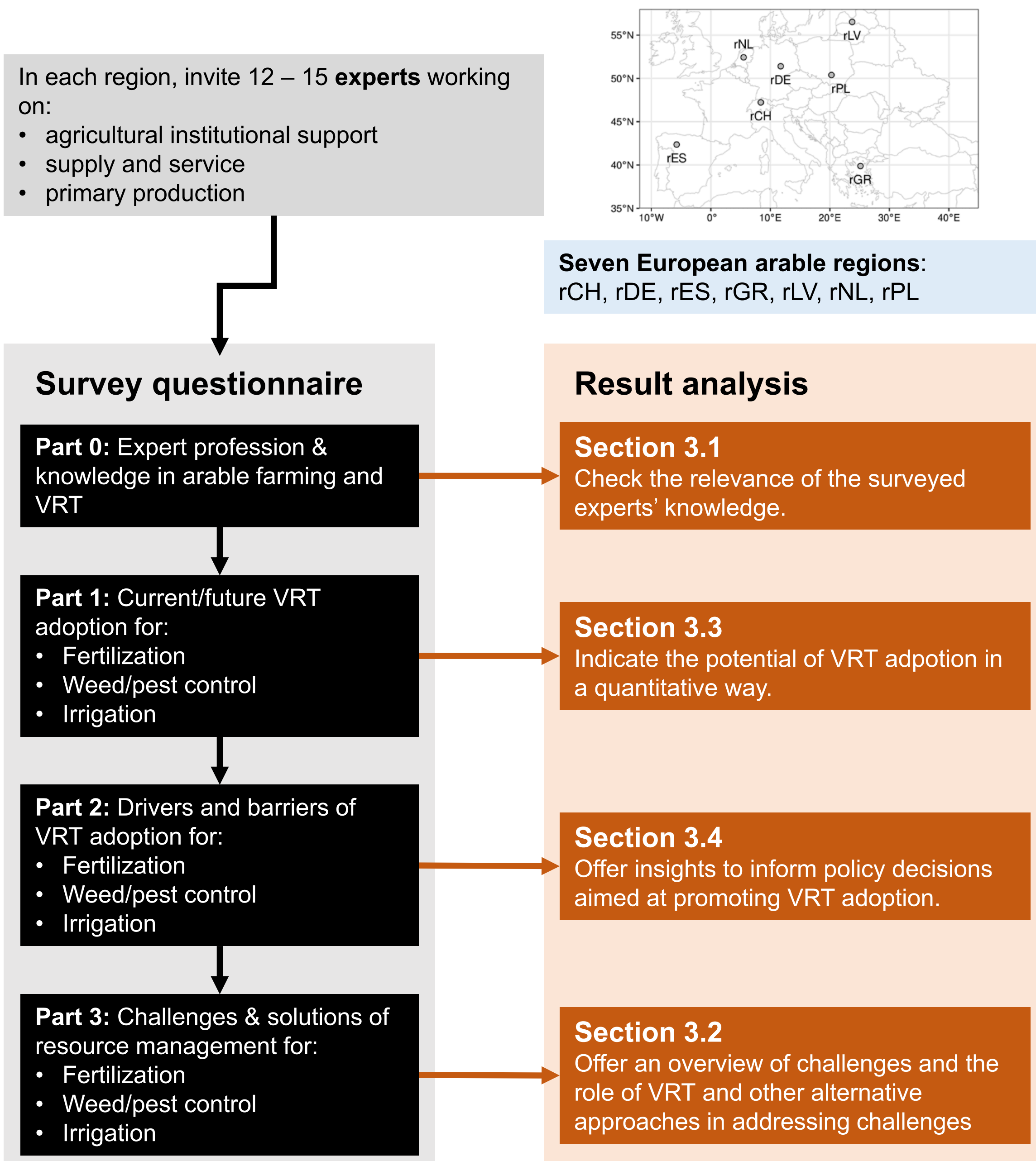

Fig. 1. Questionnaire schematics on the expert survey: expert prospects on the challenges and solutions, the adoption rates, as well as the drivers/barriers of variable-rate technology (VRT) uptake for fertilization, weed/pest control, and water management in seven European arable farming regions. To accommodate experts' response patterns and to enhance the coherence of the manuscript, the three research questions were presented in a different order in the questionnaire (see in supporting information) than in the paper.

but the adoption of VRT in Europe is generally less than 10 %, which is lower than many other continents (Lowenberg-DeBoer and Erickson, 2019). The global VRT market size was valued at 3.68 billion USD in 2021 with an expected annual growth rate of 12.3 % until 2030. Currently, in the US, VRT adoption is about 60 % on large farms (DeLay et al., 2021; McFadden et al., 2023), but less than 25 % on small farms (McFadden et al., 2023). A survey in the 2011 crop season in Brazil reported that VRT was adopted in 44 % of farms larger than 2000 ha, but in only 1 % of farms smaller than 200 ha (Borghi et al., 2016). According to a 2017 survey, approximately 50 % of farmland in Australia and Canada is managed with VRT for fertilizer application (Lowenberg-DeBoer and Erickson, 2019). In contrast, Chinese small family-farms were reported to have limited awareness on VRT (Kendall et al., 2022). The slow adoption of VRT in Europe is linked to the lack of farmers' confidence in its value (Lowenberg-DeBoer and Erickson, 2019; Maloku, 2020), high entry costs (Barnes et al., 2019), and generally small European farm sizes (Masi et al., 2023). A survey of Italian young farmers indicates the importance of complexity, accessibility, cost and consulting services in determining VRT adoption (Masi et al., 2023).

Depending on land and crop conditions, government policies, and economic conditions, the challenges in resource management may vary and therefore affect the potential and actual adoption rate of VRT. However, there is a lack of comprehensive studies on the effectiveness of VRT in addressing agricultural challenges with respect to the management of different resources, and in different contexts of European agriculture, especially for arable land, which accounts for 60.9 % of the agricultural area (Eurostat, 2022a). Moreover, the importance of VRT in comparison to other solutions that European arable farmers may adopt is largely unclear. Our main assumption is that the starting point of farmers' thinking and decision making is the challenges that they are confronted with. Central challenges in arable farming systems include providing adequate nutrients and water, while mitigating the harm of pests and weeds on crop yields. VRT technologies are a promising new option for addressing these challenges, but other alternatives, such as crop breeding and adapted farming practices (Georges and Ray, 2017; Weltin et al., 2018), may be similarly effective. This led us to the following three research questions (Fig. 1):

1. What is the role of VRT in addressing the challenges of fertilization, weed/pest control, and water management in different arable farming regions of Europe?
2. What are the current and expected future adoption rates of VRT for fertilization, weed/pest control, and irrigation in each arable farming region?
3. What do experts perceive as the drivers and barriers to VRT adoption in each region?

We adopted a multi-region comparative approach, which is common in agricultural studies, but requires context-specific empirical data collection (Diogo et al., 2023). We selected seven European arable farming regions based on a previous study conducting farmer interviews about farm management, productivity, sustainability, and technology innovation (Helfenstein et al., 2022b). The seven selected arable farming regions span diverse geographies and farm management conditions, thus representing different agricultural contexts across Europe. We conducted an online survey on the challenges and solutions for the management of different resources, on the current and projected future adoption rates of VRT, as well as on drivers and barriers of VRT uptake (Fig. 1) in the seven case study regions (Fig. 2). Considering the influence of stakeholders' backgrounds and beliefs on their survey responses (Halbrendt et al., 2014), we captured the views and perspectives of 72 local experts working in agricultural primary production, services, and research. Non-VRT alternatives (i.e. hoe/plow for weed/pest control, and flood/furrow irrigation) were also included in the survey of VRT adoption rates, because these technologies are still dominant in Europe and VRT has not yet taken a leading role.

The challenges and corresponding solutions offer an overview of the arable farming realities and the role of VRT and other alternative approaches in addressing these challenges (See 3.2 in Results). The current and projected adoption rates of VRT, though based on expert estimates, indicate the potential of VRT adoption in a quantitative way (see 3.3 in Results). Additionally, the assessed influence of various barriers and drivers offers valuable insights to inform policy decisions aimed at promoting VRT adoption in European arable farming (see 3.4 in Results).

2. Materials & methods

2.1. Case study regions

Our study area covers 7 arable farming regions (Fig. 1) in Switzerland (Reuss Valley), Germany (Querfurt, Saxony-Anhalt), Spain

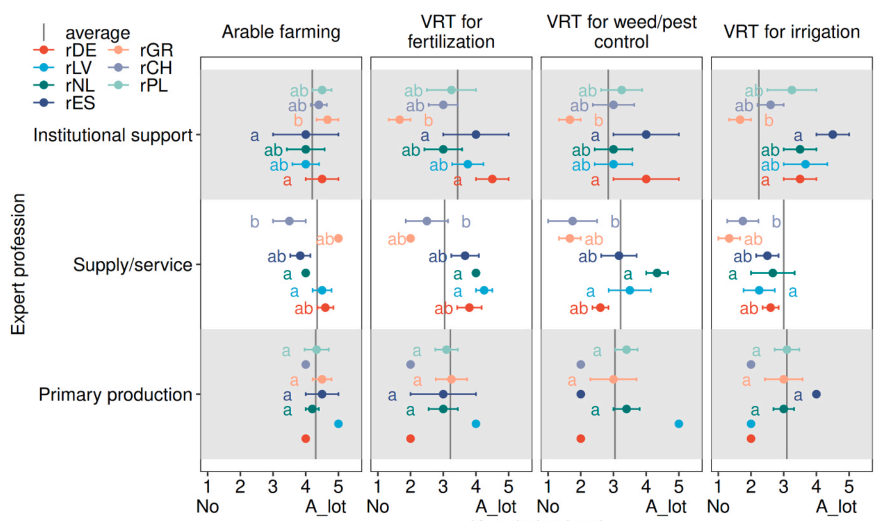

Fig. 2. Expert knowledge levels (mean and standard error) in arable farming and variable-rate technologies (VRT) classified by their professional backgrounds in agricultural primary production, supply/service, and institutional support. The letters of a–b indicate the statistical significance ($P < 0.05$) of differences between regions. Regions without significance labels are those for which only one expert responded. Knowledge levels were collected in ordinal Likert scales from 1 (no knowledge) to 5 (a lot of knowledge), and were treated as interval levels for statistical analysis.

(Santa María del Páramo), Greece (Lemnos), the Netherlands (Dronten, Flevopolder), Latvia (Lielvircava), and Poland (Słaboszów region). The selection of the regions was based on a previous study conducting farmer interviews in each case study region (Helfenstein et al., 2022b). From this set of study sites, we selected seven out of eight arable farming regions, excluding one region in France due to the loss of local collaboration. These seven arable farming regions generally represent a diversity of geographical locations, farm sizes (i.e., average area per farm and average field size in Table 1), management intensity (i.e., livestock density, main crops, nitrogen fertilizer intensity and number of pesticide applications), land ownership (i.e., own farm proportion calculated as the area of owned land divided by the total of owned and rented land), economic performance (i.e., economic situations), farm labor (i.e., off-farm work proportions, and successor index), and farm certificate (i.e., quality certificate index of farm products).

2.2. Survey procedure

To cover heterogeneous panels in our survey, we invited experts working in agricultural primary production, supply/service, and institutional support (Table 2). These stakeholders play a pivotal role in farm-level practices, resource allocation, and decision-making. Their combined expertise offers both holistic and practical perspectives of local agricultural systems.

For each study region, ten experts were initially invited to participate in the online survey translated into the local languages via the "SurveyHero" platform from December 2022 to June 2023. Potential experts were recommended by local partners in the case study regions. Additional experts were then contacted based on snowball sampling from the initial set of experts (similar to previous studies, e.g. Ammann et al., 2022). All experts were asked to complete the survey within two weeks of receiving the survey link and were reminded once if results were not submitted before the deadline. For regions with initial response rates lower than 60 %, an additional 2–5 experts were invited. We invited 85 experts in total, 72 of whom completed the survey (a response rate of 85 %; Table 2). This setup of sampling sizes follows the established guidelines for saturation in qualitative research (Hennink and Kaiser, 2022). We aimed to maintain a balanced representation of 3–4 experts for each profession type, but this could not be achieved due to the limited availability of candidates who have an in-depth knowledge of local arable farming in the respective case study regions.

2.3. Questionnaire

The survey focused on VRT adoption for different aspects of agricultural resource management, i.e., fertilization, weed/pest control, and irrigation. We also included non-VRT technologies in the questionnaire, i.e., hoe/plow for weed/pest control, and flood/furrow irrigation, because they are the common alternative to VRT. The questionnaire structure is shown in Fig. 1, and the full text of the questionnaire can be found in the supporting information.

At the beginning of the survey, experts were introduced to VRT and a short outline of our survey. All experts provided their informed written consent. The questionnaire was approved by the Ethical Commission of the ETH Zurich (ETH-EK 2020-N-146). Experts were asked about their professions in agricultural domains (see the profession distribution of respondents in Table 2) and assessed their basic knowledge in arable farming and VRT for fertilization, weed/pest control, and irrigation (see the questionnaire in supporting information) on a scale ranging from 1 (no knowledge at all) to 5 (know very well). Further, experts were asked to estimate the current and projected adoption rates (as a percentage of farms that use it) of VRT and other alternatives to VRT (i.e. hoe/plow for weed/pest control, and flood/furrow irrigation) for fertilization, weed/pest control, and irrigation. The projected adoption of VRT is defined as "in 10 years" for fertilization and weed/pest control, but as "under drier climates" for irrigation. For regions without irrigation, experts were allowed to skip the parts of irrigation technology adoption. Experts were then asked to assess the influence levels of listed potential drivers and barriers for VRT adoption on a scale ranging from 1 (no influence) to 5 (very influential). Finally, experts were asked to indicate three challenges and corresponding solutions for fertilization, weed/pest control, and water management (Fig. 1; and see the questionnaire in supporting information).

Table 1
Farm situations in each region according to farmer interviews by Helfenstein et al., (2022b).

Region	rDE	rLV	rNL	rES	rGR	rCH	rPL
Average area per farm [ha]	1032	633	125	54	51	38	15
Average field size [ha]	29.0	13.0	4.1	5.8	0.5	1.8	0.7
Livestock density (LU ha^{-1})[a]	1.17	0.03	1.07	0.15	1.23	1.84	0.28
Main crops	Wheat, maize, rapeseed, sugar beet	Wheat, alfalfa	Maize, wheat, potato, carrot, onion	Maize, bean	Barley, oat, clover	Maize, wheat, rapeseed, sugar beet, carrot	Wheat, oat, maize, potato, honey plants
Nitrogen fertilizer intensity [kg N ha^{-1} yr^{-1}][b]	147	170	221	307	52	133	62
Number of pesticide applications[b]	4.1	4.2	5.6	1.8	0	2.1	3.7
Own farm proportion[c]	36 %	65 %	60 %	39 %	23 %	48 %	79 %
Economic situation[d]	3.0	3.3	3.4	3.5	2.7	3.9	3.6
Off farm work proportion	6 %	4 %	16 %	< 1 %	24 %	23 %	37 %
Successor index[e]	0.9	0.5	0.6	0.3	0.4	0.5	0.9
Quality certificate index of farm product[f]	0.4	0.5	0.9	0.1	0.1	0.8	0

Note:
[a] See Helfenstein et al., (2022a) for the methods of calculating livestock index; LU, livestock unit; the answers from each farm were averaged to obtain the values for each region.
[b] Nitrogen fertilizer and pesticide application were estimated for main crops; the answers from each farm were averaged to obtain the values for each region.
[c] Own farm proportion is the ratio of owned land divided the total of owned and rented land; the answers from each farm were averaged to obtain the values for each region.
[d] Economic situation was based on the self-assessment of farmers in ordinal Likert scales from 1 (very difficult) to 5 (very good); the answers from each farm were averaged to obtain the values for each region.
[e] Successor index was defined as 0 for farmers who answered that they do not have successors, as 1 for farmers who answered that they may have successors, and as 2 for farmers who answered that they have successors; the answers from each farm were averaged to obtain the successor index for reach region.
[f] Certificate index was given 1 for farmers who answered they have farm certificate, 0 for farmers who answered they do not have farm certificate, and "NA" for farmers who do not answer the questions; the answers from each farm were averaged to obtain the certificate index for each region.

Table 2
Survey response rates and the professional backgrounds of experts.

Region	Invited expert numbers	Total respondent numbers	Experts in institutional support (respondent numbers)	Experts in primary production (respondent numbers)	Experts in supply and service (respondent numbers)	Expert response rate
rDE	13	8	2	1	5	62 %
rLV	12	9	4	1	4	75 %
rNL	13	11	3	5	3	85 %
rES	10	10	2	2	6	100 %
rGR	12	10	3	4	3	83 %
rCH	10	10	5	1	4	100 %
rPL	15	14	4	10	0	93 %
Total	85	72	23	24	25	85 %

2.4. Data analysis

Survey responses on expert knowledge, and drivers and barriers were recorded in a Likert scale, and were treated as interval-level data to calculate mean and standard errors (Norman, 2010). This approach is commonly used in social sciences (Norman, 2010), where Likert scales with five or more categories often approximate interval properties under certain conditions (e.g., equidistant response options, symmetrical distribution). Survey responses on current and future adoption rates were recorded in percentage, and were then analyzed to calculate mean and standard errors. Analysis of variance tests were conducted to assess differences between regions in expert knowledge, current and future adoption rates, and drivers and barriers. Multiple comparisons were determined by means of Tukey post-hoc tests, and the statistical significance of differences between different groups are marked with different letters. Simple linear regression was conducted to assess the associations between each region's average farm size and the adoption rates of VRT. The responses to challenges and solutions were translated from local languages into English using "Google Translate" and "deepL". The accuracy of the translation was supervised by the local expert that facilitated the survey. Due to the uneven number of experts across regions, the normalized frequency (i.e. the frequency divided by the number of experts in each region, multiplied by 10) was calculated to assess the frequency of responses to challenges and solutions. The solutions to the challenges of different resource management aspects were classified into four categories: VRT, adapted cultivation techniques, policy changes, and other technologies. The analysis of variance, post-hoc test and linear regressions were conducted using R-functions agricolae::HSD.test and stats::aov (De Mendiburu, 2009). Analysis and imaging were conducted in RStudio (R Core Team, 2013).

3. Results

3.1. Expert knowledge

The average knowledge levels of experts on arable farming and VRT in our sample are 4.3 and 3.0, respectively (Fig. 2; different letters of a–b indicate the statistical significance ($P < 0.05$) of differences between regions). This indicates that they have very good perceived knowledge of arable farming and good perceived knowledge of VRT, despite slight variations in knowledge levels across experts from different regions.

3.2. Challenges and solutions in arable farming

Challenges relating to pest control – specifically, pesticide bans and weed/pest complexity – were the most frequently mentioned resource management challenges across all regions (Fig. 3), particularly in the German and Swiss regions. The second most important challenge was technology and resource cost, especially in the Polish and Swiss regions. The water management challenge was related to drought stress and water availability, which was mentioned more in the German and Spanish regions. The fertilizer management challenge was related to the amount and time of applying fertilizer, the choice of fertilizer types (manure or artificial fertilizer), farmers' worry about reduced fertilizer impacting productivity, and fertilizer reduction regulation, which was more pronounced in the Dutch and Spanish regions. The challenges related to stability, compatibility, availability of technology, as well as and farmers' knowledge in technology were most frequently mentioned in the Spanish and Swiss regions. Other challenges included environmental health and farm structure among others, with varied frequency across the seven regions.

VRT was just one approach, among others (adapted cultivation techniques, policy changes, other technologies), to deal with the challenges of resource management (Fig. 4; Fig. A1). VRT was expected to be more helpful for fertilization management than for weed/pest control

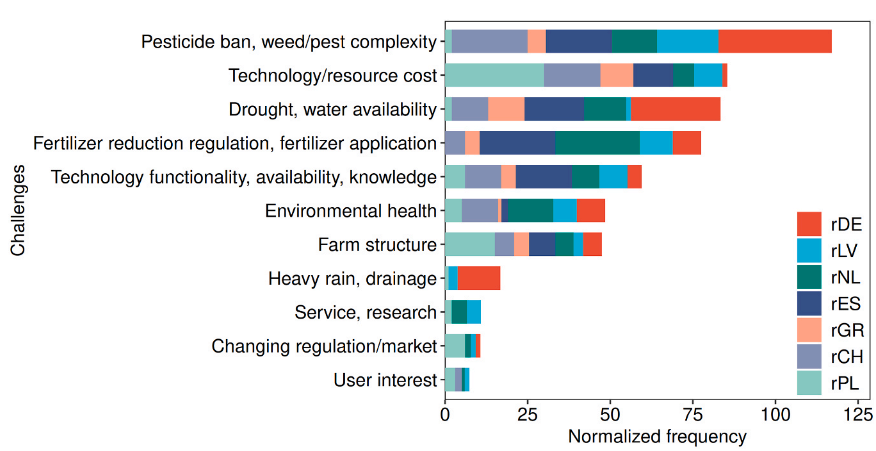

Fig. 3. Challenges of resource management in seven arable farming regions. Normalized frequency represents the frequency that experts mentioned the challenges divided by normalized expert numbers (expert numbers in each region / 10).

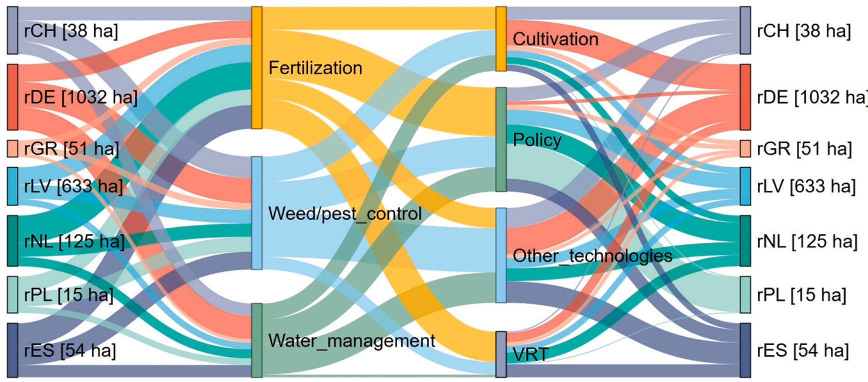

Fig. 4. Solutions to the challenges of resource management in seven arable farming regions: the first and fourth columns show the regions and the corresponding average farm size noted in "[]"; the second column indicates different resource management aspects mentioned by experts; the third column is the classification of solutions to the challenges. VRT, variable-rate technology. The width of a flow from a region category on the left column to a challenge category in the middle column reflects how frequently experts mentioned the challenges in relation to their corresponding regions. The width of the flow from a challenge category in the middle column to a solution category on the right column reflects how frequently experts mentioned the solutions to address their corresponding challenges.

and water management. Among the seven arable farming regions, VRT was expected to play a more important role in the Spanish and Dutch regions. Other technologies include crop breeding for weed-resistant and drought-tolerant crops, as well as autonomous and digital (satellite, sensor, camera, drone, and graphical user interface) technologies, which were more frequently mentioned in the German, Spanish, and Swiss regions. Policy-related solutions include services (training, consulting, contractor, research on field experiments, publicity, and promotion), subsidies, clearly defined long-term regulations, and market macro-control of technology and cultivation, which were more frequently mentioned in the Polish and Dutch regions. Cultivation-related solutions were more frequently mentioned in the German regions.

3.3. Adoption rates of VRT

Based on expert feedback from the seven arable farming regions, the current adoption of VRT across study regions is on average 11 % for fertilizer application, 2 % for weed/pest control, and 7 % for irrigation, and was expected to increase to 36 %, 23 %, and 13 %, respectively, in the next 10 years (Fig. 5a; different letters of a–e indicate the statistical significance ($P < 0.05$) of differences across managements and times (current or future)).

Approximated VRT adoption for fertilization was higher in areas with larger farms (Fig. A2; $P < 0.05$), including the German (32 %), Latvian (19 %), and Dutch (14 %) regions, where VRT adoption was expected to increase to 39–54 % in the future (Fig. 5b; different letters of a–d indicate the statistical significance ($P < 0.05$) of differences between regions for each management aspect). The most common VRT for fertilizer application was soil nitrogen sampling and analysis (21 %), which was expected to increase to 41 %, followed by software/platform (39 %), tractor-mounted sensors (32 %), and satellite (32 %) supported fertilization (Fig. 5c; the letters of a–f indicate the statistical significance ($P < 0.05$) of differences across technologies and times (current or future)).

Currently, the average adoption of VRT for weed/pest control was less than 4 % in all regions, whilst within 10 years substantially higher uptake was expected across all regions (Fig. 5b). The most widely used weed control method ($P < 0.05$; Fig. 5c) was the non-VRT method by hoeing/plowing (34 %), which was expected to increase to 46 %, followed by VRT pesticide spray with the support of robot/drone loaded sensors/cameras (20–25 %).

With less than 4 % adoption in other regions, VRT had the highest adoption for irrigation in the Dutch (17 %) and Spanish (23 %) regions ($P < 0.05$), which was expected to reach 32–36 % in 10 years (Fig. 5b). Spray (60 %) and center-pivot (25 %) irrigation supported by software/platform techniques (50 %) were commonly adopted in the Spanish region and was expected to be complemented by satellite (43 %) and soil moisture sensor information (31 %) in 10 years (Fig. A3). Spray irrigation (74 %) was widely used in the Dutch region, and was expected to be complemented by drip irrigation (39 %) with the support of soil moisture sensors (35 %) and software/platform technologies (33 %) in the future (Fig. A3), provided that the climate would become drier and irrigation demand would increase.

3.4. Drivers and barriers of VRT adoption

The high costs of VRT were identified as the strongest factor ($P < 0.05$) influencing VRT adoption (average impact level of 4.3 out of 5; Fig. 6a), followed by government regulations (4.0), subsidies (3.8), and the complexity to operate VRT (3.8). The answers of the experts from different professions were generally consistent (Fig. A4).

High costs and labor saving had a greater impact on VRT adoption for weed/pest control adoption than for fertilization ($P < 0.05$; Fig. 6b). Complexity had a greater impact on VRT adoption for weed/pest control than for water management. Government regulation and labor savings had a bigger role in VRT adoption for water management than for fertilization. Local availability, farm profitability enhancement, subsidy, neighboring farmers, user interest, contractors and consulting services had similar effects on VRT adoption for all three-resource management.

A distinct influence of factors was indicated across the regions ($P < 0.05$; Fig. 6b). For example, subsidies, local availability, and labor savings of VRT had the greatest impact in the Greek region, while in the Spanish region, government regulation was the most influential factor. User interests played an important role in the Latvian region, while contractors had the largest impact in the Swiss region. The cost, complexity of VRT, neighboring farmers, and consulting services had a similar level of impact across all seven regions.

4. Discussion

VRT and other precision agricultural technologies have been put forward as important tools to support shifts towards sustainable intensification (Späti et al., 2021; Gabriel and Gandorfer, 2023). The experts in our study confirm this potential, but they also see drawbacks and challenges, at least for the near future.

4.1. VRT application for different resource management challenges

In the regions we studied, the adoption of VRT for fertilizer

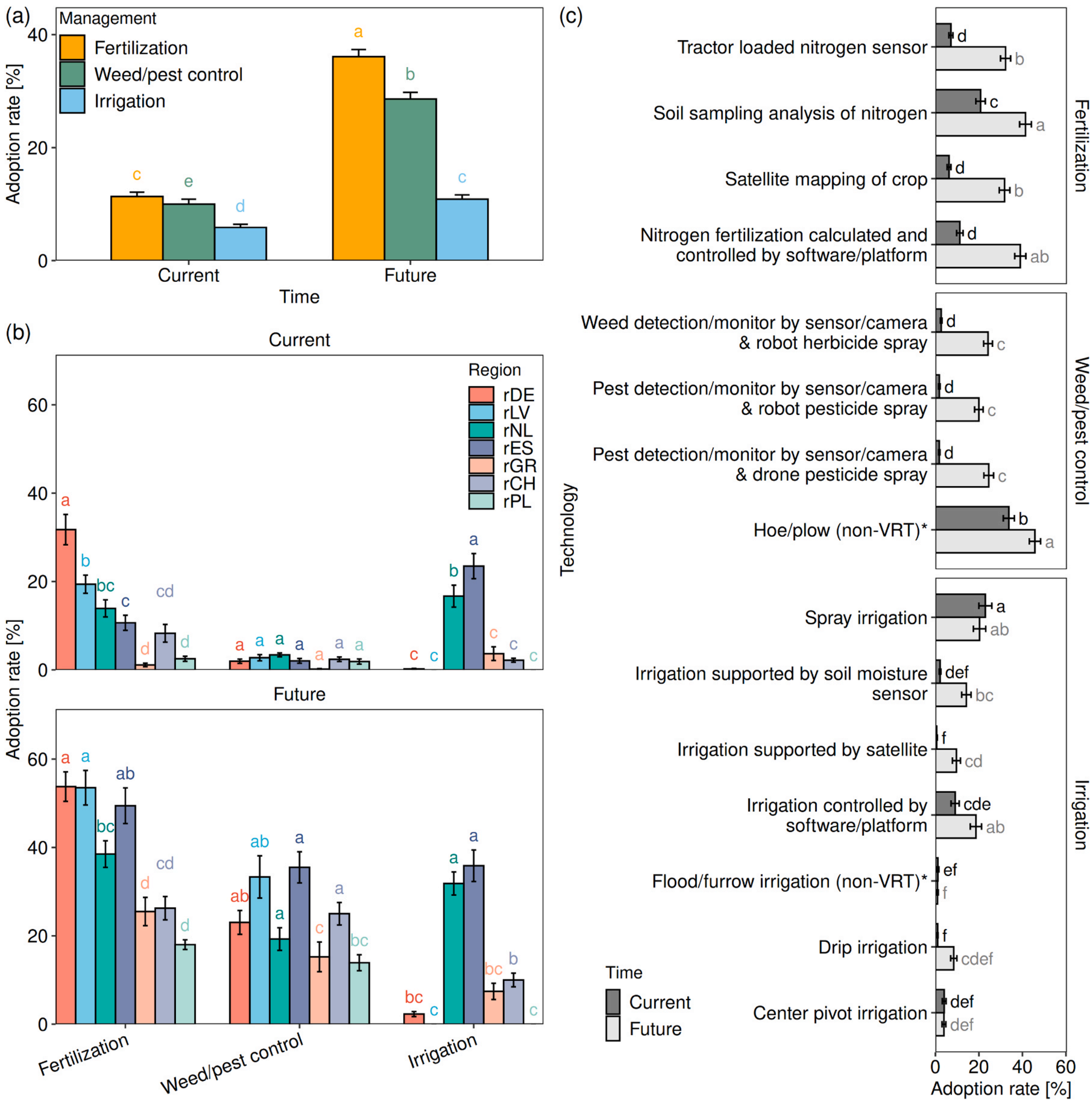

Fig. 5. Current and future adoption rates (mean and standard error) of variable rate technology (VRT) and non-VRT for fertilization, weed/pest controls, and irrigation. (a) Current and future (in 10 years or under drier climates) VRT adoption by different resource management aspects; the letters of a–e indicate the statistical significance ($P < 0.05$) of differences across managements and times (current or future). (b) Current and future VRT adoption by different resource management aspects and regions; the letters of a–d indicate the statistical significance ($P < 0.05$) of differences between regions for each management aspect. (c) Current and future adoptions of different technologies for resource management; the letters of a–f indicate the statistical significance ($P < 0.05$) of differences across technologies and times. For fertilization and weed/pest control technologies, future adoption indicates expert-prognosed adoption in 10 years. For irrigation technologies, future adoption means expert-prognosed adoption under drier climates.

application was seen as more promising than for weed/pest control and irrigation (Fig. 5). The adoption of pesticide VRT was also found to be lower than for fertilizer application in the US (Schimmelpfennig and Lowenberg-DeBoer, 2021). The prospect of uptake of VRT for fertilization is more likely on large farms (the German, Latvian, and Dutch regions) than by smallholders (Fig. A2; Adrian et al., 2005). Despite widespread legislation to reduce fertilizers in Europe (Sutton et al., 2011a), high N inputs were still observed in some areas (Leenstra et al., 2019; European Commission, 2023), including the Dutch and Spanish region in this study (Table 1). This corresponded to the frequently mentioned fertilization challenges in these regions (Fig. 3), and thus provides a motivation for the use of VRT to increase fertilizer use efficiency.

The requirement to protect water bodies and the soil environment (Batool et al., 2022), as well as the increasing cost of fertilizers (Fig. 5; Eurostat, 2022b; European Commission, 2023), require further reductions in fertilizer application, especially on arable land. This might make VRT more financially feasible by helping to offset the costs of implementing it. VRT can be effective in reducing fertilizer use based on the mapping of soil and crop demands (Robertson et al., 2012; Colaço and Molin, 2017; Nawar et al., 2017). Fertilizer VRT has been shown to save 30–40 % of N fertilizer on European arable farming (Fabiani et al., 2020; Argento et al., 2022). More efficient fertilizer application requires higher resolution soil and crop mapping supported by drones, but with increased investment in drone mapping compared to satellite mapping (Späti et al., 2021). The additional cost of high-resolution (2x2m) imagery compared to 10x10m satellite imagery is recommended to be no more than CHF 4.5 per hectare to maintain farm profitability on wheat-producing farms in Switzerland (Späti et al., 2021).

In the face of pesticide bans in Europe (Fig. 3;), and pesticide

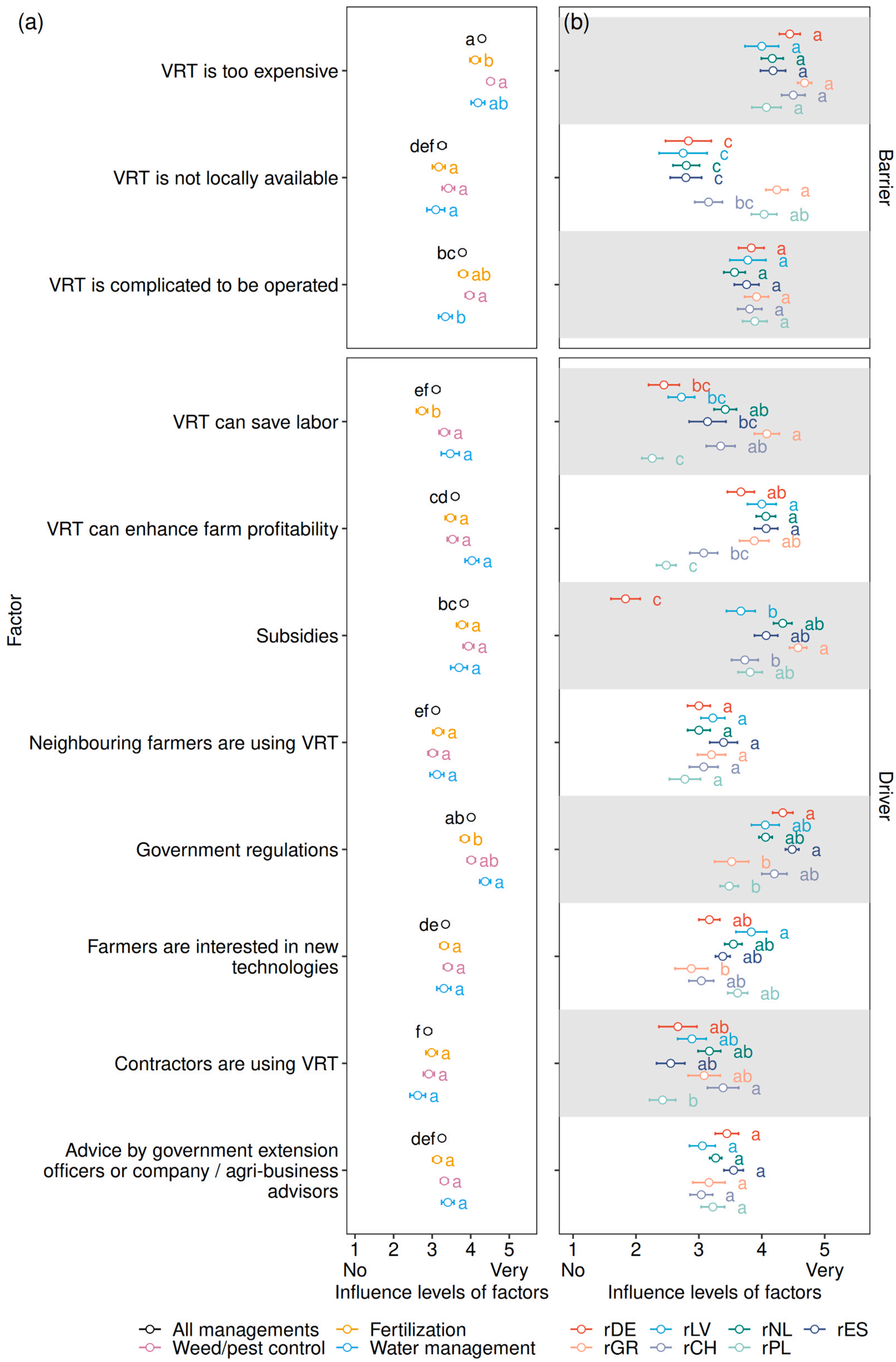

Fig. 6. The influence levels (mean and standard error) of drivers and barriers on variable-rate technology (VRT) adoption across seven arable farming regions in Europe: (a) Influence levels for each management aspect over all regions; the letters of a–f in black indicate the statistical significance ($P < 0.05$) of differences between factors across resource management issues, and the letters of a–b in orange, pink and blue indicate the statistical significance ($P < 0.05$) of differences between three management issues. (b) influence levels of each factor across regions, with the letters of a–c indicating the statistical significance ($P < 0.05$) of differences between regions for each factor. Influence levels were collected in ordinal Likert scales from 1 (no influence) to 5 (very influential), and were treated as interval levels for statistical analysis.

resistance in weeds (Fig. 3; e.g., Skevas et al., 2013), hoeing and plowing were the most common methods of weed control in our study regions and were expected to remain the most promising in 10 years (Fig. 5). Mechanical weed control reduces the risk of soil and water contamination, as well as pesticide residues in the crop, despite the potential negative effects on earthworms, spiders and beetles in the soil, soil erosion, and soil moisture loss (Tamburini et al., 2016; Sharma et al., 2017; Andreasen et al., 2022). The low adoption rate of VRT for weed/pest control can be attributed to immature decision algorithms for complex weed species identification (Jialin et al., 2019) and determining pesticide types and doses for different species (Gerhards et al., 2022). In addition, the lack of experimental evidence on the efficacy of the technology may lead farmers to be hesitant to adopt VRT for weed/pest control (Gerhards et al., 2022). Laser weeding robots are considered promising technologies to control weeds without the use of pesticides and without disturbing the soil (Li et al., 2022). These technologies use cameras and sensors mounted on unmanned vehicles to support artificial intelligence (AI)-based algorithms for weed, crop, and obstacle identification; different types of lasers, such as diode lasers, fiber lasers, and CO_2 lasers (Andreasen et al., 2022), are used to kill identified weeds (Li et al., 2022; ETH Zurich, 2022; Andreasen et al., 2022). However, the risks of laser weeding robots include laser effectiveness related to determine optimal timing for hiring costly laser weeding services, complexity of weed species, uneven field surfaces, crop-weed overlap, residue cover, dust, wind, and sun; and operational safety regarding fire risk, and damage to farmers and animal health from the laser beam (Osadčuks et al., 2020; Andreasen et al., 2022). Also, the legal framework for autonomous vehicles is still being discussed (e.g. liability issues, and data protection; Basu et al., 2020).

VRT irrigation can improve water use efficiency (Dukes and Perry, 2006; O'Shaughnessy et al., 2019) and help to cope with more frequent drought stress in Europe (Debonne et al., 2022; Nendel et al., 2023). Among the seven regions we studied, irrigation of arable land was rare in five regions, except for the Spanish region, where software/platform-controlled spray irrigation is predominant, and the Dutch region, where spray irrigation is commonly used (Fig. 5). However, among the arable farming challenges, drought stress was a common and frequently cited water management challenge in all seven regions of our study, especially in the German region (Fig. 3). The contradiction between drought stress and low VRT adoption for irrigation may be related to the lack of required irrigation infrastructure, water availability, and agricultural irrigation water withdrawal rights (Möck et al., 2022; Lehmann and Finger, 2013; Scherer et al., 2018). This is the case, for example, in the German region, where irrigation needs are urgent but the groundwater table is deep (60 m depth) and groundwater withdrawal flows are low (<2 L/s, which means that one groundwater well is required per 0.34 ha of farmland to achieve an irrigation rate of 5 cm d^{-1}; Müller et al., 2019). Investing in irrigation facilities is less profitable for arable farmers than for vegetable or potato growers. Thus, coping with drought stress requires a combination of improved irrigation technology and state-supported irrigation infrastructure, and the granting of water withdrawal rights.

4.2. Framework conditions that enable and support VRT

The technology-related challenges of arable farming include high costs, complexity, incompatible operating systems, and uncertain efficacy of new technologies (Fig. 3; Fig. 6). As one of the precision agricultural technologies, VRT needs to be supported by satellites, as well as digital technologies including sensors, computers, robotic systems, and cloud-based decision models, among others (Khanna, 2021). In addition to the costs of the technologies mentioned above, investments in technology include the knowledge costs of technical training and education, and the capital costs of localized knowledge for resource applications (Khanna, 2021). The complexity of VRT and other precision agricultural technologies makes it difficult for farmers to operate new machines, which requires the support of training in technology operation (Pathak et al., 2019). In addition, it is recommended that technology producers integrate off-the-shelf software packages (Khanna, 2021) that address farmer-specific issues, temporal and spatial variability in crop management, and technical stability under extreme weather conditions and special terrain; and integrate weather forecasting models (Ukhurebor et al., 2022). Free and open platform services can break monopolies and provide easy access to consulting for localized problems (Deichmann et al., 2016), especially for smallholder farmers who currently have poor access to information (Magesa et al., 2020, Jones-Garcia and Krishna, 2021).

The adoption of VRT and other precision agricultural technologies requires long-term state support in terms of price macro-regulation, subsidies, internalization of environmental costs (e.g., by taxing fertilizers and pesticides), and clearly defined long-term regulatory frameworks (Fig. 3). Due to the high cost of precision agricultural technologies (Fig. 3; Fig. 4; Fig. 6), it is currently not cost-effective for smallholder farmers to purchase them (Fig. 5; Bhakta et al., 2019), unless they form collaborative schemes (Haughey et al., 2023). Uncertainty about markets, regulations (Zahraee et al., 2022), and outcomes (Barnes et al., 2019) make farmers hesitant to adopt new technologies. In particular, in the Polish study region, farmers were affected by increased grain imports from Ukraine (EURONEXT, 2023) during our survey period in March 2023, and grain prices decreased. However, the potential benefits of VRT are becoming more promising as the additional cost of fertilizer application using VRT is reduced compared to broadcast fertilization (McClure, 2018; McClure, 2022). Subsidies can build awareness and reduce financial risks and thus facilitate the uptake of new technologies (Omotilewa et al., 2019). The actual efficiency of subsidies depends on the type of subsidy (e.g., input or output-oriented subsidies; environmental or technology subsidies), and the efficiency of technology conversion (Chen et al., 2020). In addition, uncertainty in farmers' behavior makes it difficult to sustain the governments' initial intention of technology diffusion. The experts in our study mentioned that some farmers, who received technology subsidies, abandoned the new machines they purchased within 1–2 years and sold them to contractors. This may be because the new technology did not achieve the expected outcome for the farmers, or that unobservable outcome left farmers with a lack of motivation to learn the operation of complex technologies (Chavas and Nauges, 2020). The support of localized consulting services, as well as experimental evidence of long-term technology efficacy can mitigate farmers' operational uncertainty (Martin et al., 2016; Hijbeek et al., 2019).

4.3. Substitutes and limitations of VRT

Besides the high cost and complexity of VRT (Fig. 4; Fig. 6), low adoption of VRT can also be related to the substitute measures of VRT. Crop breeding, crop rotation, and special crop cultivation are alternative solutions to improve resource use efficiency (Fig. 4; Fig. A1). In addition, agroecological measures such as reduced tillage and buffer strips can improve agricultural sustainability that cannot be reached by VRT.

The crop-livestock cycle is suggested as a solution to stabilize the regional N cycle (Hilimire, 2011; Catarino et al., 2021; Bayram et al., 2023). Slow-release fertilizers (e.g., nano-nitrogen chelates, sulfur-coated nano-nitrogen chelates, and sulfur-coated urea) can reduce nitrogen leaching by 10–46 % compared to urea fertilizers (Zareabyaneh and Bayatvarkeshi, 2015). Green manure is an agroecological approach that improves soil fertility through atmospheric nitrogen fixation (Olesen et al., 2009; Hijbeek et al., 2019) while reducing nitrogen leaching, greenhouse gas emissions (Hansen et al., 2019), and weed pressure (Melander et al., 2020). Fertilizer reduction is more problematic in areas facing soil health issues. For example, to reduce soil salinity, soil leaching has been carried out in some areas (Raats, 2015), including our Dutch study region. Saline leaching reduces soil fertility, so arable land requires more fertilizer applications to maintain crop yields (Daliakopoulos et al., 2016). An integrated approach to address soil salinity and fertility needs to be developed when implementing fertilizer reduction legislation.

More effective, easier, and cheaper weed/pest control solutions such as mechanical weed control, genome-editing of crops (Ricroch, 2019; MacLaren et al., 2020), crop rotation (Hunt et al., 2017), and green manure (Melander et al., 2020) could limit VRT's adoption. GM crops have lower public acceptance in Europe and Africa compared to Asia and the Americas (Qaim, 2020). In contrast, non-GM crops, such as genome-edited crops, can be alternative crop breeding methods for weed/pest control (Georges and Ray, 2017; Möhring et al., 2020) that may have higher acceptance than GM-crops in Europe. Crop rotation diversification is effective at maintaining crop yields and reducing weed pressure, complemented by low herbicide application (Hunt et al., 2017). Rotation with green manure was found to reduce weed seeds by 54 %, but weed pressure increased after green manure crop cultivation was terminated (Melander et al., 2020). In addition, cover crops can reduce weed pressure (Gerhards and Schappert, 2020) and provide a habitat for beneficial arthropods that act as natural enemies of weed seeds and other pests (Pekrun et al., 2023). Also, cover crop residues can reduce soil moisture loss via evaporation (Pekrun et al., 2023). However, cover crops can occasionally serve as alternative hosts for pests (Pekrun et al., 2023). Local experiments and field guides are needed to improve the efficiency of crop cultivation for weed and pest control in the farmers' actual local contexts. The operationalization and improvement of Agricultural Knowledge and Innovation Systems (AKISs), currently obligatory under CAP 2023–2027, can also support innovation adoption (Kountios et al., 2024).

In addition to the adoption of water-saving VRT for irrigation, our experts express the urgency of state-funded irrigation infrastructure such as dam construction (Fernandez et al., 2014), rainwater harvesting (Cipolletta et al., 2021), and irrigation water distribution systems. New European regulations on minimum quality requirements for water reuse (EU, 2020/741) regulate the use of reclaimed water for agricultural irrigation (European Commission, 2020), but lack public acceptance due to concerns about food security (Baawain et al., 2020). However, the use of treated greywater is perceived more favorably in drought-prone regions or for the cultivation of non-food crops (Silva et al., 2023). Breeding drought-tolerant crop varieties or introducing new crop types (e.g., sorghum in temperate regions) can help farmers to face more frequent drought stress (de Vries et al., 2020) without further investment in irrigation facilities.

Agroecological approaches such as reduced tillage (Armengot et al., 2015), flower strips, hedgerows (Albrecht et al., 2020), and agroforestry (Herzog, 2022) can complement VRT to address future challenges in arable farming. In contrast to rotary tillage and plows that support mechanical weed control, reduced tillage can reduce greenhouse gas emissions, soil water loss and erosion, and improve carbon sequestration and biodiversity (Armengot et al., 2015), but has the potential to increase weed pressure because weed seeds are exposed at the surface rather than buried underground through rotary tillage (Pekrun et al., 2023). This may increase farmers' workload to control weeds and pests. Flower strips and hedgerows can provide a source of pollinators, increase species diversity, and contribute to natural pest control (Albrecht et al., 2020). Arable agroforestry systems (e.g., alley cropping) may reduce soil erosion, enhance water quality and increase carbon sequestration and biodiversity (Palma et al., 2007, Kay et al., 2019; Giannitsopoulos et al., 2025). In our study regions, regulated buffer strips are mentioned to be too wide for the limited farmland. Therefore, more localized experiments and studies are needed to minimize trade-offs between farmers' profitability and environmental protection and to approve the profitability of agroecology (De Leijster et al., 2020), which can be complemented by greening agricultural subsidies (Levidow, 2015).

4.4. Limitations of the study

In this study, we explored the potential of VRT to promote sustainable intensification of agriculture through an expert online survey. We investigated a diversity of arable farming systems regarding their geographical locations, farm size, and intensity levels, but they may not statistically represent the full spectrum of European arable farming (Diogo et al., 2023). A major limitation of our study is, therefore, the lack of up- and outscaling or generalization possibilities.

Our estimation of VRT adoption is based on the experience from local experts on their knowledge of our case study regions. Due to the unavailability of official local data, it was not feasible to gather the information on VRT adoption from official statistics or industry reports. Farm-scale surveys can indicate the existing adoption rates, but are not applicable for indicating the potential of VRT at regional scales, due to the limited knowledge of farmers beyond their own farm. Existing tools like ADOPT (Kuehne et al., 2017) have been shown to be effective in predicting the adoption trends of new practices in a wider range of industries. However, their broad applicability does not align with the specific focus of our study, which examines the potential of VRT in addressing local arable farming challenges. In a previous study, we indicated the matches and mismatches between farmer interviews and expert surveys regarding the past and future uptake of technologies (Li et al., 2025). Expert surveys are thus a pragmatic solution for gaining insight about regional technology trends, but may not always reflect the full complexity of farmers' decision-making (Parra-López et al., 2025).

When designing the questionnaire, emerging technologies (e.g., laser weeding robots) that are not yet commercially available were excluded based on feedback from peers and local partners, because estimating the adoption of such technologies at the local scale is premature and lacks practical relevance. Our survey opinions captured in 2022–2023 represent a snapshot in time and may soon be outdated when new technologies become available on the market.

Our survey invited diverse stakeholders who offered both holistic and practical perspectives on local agricultural systems and play a vital role in farm-level practices, resource allocation, and decision-making. Though experts' background had no statistically significant effect on their survey responses, the unbalanced distribution of expert professions in our survey might affect the results. Other stakeholders like consumers, environmental NGOs, scientific communities, technology designers, and industrial communities were not involved. This decision was made based on the situations that these stakeholders, who have in-depth knowledge of local agriculture, were not available in each case study region.

5. Conclusion

Based on the results of an online survey of experts from seven European arable regions involved in primary agricultural production, services, and research, we present prospects for the adoption of VRT in European farming, factors for the uptake of VRT, and the potentials and limitations of VRT for addressing local challenges in European farming. We concluded that:

(1) The adoption of VRT for fertilizer application is more promising than for weed/pest control and irrigation. The adoption of VRT for fertilizer application is expected to be higher among large-scale farmers. VRT adoption for weed/pest control will probably be lower than the adoption of non-VRT measures such as weed control by hoeing/plowing. Despite frequent mentions of drought stress challenges, the adoption of VRT for irrigation was generally expected to be low, which is linked to water availability and withdrawal rights constraints, rather than innovations in irrigation technology.
(2) High costs, government regulations, subsidies, and VRT complexity are the top factors that influence the adoption of VRT

in European arable farming. Overcoming these barriers may require a combination of policy instruments, for example: i) tax breaks, low-interest loans, and credit guarantees to help farmers manage the high upfront costs of VRT systems; ii) simplified regulations streamlining interoperability, standardized data formats, and clear rules around data ownership and privacy; and iii) training, advisory support, and demonstration projects for addressing knowledge gaps and complexity of technology use. Different instruments may have to be prioritized according to the specific agricultural contexts in a region.

For example, these barriers can more easily be dealt with by large farms with capacity to employ specialized personnel and afford training programmes. In regions characterized by small farms, service providers and cooperatives for agricultural machinery may play an increasingly important role for supporting the implementation of VRT. Future research on VRT should thus be guided by farmers' needs and the pressing challenges they face, rather than by technological possibilities that, while intriguing, may lack practical relevance.

Our findings suggest that VRT alone is insufficient to drive the paradigm shift toward sustainable intensification. VRT can contribute, but only in combination with other digital and autonomous technologies, cultivation and agroecological management, as well as policy support. Further, we found a diversity of challenges across the different arable farming regions, underscoring that technology — and the policies supporting such technology — needs to be tailored to address local contexts and challenges.

CRediT authorship contribution statement

Franziska Mohr: Writing – review & editing. **Vasco Diogo:** Writing – review & editing. **Tim G Williams:** Writing – review & editing. **Christian Levers:** Writing – review & editing. **Michael Beckmann:** Writing – review & editing. **Rigas Zafeiriou:** Writing – review & editing. **Víctor Rolo:** Writing – review & editing. **Felix Herzog:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition. **Jeanine Ammann:** Writing – review & editing, Methodology. **Julian Helfenstein:** Writing – review & editing, Methodology. **Józef Hernik:** Writing – review & editing. **Kozos Thanasis:** Writing – review & editing. **Yafei Li:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Consent for publication

This study does not need publication consent.

Consent to participate

This study does not need participating consent.

Code availability

Custom code is available from the corresponding author on reasonable request.

Ethics approval

This study does not need ethical approvement.

Funding

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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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Appendices

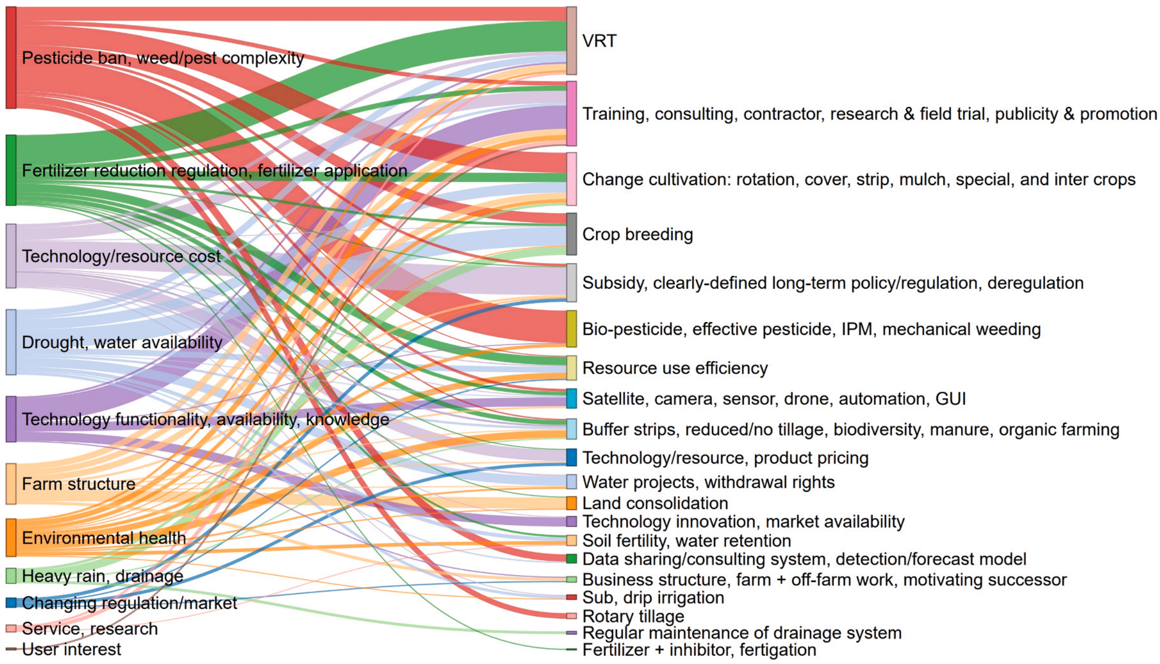

Fig. A1. Solutions to the challenges of arable farming. VRT, variable-rate technology. GUI, graphical user interface. The width of a flow from a challenge category on the left column to a solution category on the right column reflects how frequently experts mentioned the solution to address their corresponding challenges

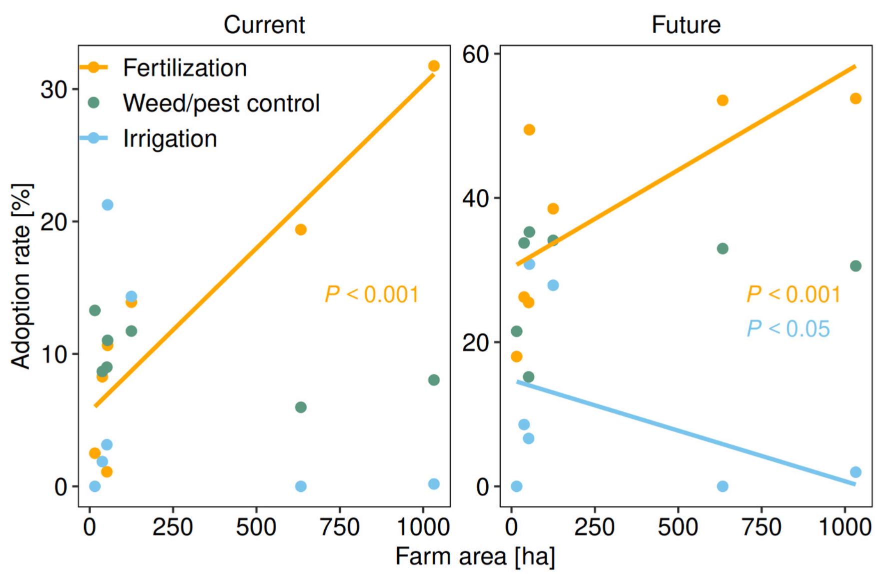

Fig. A2. Correlation of farm area with the adoption rates of variable-rate technology (VRT) for fertilization, weed/pest control and irrigation. Linear regression indicates statistical significance ($P < 0.05$, $P < 0.01$ or $P < 0.001$) of the corresponding items, and the statically insignificant regressions are not plotted

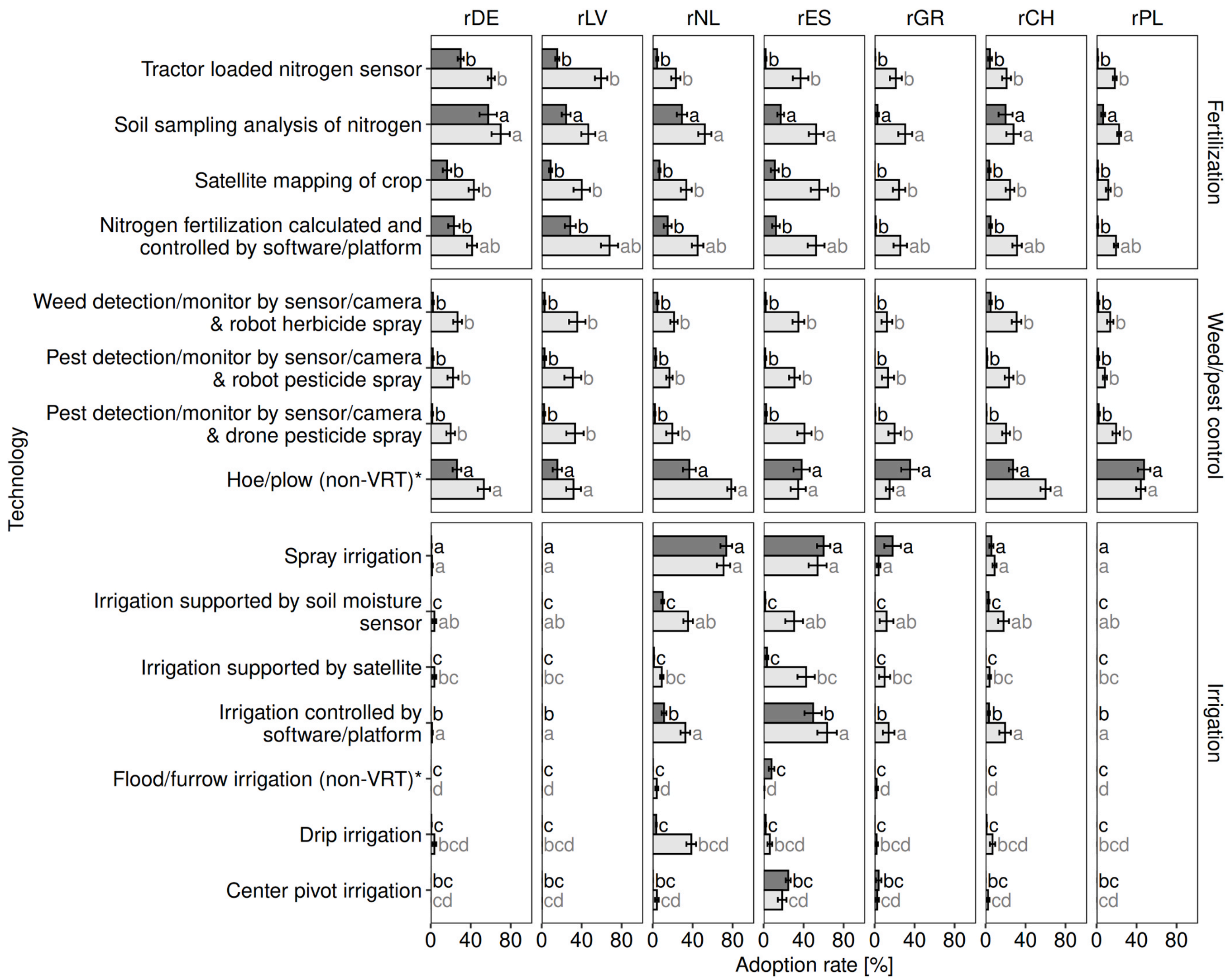

Fig. A3. Current and future adoption rates (mean and standard error) of variable rate technology (VRT) and non-VRT for fertilization, weed/pest controls, and irrigation. The letters of a–d indicate the statistical significance ($P < 0.05$) of differences between technologies for each region and each management aspect. For fertilization and weed/pest control technologies, future adoption indicates expert-prognosed adoption in 10 years. For irrigation technologies, future adoption means expert-prognosed adoption under drier climates

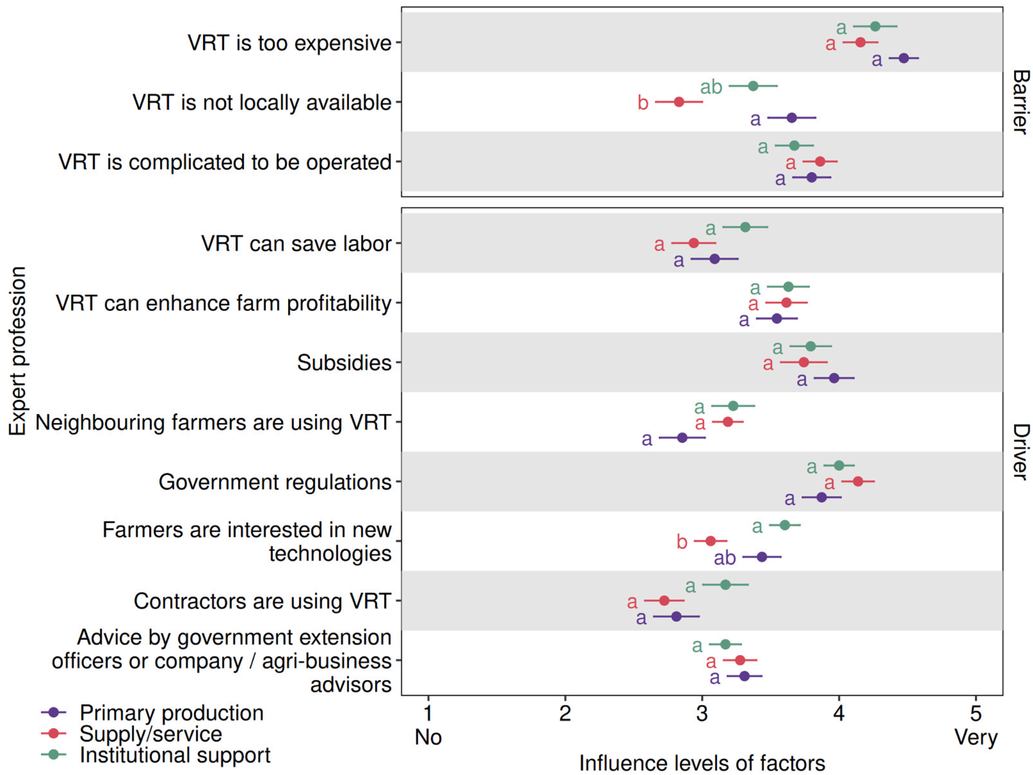

Fig. A4. The influence levels (mean and standard error) of drivers and barriers on variable-rate technology (VRT) adoptions depending on the expert professions. The letters of a–b indicate the statistical significance of each factor across expert professions. Influence levels were collected in ordinal Likert scales from 1 (no influence) to 5 (very influential), and were treated as interval levels for statistical analysis

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2025.127868.

Data availability

Data will be made available on request.

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