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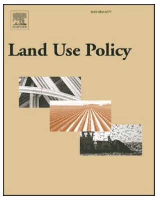

Agroecological and technological practices in European arable farming: Past uptake and expert visions for future development

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ABSTRACT

Agroecological and technological innovations are two important approaches in the transition towards agricultural sustainability. We lack knowledge about how current agricultural contexts may influence future development pathways and the relative importance of the two approaches. This study explores the alignment between past uptake of agroecological and technological practices and future visions of agricultural development in seven European arable farming systems. By combining landscape mapping with farmer interviews, we first assessed the past adoption of agroecological and technological practices in each region. Then, we compared our findings with expert surveys about the future directions of agricultural development that can address local arable farming challenges. We found that in regions with intensive arable farming, agroecological approaches lagged behind the uptake of technological measures, both in the past and in future prospects. In low-intensity regions, we found large gaps between past uptake and future prospects of agroecological and technological practice adoption. These gaps need to be overcome in the context of future challenges of climate change adaptation and of environmental obligations. Our results indicate the need to take differentiated measures depending on farm management intensity and landscape conditions to enhance the future uptake of agroecological and technological solutions that can address the local challenges.

1. Introduction

Agricultural production is facing challenges of increasing food demand, climate change, environmental degradation, and biodiversity loss among others (Howden et al., 2007; Tilman et al., 2011; Kehoe et al., 2017; IPCC, 2022). The predominant direction of agricultural development has been conventional intensification with the main objective of bolstering agricultural production, often incurring biodiversity loss and failing to address other challenges (Beckmann et al., 2019). To meet the demands of improving productivity while also increasing the provision

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of other ecosystem services, sustainable agriculture has come to the fore (Hobbs et al., 2008; Roy et al., 2024). Among the pathways to reach sustainable agriculture, both agroecological approaches and technological improvements have received prominent attention (Ewert et al., 2023; Sullivan, 2023; Dassou et al., 2024). Agroecology is a bottom-up and territorial process involving principles such as diversification, external input reduction, and alternative market channels among others; it is often labor and time intensive (Dumont et al., 2018; FAO, 2018a). As of 2020, around 30 % of farmers worldwide adopted agroecological practices (Gliessman; 2020). Agroecological practices have been shown to increase farmers' income through strategies of diversification, external input reduction, and alternative market channels among others (FAO, 2018b). Technology development, in contrast, is largely a top-down approach to save inputs, time and labor, and improve productivity by means of more efficient and smart machinery and management systems (Dumont et al., 2018; Ruzzante et al., 2021; Moreno et al., 2024). Technology is adopted globally, and the adoption and benefits of technology vary by technology types (Barnes et al., 2019).

In the past decades, since the green revolution (Pingali, 2012), the two approaches of agroecology and technology development were opposed, with prevailing agricultural development prioritizing technology over agroecological approaches (Altieri, 1989), e.g., through larger farm machinery, mechanization, and automation. More recently, the two paradigms are now seen as potentially aligning, with agroecological practices, such as introducing landscape features (Apan et al., 2002; Jeanneret et al., 2021) and cropping adaptation (Materne and Siddique, 2009; Gerhards and Schappert, 2020) being supported by digitalization and breeding technologies among others (Gliessman, 2013; Maurel and Huyghe, 2017; Mao et al., 2024; Salse et al., 2024). This change in perspective raises questions about how the past adoption of agroecological and technological development may influence their future uptake.

In this paper, we focus on European arable farming, which faces urgent sustainability issues. Farmers are facing new challenges under changing climates, regulations, and markets (Tomek and Peterson, 2001; Niles et al., 2013; Debonne et al., 2022). Hence, it is vital to envision what kinds of solutions to those challenges – agroecological and/or technological – can be expected. Assessing agroecology and technology together can help to identify complementarities between these historically opposed paradigms.

Our objective is to understand how the previous roles of agroecological and technological developments relate to the perceived developments needed to cope with the future challenges of seven European arable farming regions in Switzerland, Germany, Spain, Greece, Latvia, the Netherlands and Poland. In fact, empirical evidence that relates the past uptake and future directions of agroecological and technological practices in European arable farming is lacking (Huang and Cassatella, 2024). However, based on the theory of "increasing returns to adoption" (Arthur, 1989; Meynard et al., 2018; Farstad et al., 2021; Williams et al., 2024), we hypothesized that future agroecological and technological practice adoption will match their past uptake, and the past uptake and future envisioned practices are linked to local farming systems, with technological innovations playing a larger role in high farm intensity regions. We adopted a combined farm and landscape scale approach to capture the interaction between the two. Firstly, we characterized changes in farm and landscape structure over the past two decades and evaluated farmers' uptake of agroecological and technological practices. Secondly, we asked experts in the respective regions to identify the main future challenges for arable farming, and the solutions that they expect to be adopted. This allowed us to evaluate the alignment of past trends with expected future pathways of agricultural change in the study regions.

2. Materials and methods

2.1. Case study regions

Combining the methods of landscape mapping with farmer interviews and expert online-surveys (Fig. 1), we conducted this study in seven arable farming regions, including a Swiss (rCH in the Reuss valley region), German (rDE in the Querfurter Platte region), Spanish (rES in the Santa María del Páramo region), Greek (rGR in the Lemnos region), Latvian (rLV in the Lielvircava region), Dutch (rNL in the Flevopolder region), and Polish (rPL in the Powiat Miechowski region) region, respectively. The regions were part of a larger sample of case studies that also involved other farm and landscape types and that had been selected to analyze their development pathways, partly relating to investigations conducted 20 years ago (Billeter et al., 2008; Helfenstein et al., 2024). They are not necessarily representative of the countries they are located in and thus do not represent European arable farming in a statistical sense, but the case study regions generally reflect the diversity of European arable farming in terms of factors such as geographical locations, landscape features, farm sizes, and intensity levels (Diogo et al., 2023). Analyzing multiple case studies is a common approach in research on agricultural systems that requires context-specific empirical data collection (Diogo et al., 2023).

The rCH region "Reusstal (Reuss valley)" is an agricultural area next to nature conservation and residential areas (Helfenstein et al., 2022a). The rDE region "Querfurt" and rLV region "Lielvircava" are intensive arable areas with fertile soils, and still mirror the large-scale farming structures introduced during collectivization by communist governments in the 1950s (Mohr et al., 2023). The rES region "St. Maria del Paramo" was strongly impacted by a farm consolidation program in 2012, aiming at modernizing the irrigation facility from flood to subsurface drip irrigation (Berbel et al., 2019). In the rGR region "Lemnos", there are traditional low-input and mixed farms (Dimopoulos, 2019; Dimopoulos et al., 2023). The rNL region "Flevopolder" is a recently (1955–1968) created agricultural landscape in a large polder that was reclaimed from the sea (Mohr et al., 2023). The rPL study region "Powiat Miechowski" is located in the province of Małopolskie that is strongly affected by land abandonment (Grontkowska, 2021; Mohr et al., 2023).

In each case study region, we selected an arable landscape of 25 km^2, which is representative for the geography and agricultural practice of the larger region. Within each case study region, we employed three research approaches. Firstly, we evaluated landscape changes in the past two decades, based on a comparison of aerial photographs between (roughly) the years 2000 and 2020. Secondly, we interviewed farmers about their past and current practices and derived indicators for the intensity of management. Thirdly, we conducted an online survey with local experts on future challenges of arable farming in each region (Fig. 1).

2.2. Landscape mapping

Habitat diversity and the amount and configuration of semi-natural habitats (here termed "landscape features") are indicators of biodiversity (Brusse et al., 2024). Landscape features extracted from aerial photographs can provide valuable retrospective information in the absence of ecosystem services valuation datasets.

We digitized landscape maps of 25 km^2 (Fig. A1) from orthophotos (aerial photographs, geometrically corrected) of two decades ago and from recent years for comparison. The historical photographs stemmed from 1998 for rCH, 2000 for rNL, 2002 for rES, 2003 for rGR, rLV and rPL, and 2006 for rDE; and the recent photographs stemmed from 2017 for rCH, rES, rGR, and rLV, 2018 for rDE, 2019 for rPL, and 2020 for rNL.

The spatial resolution of the orthophotos was around 50 cm or less. Hedges and tree rows were mapped as lines (minimal mapping unit 40 m) and the other habitats were mapped as polygons (minimal mapping unit 25 m^2). The land cover classification was based on the EUNIS

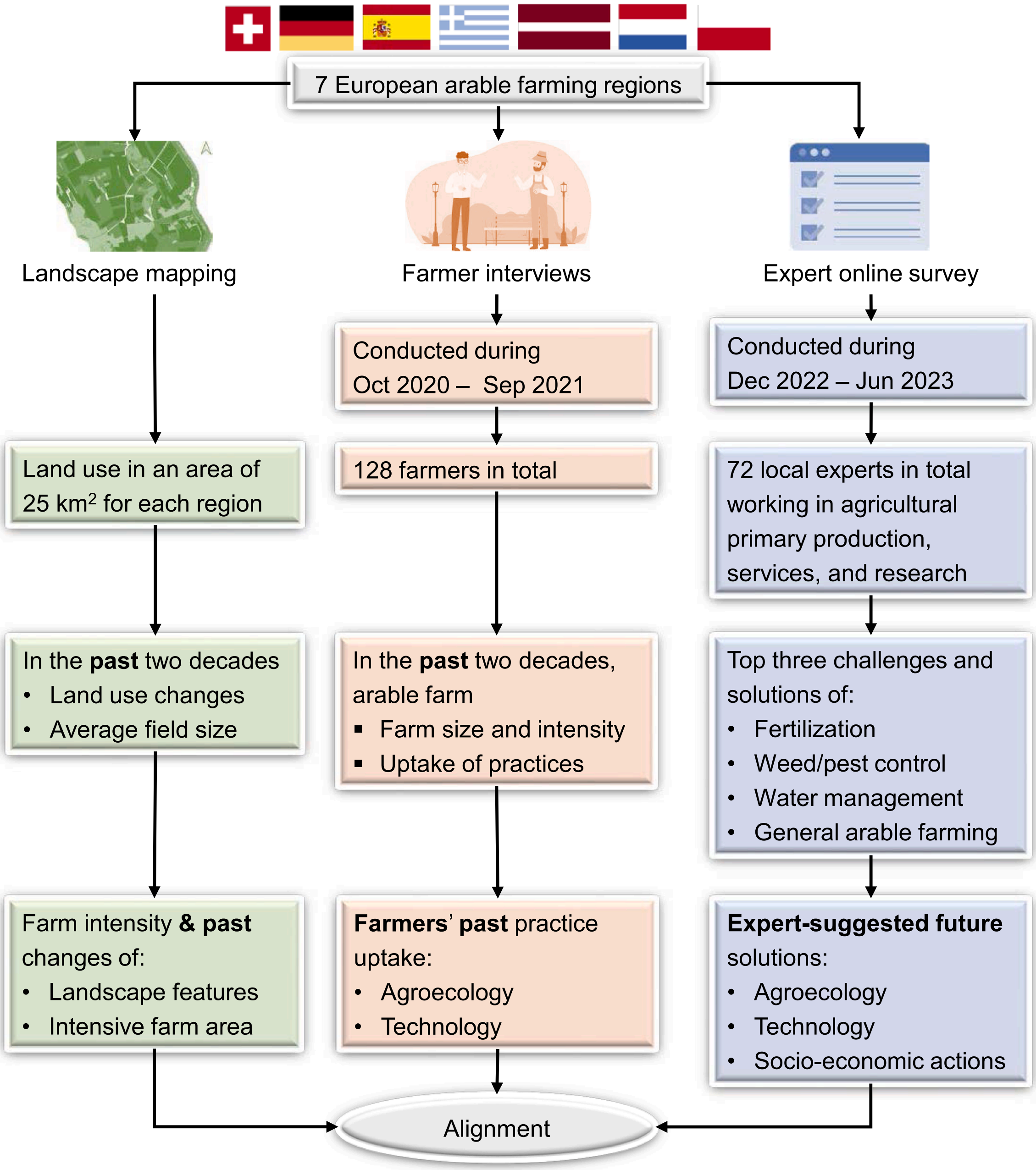

Fig. 1. Schematic diagram of the research methodology.

classification (EEA, 2019) and interpreted as land use for landscape features (small fragments of natural or semi-natural vegetation in agricultural land; Czucz et al., 2022), intensive farm areas, water bodies and settlements (for more details see Helfenstein et al., 2024). Landscape features were classified into the following land-use types: barren land, extensive grassland, field margin vegetation, forest, high-stem orchard, unused land, and wetland (Herzog et al., 2017). Intensive farm areas include the following land-use types: crops, intensive grassland, intensive olive grove, intensive orchard, shrub plantation, and vineyard.

2.3. Farmer interviews

We planned to interview 15–20 farmers in each case study region from October to November 2020, but the plan was postponed by the second wave of Covid-19. In the end, we conducted farmer interviews between October 2020 and September 2021, with 14–21 farmers from each case study region (20 farmers for rCH, rES and rPL regions; 19 farmers for rGR and rNL regions; 15 farmers for rDE region; and 14 farmers for rLV region). The selection of farmers was primarily based on their locations within our study area. But for case study regions with a limited number of interview partners because of larger farm sizes (rDE, rLV, and rNL), neighboring farmers operating in a similar landscape were involved. The questionnaires were translated into the respective languages and validated by the local partners, who conducted the interviews either personally or by telephone. In total, we interviewed 128 farmers about their farm size and intensity, and their uptake of agricultural practices in the past two decades (for more details see Helfenstein et al., 2022b and Helfenstein et al., 2024; Swart et al., 2024 submitted).

We calculated farm intensity following Helfenstein et al. (2024) based on average intensity ranks of the following four indicators as at the survey date (in 2020 or 2021): N fertilizer use on the main crops, number of pesticide applications on the main crops, livestock density, and feed import (percentage of feed from retailer multiplied by livestock units), all normalized from 0 to 1.

The questionnaire of farmer interviews was approved by the Ethical Commission of ETH Zurich (ETH-EK 2020-N-146).

2.4. *Expert online-survey*

We conducted expert online-surveys between December 2022 and June 2023 in local languages via the "SurveyHero" platform (Fig. 1). The questionnaires were translated into the respective languages and validated by the local partners. We initially planned to invite 10–14 experts from each case study region, aiming for a balanced representation of 3–5 experts specializing in agricultural production, supply/service, and institutional support each. However, due to the limited availability of candidates with in-depth knowledge of local arable farming, this could not be achieved in each study region. In total, 85 experts agreed to participate in the survey, with 72 successfully submitting their responses. Ultimately, 8–14 respondents per study region could be analyzed, with uneven professional distribution of experts across the regions (Fig. A2a).

In the online-survey, we asked the experts to provide their professions in agricultural domains and assess their knowledge levels in arable farming on a scale ranging from 1 (no knowledge at all) to 5 (know very well). The average knowledge level of experts in our samples was 4.3, indicating that they had very good knowledge in arable farming, and were eligible for the survey (Fig. A2b). Further, we asked experts to list three challenges and corresponding solutions in their respective regions regarding fertilization, weed/pest control, water management and arable farming in general. We also asked about solutions to the toughest regional challenges identified in the farmer interviews (i.e., water management and weed/pest control in rDE region, and fertilization in rES and rNL regions). We translated the experts' responses to challenges and solutions using "Google Translate" and "deepL", and the translations were reviewed by the local partners.

The questionnaire of the expert online-surveys was also approved by the Ethical Commission of ETH Zurich (ETH-EK 2020-N-146).

2.5. *Assessment of agricultural practices*

Farmers' past uptake of agricultural practices includes various agroecological and technological approaches. Accordingly, we classified expert-suggested future solutions as relating to either agroecology, technology, or additional socio-economic actions (Table 1). The agroecological and technological practices included in this study only encompass the aspects that were adopted by farmers or suggested by experts, but do not encompass all elements of agroecology or all types of technology.

We assessed how farmers' past uptake of practices matched with expert-suggested future directions of practice adoption by quantifying their co-occurrence. Given the past uptake rate of practices by farmers as F_{past}, and the future suggesting rate of practices by experts as F_{future}, the co-occurrence is expressed as:

$$\text{Co}-\text{occurrence} = \begin{cases} \dfrac{F_{\text{past}} + F_{\text{future}}}{2}, & F_{\text{past}} \neq 0 \text{ and } F_{\text{future}} \neq 0 \\ 0, & F_{\text{past}} = 0 \text{ or } F_{\text{future}} = 0 \end{cases} \tag{1}$$

The co-occurrence score for a particular practice thus takes values between zero and one; it is one if mentioned by all farmers and other experts, 0.5 if mentioned by half of either farmers or other experts, and zero if not mentioned by anyone.

Table 1

Classification of agricultural practices and their descriptions. These encompass the practices that were adopted by farmers or suggested by experts, but do not encompass all elements of agroecology or all types of technology.

Classification	Agricultural practice	Description
Agroecology	Biological weed/pest control	Sterile flies, integrated pest management (IPM)
	Cropping adaptation	Crop rotation, intercrop, green manure
	Management of landscape elements	Flower strips, natural area, barren land, trees and hedgerows
	Mechanical weed/pest control	Mechanical weeding, insect trapping
	Organic farming	Organic farm, farm label
	Organic fertilizer	Compost, slurry, manure
	Soil conservation	Reduced tillage, no-tillage, minimum tillage
Technology	Crop breeding	Disease-resistant crop breeding
	Environment monitoring	Weather forecast model
	Machinery, digital, precision, automation in general	New tractor, GPS, Real Time Kinematics (RTK),
	Precision fertilization	Dribble bar system, N-sensor, fertilization mapping, soil analysis, precision spreader
	Precision irrigation	Overhead spray
	Precision pesticide spray	Reduced drift sprayer, GPS-supported sprayer, automatic sprayer, weeding robot
	Renewable energy	Solar panels, wind turbines
Socio-economic actions	Economic measures	Business structure, market pricing
	Education, research, consult, contractor	Training, field experiment, consulting service, contractor service
	Policy	Farm/land consolidation, water withdrawal rights, motivating young successor
	Water projects	Drainage system, rainwater collection

3. Results

3.1. *Past farm and landscape changes*

The seven arable farming regions varied in farm size and intensity (Fig. 2). Farms in the rDE, rES, rNL and rLV regions were and still are large (> 50 ha per farm; Fig. 2c), management intensity is high (Fig. 2f), and average field size is > 4 ha (Fig. 2b). In contrast, the rCH and rGR farms were and still are comparatively smaller (< 50 ha per farm) with moderately intensive management and smaller fields (< 2 ha per field). The farms of the rPL region were and still are even smaller and less intensively managed, also with small field sizes. Over the past two decades, farm size expansion occurred across all case study regions ranging from 16 % to 82 %. Field sizes increased by 29–178 %, except for rDE and rGR that had no substantial field size changes. In the rES, rLV and rPL regions, farmers applied more nitrogen fertilizer and pesticides than two decades ago (Fig. 2d, e). In the rES region farmers applied twice as much fertilizer (329 kg N ha^{-1} yr^{-1}) than in the other intensively managed regions. Farmers of the rLV region used the highest numbers of pesticide applications, whilst no pesticides were used in the rGR region.

In all regions, the area of intensively managed land and the area of landscape features remained almost stable over the last two decades, the latter increasing when overall farming intensity decreased (Fig. 2g). Compared to other regions, large landscape feature areas in the moderate-intensity rGR and rCH regions were dominated by extensive grasslands, wetlands, and forests, respectively (Fig. A3). Unused land and barren land in proportion to total landscape feature areas increased in high-intensity regions, but the proportion of forest decreased in high-intensity regions except for rLV.

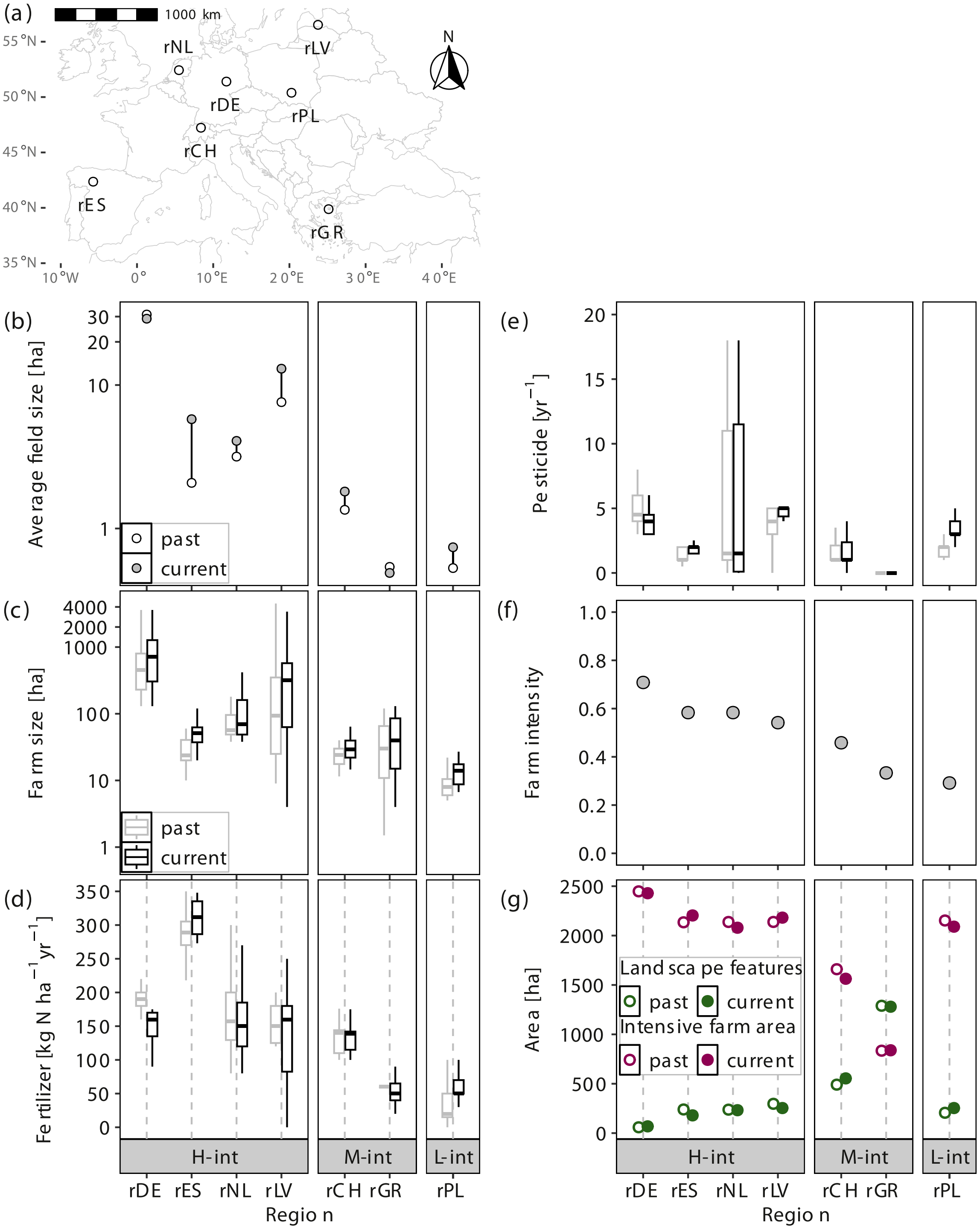

Fig. 2. Farm and landscape characteristics of the seven case study regions: (a) Geographic locations, and past (two decades ago) and current (b) Average field size, (c) Farm size, (d) N fertilizer intensity, and (e) Pesticide use. (f) Farm intensity levels calculated from current values of N fertilizer intensity, pesticide use, livestock density, and livestock feed import. (g) Changes of landscape feature and intensive farm areas in the past two decades, with an offset from the horizontal to make small changes visible. “H-int”, “M-int” and “L-int” represent high, moderate and low farm intensity of respective regions. In panels (c) – (e), 25 %, 50 % and 75 % percentile are shown.

3.2. *Past uptake and future prospects of agricultural practices*

Farmers adopted numerous new technologies over the past two decades in all regions, except for rGR (Fig. 3a; Fig. A4a). New machinery, digital, precision, and automation technologies in general, and precision fertilization in particular, were the most frequently adopted technologies in the past two decades in all high-intensity regions and the moderate-intensity rCH region. Renewable energy technology was mostly adopted by farmers in the high-intensity rDE and rNL regions, the moderate-intensity rCH region, and the low-intensity rPL region. Among agroecological practices, management of landscape elements were key practices adopted by farmers in the high-intensity rDE, rES, rNL regions and the moderate-intensity rCH region.

The main future challenges of arable farming (Fig. 3b) expected by

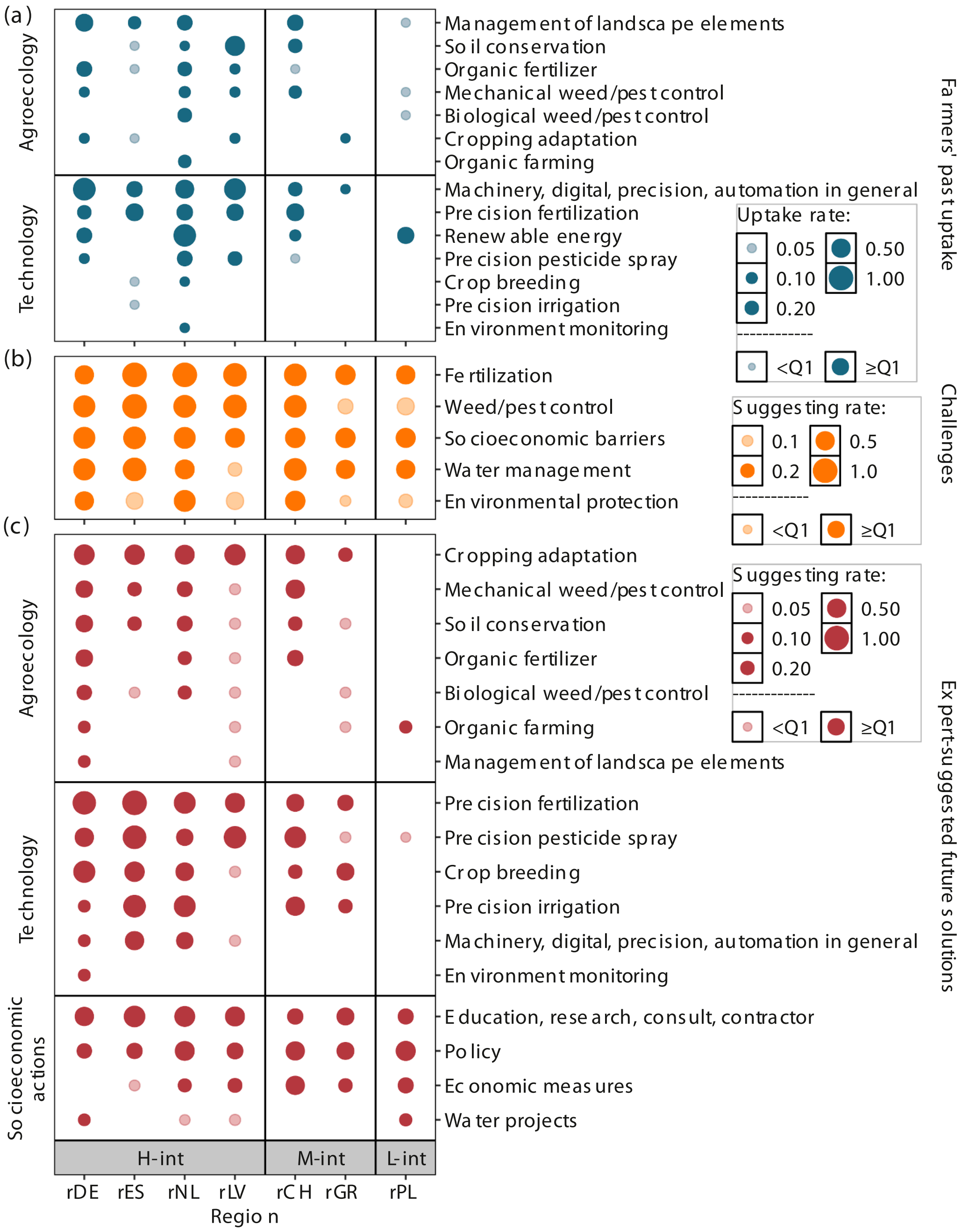

Fig. 3. Farmers' past uptake of agricultural practices and expert-suggested future solutions to arable challenges: (a) Past uptake rate of practices by farmers. (b) Frequency of challenges and (c) their future solutions suggested by experts. "H-int", "M-int" and "L-int" represent high, moderate and low farm intensity of respective regions. Q1 indicates 25 % percentile of farmers' past uptake rates, or experts' future suggestion frequency of challenges/solutions.

local experts were classified as relating to either resource management (i.e., fertilization, weed/pest control, and water management), environmental protection, or socio-economic barriers (e.g., regulation and market impacts, labor shortage, need for business structure changes, and need for profitability). Of these challenges, fertilization and socioeconomic barriers were the most frequently mentioned challenges across all case study regions. Weed and pest control was also considered a top challenge, being mentioned by more than 50 % of experts in all regions except for rGR and rPL. Water management was mentioned as a top challenge in all regions except for rLV. Environmental protection was only mentioned as a top challenge in rDE, rNL, and rCH regions.

Experts expected technology to play a more important role than agroecological practices or socio.economic actions in addressing arable farm challenges in all high-intensity regions and in the moderate-intensity rCH region (Fig. 3c; Fig. A4b). In contrast, socioeconomic actions were suggested to be more important than agroecological and technological practices in the low-intensity rPL region. Among varying technological practices, precision fertilization, precision pesticide spraying, and crop breeding were suggested as the solutions in the high-intensity and moderate-intensity regions. Besides, machinery, digital, precision, and automation technologies in general were suggested by experts as the solutions to arable farming challenges of the high-intensity regions. Precision irrigation was suggested as the future solution in the high-intensity regions except for rLV, as well as the moderate-intensity regions. Among agroecological practices, cropping adaptation and soil conservation were suggested as the solutions to arable farming challenges of the high-intensity and moderate-intensity regions. Besides, mechanical and biological weed/pest control were suggested as the solutions in all high-intensity regions. Socio-economic actions supported by education, research, consulting and contractor services, as well as policy, were seen as solutions to arable farming challenges of all case study regions. Economic measures were suggested in all regions except for rDE.

The high-intensity farming regions showed a stronger overlap of agroecological and technological practices between farmers' past uptake and expert-suggested future directions, compared to the moderate-intensity and low-intensity farm regions (Fig. 4). However, the match was substantially stronger for technological practices than for agroecological practices. For example, in the high-intensity regions, past uptake of technological practices in machinery, digital, precision, general automation, precision fertilization, and precision pesticide spray matched well with expert-suggested future directions (Fig. 4). The relation between past uptake and future directions was lower for agroecological practices, especially for organic farming, biological weed/pest control, and management of landscape elements. Biological weed/pest control was expected to play a significant role in adapting to future challenges by experts, yet it was only taken up by farmers in two study regions. On the other hand, management of landscape elements, which had high adoption rates in four study regions, was only expected to play an important role in addressing future challenges in one study region.

We observed another significant adoption gap for precision irrigation (Fig. 4). Renewable energy was adopted in different intensity-level farm regions, but was not mentioned as a solution to arable farming challenges. Organic farming was only mentioned in farmers' past adoption in the high-intensity rNL region, but was thought to be vital in addressing arable farming challenges of the high-intensity rDE and rLV regions, the moderate-intensity rGR region, and the low-intensity rPL region. Socio-economic supports including economic measures, policy (i.e., farm/land consolidation, water withdrawal rights, motivating young successor), education, research, consulting and contractor services, as well as water projects were not included in the survey of farmers' past uptake, but their importance was asserted by experts in all case study regions (Fig. 4).

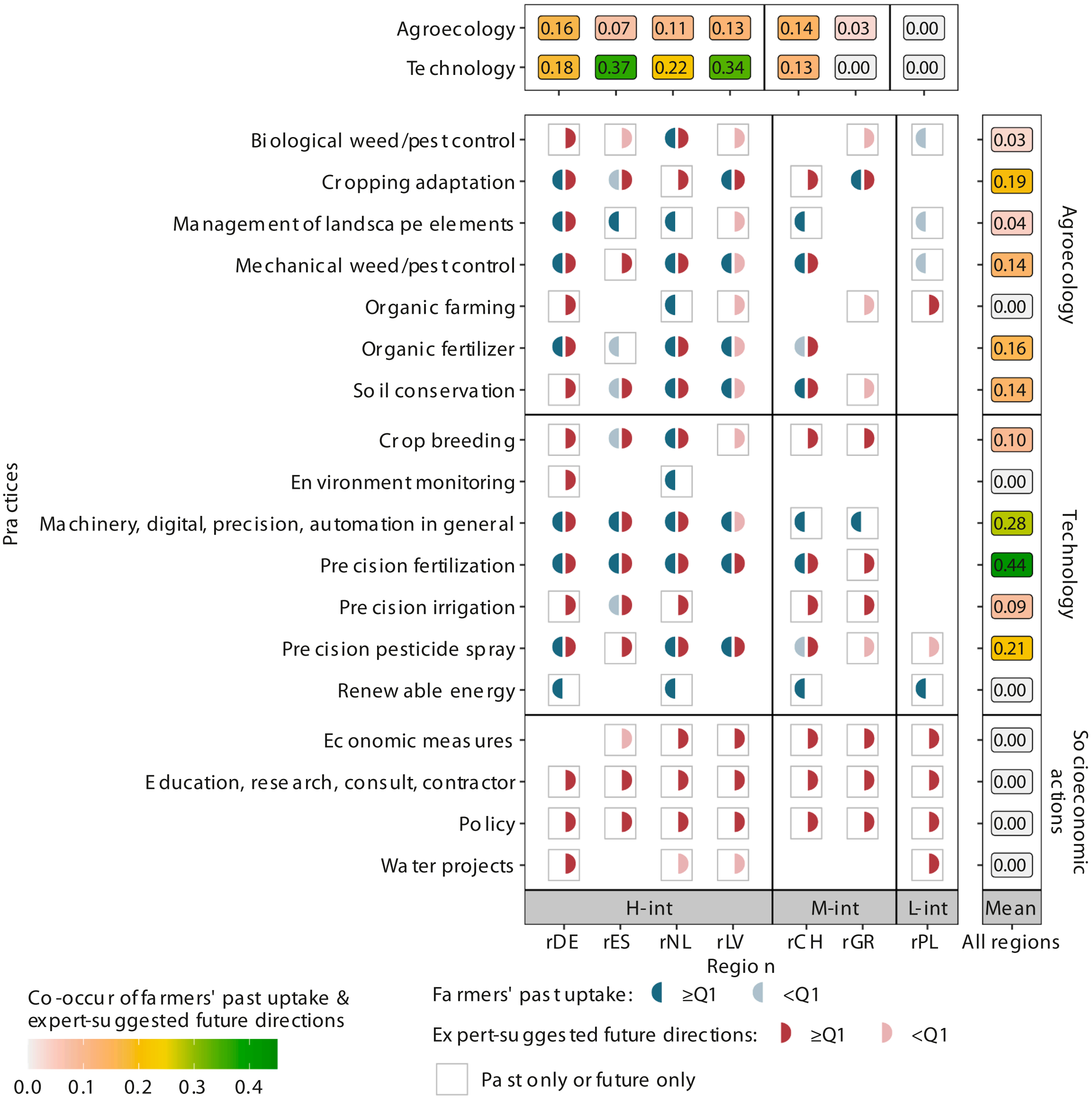

Fig. 4. Matching of farmers' past practice uptake with expert-suggested future solutions. Co-occurrence (see Eq. 2) of farmers' past uptake and expert-suggested future directions of agricultural practices are shown. The top panel displays the average past-future co-occurrence in each region, and the right panel displays the average past-future co-occurrence for each practice. "H-int", "M-int" and "L-int" represent high, moderate and low farm intensity of respective regions. Q1 indicates the 25 % percentile of farmers' past uptake rates or experts' future suggestion frequency.

4. Discussion

While there is a broad base of literature documenting farmers' adoption of sustainable agricultural practices (Swart et al., 2023), this is rarely systematically juxtaposed with other stakeholders' perceptions of future agricultural challenges and associated agroecological and technological innovations. Here, we surveyed both farmers and experts to assess the degree to which actual adoption aligns with practices identified by experts to be crucial for the future. The results reveal interesting and consequential overlaps, but also adoption gaps. In the following paragraphs, we will first discuss several relevant developments as identified by this approach, followed by what this may imply for sustainable arable farming in Europe, and finally discuss limitations of this study.

4.1. Farm intensity and landscape changes

The ecological degradation caused by agricultural intensification can be counteracted to a certain degree by spatial landscape design (Gebhardt et al., 2023) to realize sustainable transitions. Natural and semi-natural habitats support agroecology by biological control, pollination and soil conservation among others (Holland et al., 2017). However, in this study, landscape feature areas were negatively correlated with farm intensity levels (Fig. 3a) in all regions except for rPL. Large landscape feature areas in the moderate-intensity rCH region are probably due to the early introduction of cross compliance (i.e., the interplay between farmers' respect for rules and the support provided to farmers; Aviron et al., 2009), and to the elaborated agri-environmental programs (Home et al., 2014; Meier et al., 2024). In the past decades, the high-intensity regions with only few landscape feature areas experienced ecological degradation. In the rLV region, ecological degradation was linked to the straightening of rivers, the removing of riparian vegetation, and the incorporating of agricultural drainage systems during land consolidation (CIRCABC, 2004; Mohr et al., 2023). Similarly, in the rDE region, old streams were buried during land consolidation (Mohr et al., 2023). In the rES region, trees and hedges were removed during the modernization of the irrigation systems (Mohr et al., 2023). In the low-intensity rPL region, where small family farms prevail, the landscape feature areas were at similar levels as the high-intensity regions. This agreed with previous findings that small family farms are not necessarily more sustainable (based on the structural survey of German farms in 2010; Wuepper et al., 2020). These findings suggest that while landscape changes significantly impact agroecological practices, the past design did not fully compensate for agricultural intensification in our case study regions. Bridging the gap between past uptake and future expectations requires holistic landscape and farm management strategies, aligning farmers' practices with expert recommendations.

4.2. Uptake and prospects of different agricultural practices

In this study, agroecology and technology, together with socio-economic actions, played different roles for farming systems of varying intensity levels, and their past uptake and future prospects also differed (Fig. 4). Previous studies found that the application of agroecology and technology varied across farm sizes in China and North America (Brown et al., 2020; Hu et al., 2022; Liebert et al., 2022). However, in this study, the correlation of farm size and agroecological applications are not consistent between case study regions. This can be explained by previous findings that the uptake of sustainable agricultural practices in Europe is more affected by farmers' attitude and intention than economic outcomes and environmental awareness (Swart et al., 2023). Farm size was found to correlate with lower fertilizer and pesticide uses in China's crop farming (Ren et al., 2019), but we did not find a direct link between external inputs and farm sizes (Fig. 2). This aligns with Herzog et al. (2006) who reported that nitrogen inputs are influenced by livestock density, land use types and management intensity, while pesticide inputs can be influenced by crop rotation and the cultivation of special crops. According to Liebert et al. (2022), small farms are more likely to adopt intercropping, insectary plantings, and border plantings compared to large farms. In contrast, in this study, cropping adaptation was mostly adopted in large farm regions, but could play a key role in future agricultural development in both large and small farm regions (Fig. 3). Higher access to resources could explain the crop adaptation in large farm regions, while environmental concerns and future drought stress across Europe may highlight the need of crop adaptation in farms of different sizes. Furthermore, Liebert et al. (2022) found that reduced tillage was less likely to be adopted by smaller farms compared to medium farms in the US. Similarly, in our study, soil conservation measures such as reduced tillage were mainly adopted in the large-farm rLV region, and would be vital for both large and small farms in their future agricultural development (Fig. 3), which could be driven by the needs of soil protection in Europe (Achankeng and Cornelis, 2023). Riparian buffers were found to be more likely adopted in small than in medium size farms (Liebert et al., 2022), but in this study, the introduction of landscape features was widely adopted in large farm regions (Fig. 3). This could be due to the fact that larger farms can spare or share more lands for ecological purposes (Alarcón-Segura et al., 2023). We cannot directly identify the reasons for these discrepancies with our data, but it is possible that farmers managing large farms have more resources to adopt these practices.

We investigated the importance of different agricultural practices from the perspectives of both past uptake by farmers and future prospects suggested by experts. A former survey by Van Hulst et al. (2020) had found that both, farmers and the scientific community, stressed the importance of cropping adaptation in agroecological transition. This is supported by this study, with cropping adaptation being addressed in both past agroecological uptake by farmers and suggested by experts for future agroecological prospects (Fig. 4). Due to its potential to improve resource use efficiency, agricultural equipment plays a key role in agricultural development (Maurel and Huyghe, 2017). Correspondingly, we found that machinery, digital, precision and automation technologies were adopted by farmers in the past, and experts suggested that this trend will continue also in the future, especially in high-intensity farm regions (Fig. 4). This confirms our hypothesis that future agroecological and technological practice adoption aligned with their past uptake. The alignment of past uptake and future development can be explained by the concept "increasing returns to adoption (Arthur, 1989; Meynard et al., 2018; Farstad et al., 2021; Williams et al., 2024), i.e., the competitive advantage of adopted technology is constantly reinforced by future innovations.

Experts in our survey also stressed the importance of socio-economic supports in future agricultural development (Fig. 4), which corresponds to previous findings that the adoption and scaling of technology and agroecology can be affected by a complex amalgam of factors including the effectiveness of practices, favorable markets, targeted policy support, and farmers' socio-psychological factors (Meier y Terán Giménez Cacho et al., 2018; Epule and Bryant, 2017; Swart et al., 2023; Wuepper et al., 2024).

4.3. Implications for sustainable development of arable farming in Europe

Based on the past uptake and future prospects of agricultural practices, some future directions of sustainable agricultural development in European arable farming emerge. Increasingly stringent regulations on pesticides (Rinke et al., 2019) trigger the needs for alternative and efficient measures of weed control, such as precision pesticide spray, mechanical weeding, biological weed/pest control, landscape ecology, and the newly emerging laser weeding robots (Andrew et al., 2015; Deguine et al., 2021; Andreasen et al., 2022; Yousefi et al., 2024). Furthermore, shifts to low pesticide and even pesticide-free production systems can be an alternative pathway of agricultural development

(Finger, 2024). Political and social pressure to reduce fertilizer use already has, and will continue, to promote the development and adoption of precision fertilization and cultivation adaption to improve circularity and resource use efficiency (López-Bellido and López-Bellido, 2001; Bongiovanni and Lowenberg-DeBoer, 2004).

Development pathways of the individual regions will also be affected by general agricultural development. For the operation of precision technologies and the increase of productivity, further field expansion can be expected in small farm regions (rES, rGR, rCH, and rPL) through land merge and lease (Coelho et al., 2001; Helfenstein et al., 2022a; Georgiadis et al., 2022; Qian et al., 2022; Rachele, 2022). The use of large machines for improving work efficiency in the largest arable regions rDE and rLV is expected to continue to cause soil compaction and ecological degradation (Daum, 2021), highlighting the potential trade-offs associated with technological development. Therefore, agroecological strategies need to be implemented to improve agroecosystem sustainability (Grass et al., 2019). In the rPL region, despite the enlargement of farm and field sizes in the past two decades, the farm and field scales are still relatively small compared to other case study regions (Fig. 2). The region has suffered from land abandonment in the past decades, and off-farm work load has also increased in the past two decades (Grontkowska, 2021). To increase farm profitability, socio-economic support involving, amongst others, capacity building, promoting farm entrepreneurship, farmers' networks and groups, vertical integration will be vital in motivating young farmers to succeed their parents (Daniele, 2024), subsidizing precision farming technologies and the development of tailor-made solutions (Barnes et al., 2019), and implementing farm consolidation (Looga et al., 2023). Investing in new technologies requires access to large capital stocks, which is often not available for smaller farms or farms in economically marginal areas (Tamirat et al., 2018; Gabriel and Gandorfer, 2023). Subsidy and taxation can be positive drivers of technology uptake, but turning towards agroecological route, which requires less financial capital expenditure, may be a more feasible pathway for small-scale farms towards sustainable transition (Smith et al., 2020).

Climate change will accelerate the need for transition towards precision irrigation and water projects (Fig. 4). The large gaps of past uptake for these practices indicated that we are not ready for climate change adaptation (Farstad et al., 2021), because the current agricultural adoption is locked-in into dominant industrial innovations, and "increasing returns to adoption" restrained farmers to adopt new practices for new challenges (Williams et al., 2024). Because of prolonged summer droughts, irrigation infrastructure or crop adaptation need to be implemented in the rDE, rES, rNL, rCH and rGR regions (Fig. 3). In the rDE region, the small fluxes of groundwater withdrawal and deep (60 m) groundwater levels constrain the irrigating of large tracts of arable land (Müller et al., 2019). In the rES and rGR regions, irrigation has already been applied in the past decades, but scarcity of irrigation water during dry spells is an issue. The rNL region also faced groundwater level lowering and water scarcity due to more frequent drought events since 2003 (De Bruin and Duel, 2023; Verberne et al., 2023). Therefore, besides promoting water-saving and precision irrigation technologies, farmers need to adopt soil conservation practices (e.g., reduced tillage), and turn to the cultivation of drought-tolerant crops or adopt on-farm water harvesting techniques to improve arable farming resilience during drought periods (Cooper and Messina, 2023). Besides the rGR region, in which a well-adapted drought-tolerant barley landrace is already cultivated ("Panagias", Bebeli et al., 2020), drought-tolerant crops are also recommended by the experts to be cultivated in other study regions (rCH, rDE, rES, and rNL), which will face more frequent drought stress. Crop rotations, drought tolerant/resistant crops, intercrops, cover crops and agroforestry can contribute to resolving challenges related to water and nutrient use efficiency, biodiversity and weed/pest control (Belter, 2016; Hunt et al., 2017; Cooper and Messina, 2023).

4.4. Limitations of this study

This study assessed the relationships between landscape changes, past uptake and future prospects of agricultural practices to explore the diversity of transition pathways in European arable farming. Our case study regions cover a wide range of farm sizes, agricultural intensity, and landscape characteristics. However, our research may be limited by the following factors. Firstly, the past and future practices assessed in this study might be limited by the knowledge of farmers and experts in agroecology, technology, and socio-economic actions, as well as their professional backgrounds. Some new technologies and practices are not yet available or widely used in Europe, but could be highly efficient in addressing sustainable targets. For instance, laser weeding robots show a high potential in reducing pesticide use and soil disturbance, but are not yet available in the market (Andreasen et al., 2022; Li et al., 2024). Secondly, because we inquired about the challenges and solutions of resource management and general arable farming, the suggestions of experts might be limited by the setup of our questionnaire. This may explain the high proportion of resource-management related practices among the suggestions made by experts. Thirdly, farmer interviews were conducted during the Covid-19 pandemic, whilst the expert survey took place after the pandemic. Especially in the rPL region, the economic situation was then strongly affected by war. These factors may lead to an overestimation of the importance of socio-economic aspects for the future prospects of agricultural practices. Fourthly, the case study regions in each country might not be the typical farming systems in their respective country, hence the representativeness of our case study regions is unknown. A large sampling size or analysis of the representativeness of case study regions (Diogo et al., 2023) would allow investigating how different socio-economic backgrounds influence the practice adoption in regions with similar environmental conditions (Huang and Cassatella, 2024). Fifthly, quantitative metrics such as biodiversity indices, soil quality indicators, and ecosystem flux measurements would enable an objective assessment of ecological functions, but are unfortunately not available in our case study regions. Lastly, this study focuses on the general directions of technology and agroecology adoptions, the different factors that influence the actual adoptions of individual practices will need further investigation based on survey data, literature review, institutional analysis and legal evaluations (Swart et al., 2024 submitted; Li et al., 2024 submitted).

5. Conclusion

Based on the results of landscape mapping, farm and landscape changes, farmers' past uptake and expert-suggested future directions of agricultural practices, we conclude that:

High-intensity regions showed a strong continuity between past uptake and future prospects of technological practices. Low-intensity farm regions with small landscape feature areas showed a weak relation between past uptake and future directions of agroecological and technological practices, but there the importance of socio-economic support for local sustainable agriculture was perceived. Moderate-intensity regions with large landscape feature areas showed varying overlap of past uptake and envisioned future agricultural practices. The future sustainable challenges in the context of climate change adaptation and of environmental obligations will drive the transition of future innovation development to fill these gaps, with the support of different combinations of agroecological and technological practices. Farmers and experts tend to suggest a pragmatic approach to support sustainable agriculture. Socio-economic support will remain vital in all study regions.

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CRediT authorship contribution statement

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

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

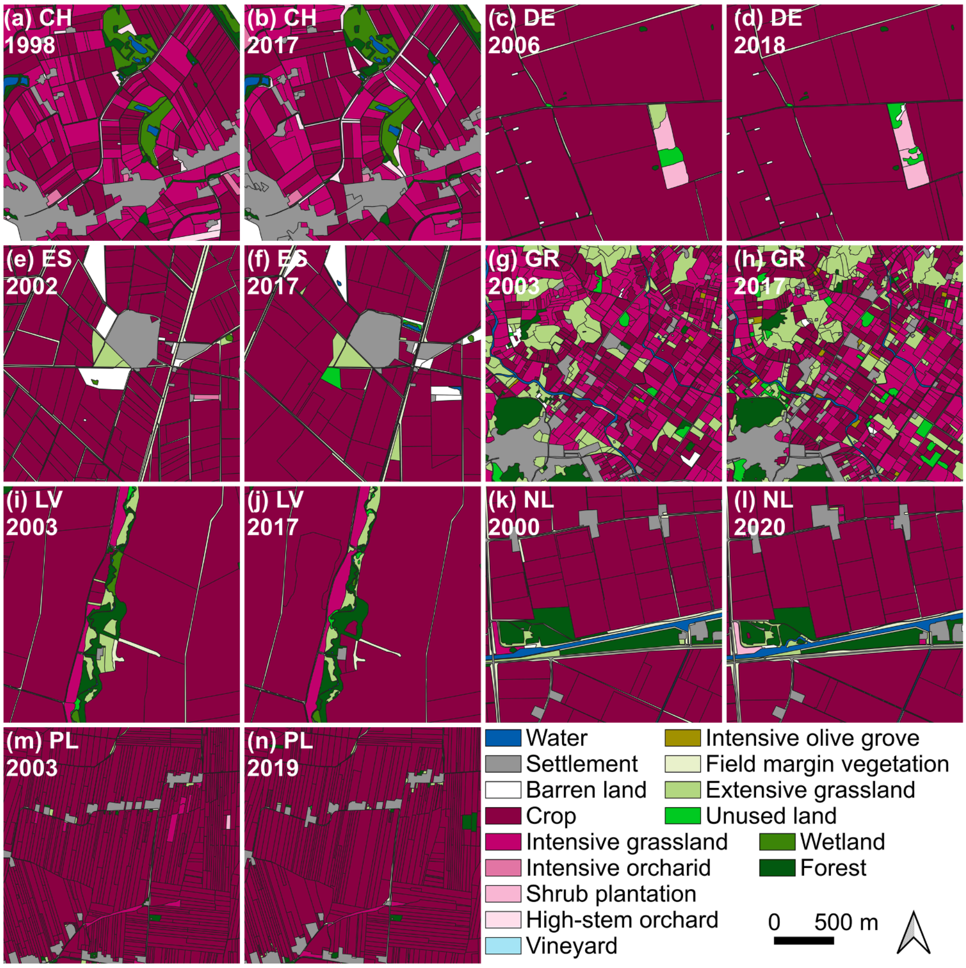

Fig. A1. Landscapes maps in the past two decades in seven case study regions

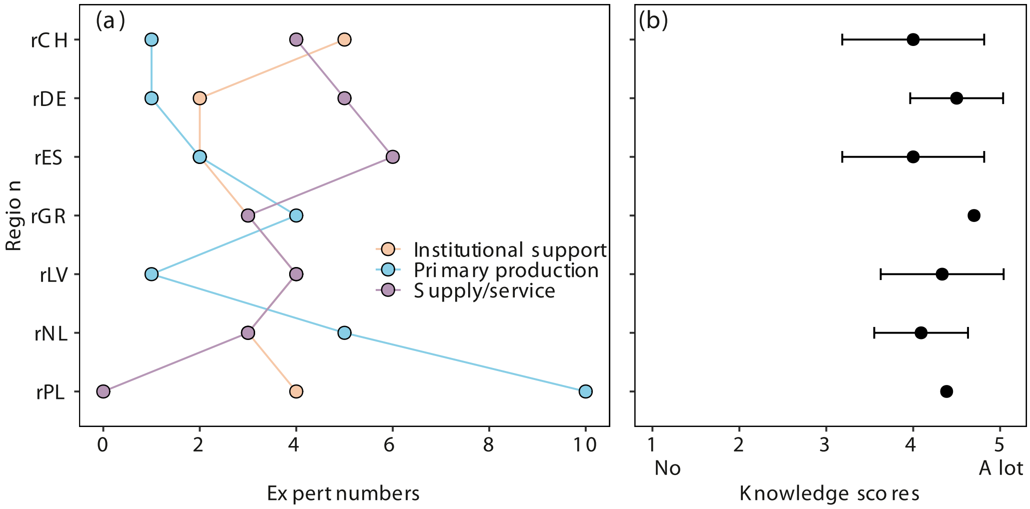

Fig. A2. The (a) profession domains and (b) arable farming knowledges of respondents for expert online-survey in seven case study regions

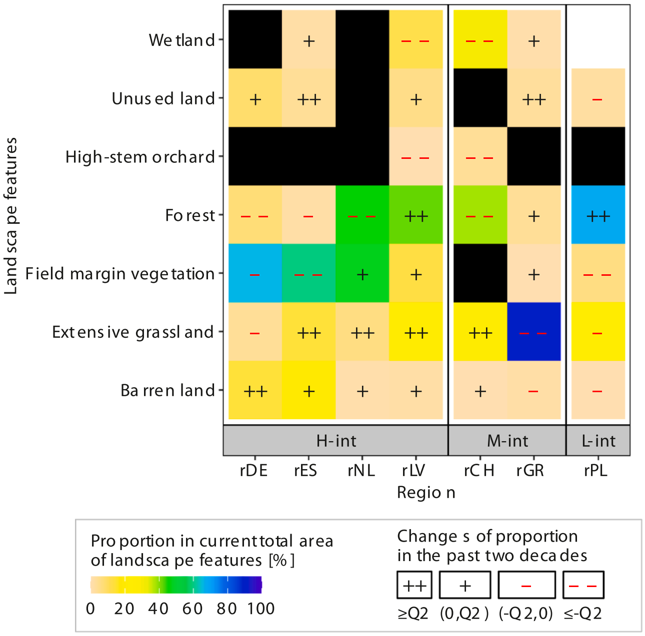

Fig. A3. Proportions of different landscape features in total areas of landscape features in each case study region. "+ " and "–" indicate the increase or decrease of the proportions of different landscape features in total areas of landscape features compared to two decades ago. "H-int", "M-int" and "L-int" represent high, moderate and low farm intensity of respective regions. Q2 represents the 50 % percentile of the absolute change of different land uses in proportion to the total landscape feature areas over the last two decades

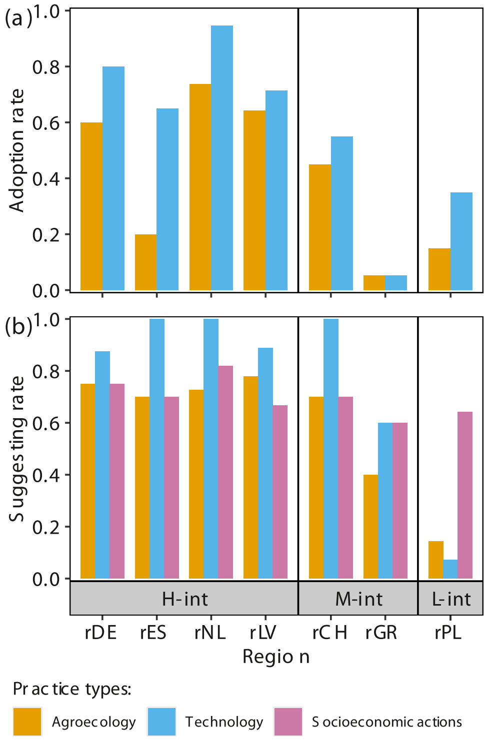

Fig. A4. (a) The rate of farmers adopting different types of practices in the past two decades, and (b) the rate of experts suggesting different types of practices for future. “H-int”, “M-int” and “L-int” represent high, moderate and low farm intensity of respective regions

Data availability

Data will be made available on request.

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