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SURVEY ARTICLE

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# Towards enhanced adoption of soil-improving management practices in Europe

Olivier Heller[1] | Claudia Di Bene[2] | Pasquale Nino[3] | Bruno Huyghebaert[4] | Aušra Arlauskienė[5] | Nádia L. Castanheira[6] | Suzanne Higgins[7] | Agota Horel[8,9] | Alev Kir[10] | Miriam Kizeková[11] | Marine Lacoste[12] | Lars J. Munkholm[13] | Lilian O'Sullivan[14] | Paweł Radzikowski[15] | M. Sonia Rodríguez-Cruz[16] | Taru Sandén[17] | Lina Šarūnaitė[5] | Felix Seidel[18] | Heide Spiegel[17] | Jarosław Stalenga[15] | Jaana Uusi-Kämppä[19] | Wieke Vervuurt[20] | Thomas Keller[1,21] | Frédéric Vanwindekens[4]

[1]Department of Agroecology and Environment, Agroscope, Zürich, Switzerland

[2]Centre for Agriculture and Environment, Council for Agricultural Research and Economics-Research, Rome, Italy

[3]Centre for Agricultural Policies and Bioeconomy, Council for Agricultural Research and Economics-Research, Perugia, Italy

[4]Department of Sustainability, Systems & Prospective-Unit of Soil, Water and Integrated Crop Production, Walloon Agricultural Research Centre, Gembloux, Belgium

[5]Institute of Agriculture, Lithuanian Research Centre for Agriculture and Forestry, Akademija, Lithuania

[6]Soil Lab, National Institute of Agricultural & Veterinary Research, Oeiras, Portugal

[7]Agri Food and Biosciences Institute, Belfast, UK

[8]Department of Soil Physics and Water Management, Institute for Soil Sciences, Centre for Agricultural Research, Budapest, Hungary

[9]National Laboratory for Water Science and Water Security, Institute for Soil Sciences, Centre for Agricultural Research, Budapest, Hungary

[10]Department of Soil and Water Resources, Olive Research Institute, Izmir, Türkiye

[11]Grassland and Mountain Agriculture Institute, National Agricultural and Food Centre, Banská Bystrica, Slovakia

[12]Info&Sols, INRAE, Orléans, France

[13]Department of Agroecology, Aarhus University, Tjele, Denmark

[14]Crops, Environment and Land Use Programme, Teagasc, Wexford, Ireland

[15]Department of Systems and Economics of Crop Production, Institute of Soil Science and Plant Cultivation, State Research Institute, Pulawy, Poland

[16]Institute of Natural Resources and Agrobiology of Salamanca, Spanish National Research Council (IRNASA-CSIC), Salamanca, Spain

[17]Department for Soil Health and Plant Nutrition, Austrian Agency for Health and Food Safety (AGES), Vienna, Austria

[18]Institute of Climate-Smart Agriculture, Johann Heinrich von Thünen-Institut, Braunschweig, Germany

[19]Natural Resources Institute Finland, Helsinki, Finland

[20]Field Crops, Wageningen University and Research (WUR), Lelystad, The Netherlands

[21]Departments of Soil and Environment, Swedish University of Agricultural Sciences (SLU), Uppsala, Sweden

Thomas Keller and Frédéric Vanwindekens contribued equally.

**Correspondence**
Olivier Heller, Department of Agroecology and Environment, Agroscope, Reckenholzstrasse 191, 8046 Zürich, Switzerland.
Email: olivier.heller@agroscope.admin.ch

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**Abstract**

Sustainable agricultural soil management practices are key to restore, maintain and improve soil health. The European Joint Programme for SOIL (EJP SOIL) has identified twelve main soil challenges in Europe. To assess the potential and eventually increase the adoption of soil-improving management practices, it is necessary to know (i) the current levels of adoption of the practices, (ii) socio-technical barriers influencing their adoption, and (iii) their bio-physical limits. This study compiled an inventory of soil-improving management practices relevant to European conditions, and used a survey among soil scientists to assess the levels of adoption of these practices in Europe. In total, 53 soil management practices were identified that address one or several of the soil challenges. The adoption of most practices was low or spatially heterogeneous across Europe, highlighting region-specific limitations to sustainable soil management. Qualitative interviews were conducted to explore the importance of socio-technical aspects of adoption. Using conservation agriculture as an example, factors that can hinder adoption included the availability of knowledge and adequate machinery, financial risks, and farming traditions. Through a modelling approach, 54% of arable land in Europe was found to be suitable for cover cropping, indicating that the adoption of soil management practices is frequently limited by climatic constraints. We propose a region-specific approach that recognizes the importance of identifying and overcoming socio-technical barriers, and by acknowledging bio-physical limits that may be expanded by innovation.

**KEYWORDS**

conservation agriculture, cover crops, EJP SOIL, soil challenges, soil degradation, soil health, soil restoration, soil threats, sustainable soil management

## 1 | INTRODUCTION

Soils provide vital ecosystem services to our society, including the provision of food, fibre and fuel, water and climate regulation, nutrient cycling, habitat provision for biodiversity, and cultural services (Dominati et al., 2010). Certain agricultural soil management practices place the sustained functioning of soils and proliferation of the soil-derived ecosystem services at risk (European Commission, 2022; ITPS, 2015; Montanarella et al., 2016). In the last decade, national and international initiatives and programmes have been developed to achieve sustainable soil management, including the Global Soil Partnerships voluntary guidelines for sustainable soil management (FAO, 2017), the 4p1000 initiative (Minasny et al., 2017), the European Union's Green Deal (Montanarella & Panagos, 2021), Horizon Europe's Soil Mission (European Commission, 2022), and the European Joint Program for SOIL (EJP SOIL; Keesstra et al., 2021). EJP SOIL aims at *climate-smart sustainable management of agricultural soils* and identified twelve soil challenges (Keesstra et al., 2023). These challenges relate to soil properties, processes and functions that need to be managed to reduce soil degradation and optimize soil functions and ecosystem services (EJP

**Highlights**

- The adoption rate of 53 soil-improving agricultural practices was assessed across Europe.
- Adoption was low or heterogeneous for most soil management practices.
- Two case studies highlight the socio-technical and bio-physical constraints influencing adoption.
- A region-specific approach to foster the adoption of soil-improving management is proposed.

SOIL, 2022). The twelve soil challenges identified by EJP SOIL (Keesstra et al., 2023) are: (i) maintain or increase soil organic carbon (SOC), (ii) minimize nitrous oxide ($N_2O$) and methane ($CH_4$) emissions, (iii) avoid peat degradation, (iv) minimize soil erosion, (v) avoid soil sealing, (vi) avoid salinization, (vii) avoid acidification, (viii) avoid contamination, (ix) maintain optimal soil structure, (x) enhance soil biodiversity, (xi) enhance nutrient retention and nutrient use efficiency, and (xii) enhance water storage capacity. The soil challenges include the soil threats relevant to agricultural soils identified in the European Commission's proposal for a soil thematic strategy (European Commission, 2006) and in the Report on the Status of the World's Soil Resources (ITPS, 2015).

Increased adoption of sustainable agricultural soil management practices is crucial to overcome these soil challenges (Helming et al., 2018). In this article, we consider any agricultural practice that was proven to influence soil functioning to be a *soil management practice*. The soil health benefits of certain soil management practices and principles have been described in recent years, such as conservation agriculture (Cárceles Rodríguez et al., 2022; Palm et al., 2014), agroforestry (Torralba et al., 2016), liming (Holland et al., 2018), or cover cropping (Blanco-Canqui et al., 2022; Koudahe et al., 2022). Current knowledge has been compiled in inventories that contain assessments of the soil management practices in relation to one or multiple soil challenges and/or economic outcomes (e.g., Mallast et al., 2014; Sandén et al., 2018; Schwilch et al., 2018; WOCAT, 2023). Despite the availability of inventories of certain soil management practices, there is limited documented knowledge on the current and potential adoption level of soil management practices in Europe. Information on the levels of adoption is needed to identify where there is potential to increase the use of soil-improving management practices, and to ascertain the magnitude of that potential. To tap the potential, information about socio-technical limitations and bio-physical constraints of specific management practices are needed. Only with knowledge of all these aspects (i.e., current level of adoption, socio-technical barriers and bio-physical limitations) can we identify and capitalize on the potential of enhanced adoption of soil management practices to tackle the identified soil challenges.

Therefore, the overall aims of this study were (i) to quantify the current levels of adoption of soil-improving management practices in 24 European countries, (ii) to identify and discuss socio-technical barriers and enablers and (iii) to discern bio-physical constraints to the adoption of soil management practices.

An inventory of soil management practices was created and the level of adoption of these practices was assessed across Europe through a questionnaire completed by soil scientists in 24 European countries. Quantifying the socio-technical and climatic limitations of all soil management practices is extremely challenging, thus we focused on two key practices with documented beneficial impacts on soil health to illustrate how socio-technical and climatic limitations influence adoption levels. We used conservation agriculture (FAO, 2023) to exemplify the existence of socio-technical barriers and enablers and how these can influence the adoption of soil management practices. To demonstrate how climatic constraints affect levels of adoption, we used the example of cover cropping, which is a key component of conservation agriculture (FAO, 2023) and linked to several soil health benefits (Koudahe et al., 2022). Based on these analyses, we discuss the importance of considering both socio-technical and bio-physical constraints to design strategies towards enhanced adoption of sustainable soil management practices.

## 2 | METHODS

### 2.1 | Inventory and description of soil management practices

An inventory of soil management practices was compiled based on the WOCAT database (WOCAT, 2023) supplemented by reviewing existing inventories of soil management practices collected in previous research projects (Best4Soil, undated; AgForward, undated; SmartSOIL, undated; Smart-AKIS, undated; Alaoui & Schwilch, 2019; Corre-Hellou, 2017; Mallast et al., 2014; Oenema et al., 2018; Paz et al., 2024 ; Sandén et al., 2018; Schwilch et al., 2018). The soil management practices were considered relevant if scientific studies reported that they tackled at least one of the twelve soil challenges, and if they were compatible with European farming systems. Consequently, we excluded practices that were focused on smallholders or tropical agroecosystems. Practices that were similar in nature were merged into one practice (e.g., different forms of reduced tillage were merged into "reduced tillage", or different varieties of cover crops were merged into "cover crops").

### 2.2 | Survey on the current level of adoption of soil management practices

In each of the 24 European countries participating in EJP SOIL (Figure S1a), soil scientists reported for their respective country the adoption level of the inventoried soil management practices in each environmental zone (Figure S1b) as defined by Metzger et al. (2005). We refer to an environmental zone within a country as an environmental *sub-zone*. The soil scientists were asked to base their answers on documented evidence, such as public statistics or scientific studies. However, such evidence was not available for all practices, resulting in soil scientists reporting best estimates based on expert knowledge. The levels of adoption were sub-divided into eight categories based on the theory of diffusion of innovation (Rogers, 2003): *Not relevant, not applied* (*0% of the farmers*), *few farmers* (<2.5%), *early adopters* (2.5–16%), *early majority* (16–50%), *late majority* (50–84%), *almost all* (>84%), and *unknown*.

Where possible, we compared the survey results with publicly available statistics on farmer adoption level of soil management practices. Statistics were available for cover crops, reduced tillage, no-till (EUROSTAT, 2022b), and organic agriculture (FiBL, 2021). The data from EUROSTAT (2022b) were collected in 2016 and the data from FiBL (2021) were collected in 2021. The information from FiBL (2021) is a compilation of data from statistical offices, governments and private sector actors. For comparison with our survey results, we calculated the average adoption level for each sub-zone and classified it into the eight categories of adoption mentioned above.

### 2.3 | Assessing the barriers and enablers of conservation agriculture based on expert interviews

We held qualitative interviews with conservation agriculture experts (hereafter called experts) from across Europe to identify barriers and enablers to adopting conservation agricultural practices. We interviewed 20 experts, one from each country that participated in our study (Figure S1a); however in four countries (Denmark, the United Kingdom, Slovenia, and Hungary), no interviews were held. The experts were selected by the soil scientists from the respective countries, and all experts were well acquainted with the state of conservation agriculture in their country. These experts were either farmer association representatives (7), researchers (7), or farm advisors (6). The two guiding questions of the interviews were (i) "What are the barriers to the adoption of conservation agricultural practices by farmers in your country?", and (ii) "What are the enablers to the adoption of conservation agricultural practices by farmers in your country?". If necessary, the guiding questions were supplemented with neutral follow-up questions. The interviews were held in local languages and then transcribed into English by the soil scientists. The transcripts were analysed with a social cognitive mapping approach (Vanwindekens et al., 2013) to identify reoccurring concepts and relationships between these concepts. Centrality, an indicator for the number of relationships with other concepts, was calculated for each identified concept.

### 2.4 | Estimating the climatic constraints to cover cropping

We assessed the climatic constraints to cover cropping to explore the potential for cover crop adoption across Europe. We assumed that cover crops were grown without irrigation after winter wheat, the most important crop in Europe (EUROSTAT, 2022a) and its harvest date was estimated with the crop model described by Olesen et al. (2012). This model assumes two crop development stages (from 1st January to flowering, and from flowering to maturity), with two distinct temperature sums and daylength requirements. Daylength is dependent on the day of the year and latitude and was calculated with the formula of Brock (1981) in its Forsythe et al. (1995) notation. Cover crops need a suitable average daily temperature of more than 4°C (Pullens et al., 2021) and sufficient water to grow (Arlauskienė & Šarūnaitė, 2023). We assumed that water was sufficient if the 31-day rolling mean precipitation was larger than 50% of the potential evapotranspiration from a crop canopy provided by Agri4Cast (2021). With this precipitation criterion, we excluded dry seasons with little precipitation that would not allow the growth of cover crops without irrigation. We calculated the temperature sum (difference between daily mean temperature and 4°C) of the days from harvest to the end of the year that meet the precipitation criteria. We considered the climate to be *suitable* for cover cropping if the temperature sum was at least 800°C and *marginally suitable* if the temperature sum was between 650 and 800°C (Pullens et al., 2021). In the next step, we extracted the proportion of arable land (CLC, 2018) with *suitable* and *marginally suitable* climate per environmental zone. Average climate data (1991–2020) per day of the year with a spatial resolution of a 25 km × 25 km grid was used as input for our calculations (Agri4Cast, 2021). The code for the calculations can be found in a repository (Heller, 2023).

## 3 | RESULTS

### 3.1 | Inventory of soil management practices

Our literature review yielded 53 soil management practices, which are listed in the inventory (Figure 1, Supplementary Information II, Vanwindekens and Heller

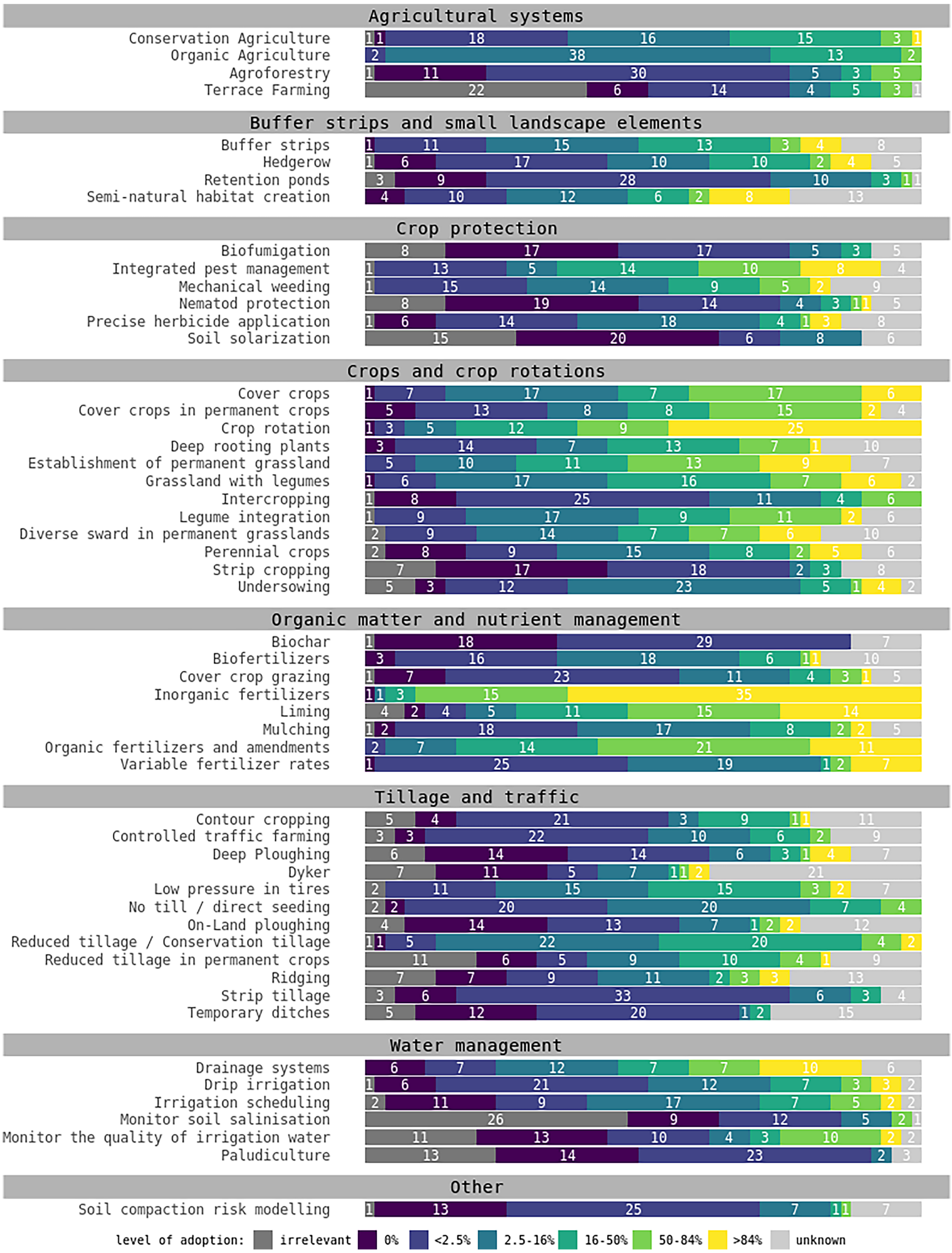


**FIGURE 1** Level of adoption of soil management practices across Europe. Results of a survey among soil scientists in 55 environmental sub-zones in 24 European countries. The numbers in the graphic relate to the number of sub-zones for a given practice and level of adoption. Reading example: Strip tillage was reported to be irrelevant in three sub-zones, not applied in six sub-zones, applied by less than 2.5% of farmers in 33 sub-zones, applied by 2.5–16% of farmers in six sub-zones, applied by 16%–50% of farmers in three sub-zones, and the level of adoption was not known in four sub-zones.

(2024)). A short description of each soil management practice and the sources where it was originally described are provided in Supplementary Information II. We asked the soil scientists to assess the impacts of soil management practices on soil challenges, productivity and farm income. The sample size of one answer per practice did not allow a statistical analysis of the impact assessments. Nevertheless, we present the reported impacts in Supplementary Information II and in the online version of the inventory (Vanwindekens & Heller, 2024). Further, through the surveys, soil scientists added 14 additional soil management practices to our inventory that were previously not described in other inventories. Thus, their adoption levels could not be assessed and they are not discussed in this article.

## 3.2 | Level of adoption of soil management practices in Europe

The level of adoption of the 53 soil management practices varied between practices and across Europe (Figure 1). In total, answers for 55 sub-zones in 24 countries were received. Figure 2 shows the level of adoption of conservation agriculture and cover cropping, which are discussed in further detail below. The adoption maps for reduced tillage, no-till and organic agriculture are presented in Figures S2–S4 in the Supplementary Information I. The adoption maps for all 53 soil management practices can be found in the online version of the inventory (Vanwindekens & Heller, 2024).

Most soil management practices, including conservation agriculture and cover cropping, showed high heterogeneity in their adoption level across Europe (from not applied to applied by almost all farmers). Only three practices, namely the application of inorganic fertilizer, the application of organic fertilizer, and crop rotation, were reported to be common throughout Europe and adopted by at least a late majority of farmers in more than 50% of the sub-zones. In contrast, agroforestry systems, retention ponds, biofumigation, soil solarization, inter cropping, strip cropping, controlled traffic farming, no-till, strip till, biochar application, paludiculture and the use of soil compaction risk models are only adopted by a few farmers in more than 50% of the sub-zones. Unlike most other soil management practices, the

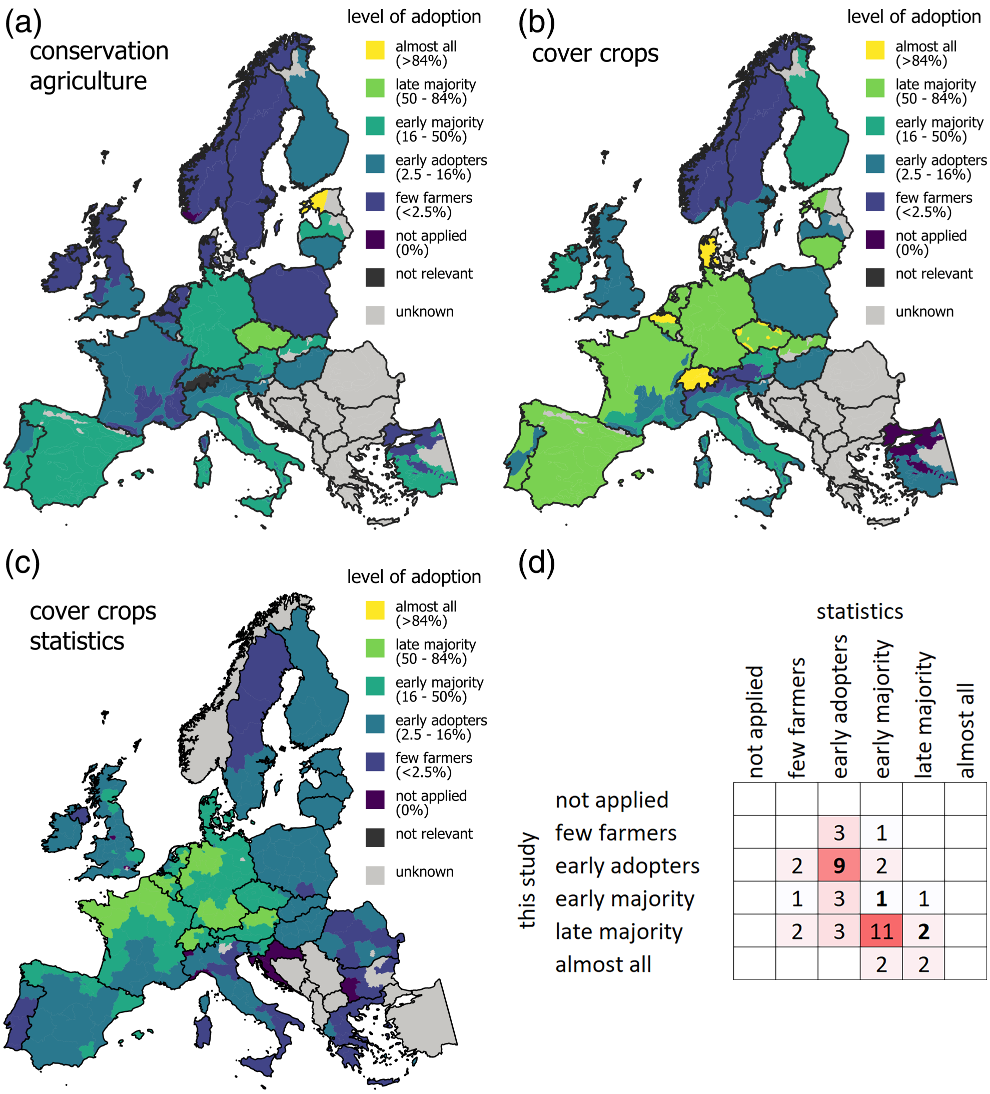


**FIGURE 2** (a,b) Adoption level of conservation agriculture (a) and cover crops (b) in 55 environmental sub-zones, based on a survey with soil scientists from 24 European countries. (c) The level of cover crop adoption reported by EUROSTAT (2022b) for the year 2016. (d) The comparison of the level of cover crop adoption reported in the survey of this study and the level of adoption reported by EUROSTAT (2022b). For (d), the adoption level reported by EUROSTAT (2022b) was averaged between administrative units in the same sub-zone.

adoption level of organic agriculture was reported to be relatively homogeneous, with early adopters among farmers in 69% of the sub-zones and an early majority of farmers in another 24% of the sub-zones (Estonia and the (pre-)alpine areas in Central Europe, see Figure S4).

We compared the reported adoption levels with existing statistics (EUROSTAT, 2022b; FiBL, 2021). Overall, in 79% to 98% of the sub-zones the reported levels of adoption and the statistics matched or deviated by only one level. For cover cropping, the reported levels of adoption and the statistics matched or deviated by one level of adoption in 80% of the sub-zones. The adoption in our survey was one level higher in 40% of the sub-zones, and one level lower in 13% of the sub-zones (Figure 2). The reported levels of adoption and the statistics matched in 51% of the sub-zones for reduced tillage (Figure S2), 53% of the sub-zones for no-till practices (Figure S3), and 71% of the sub-zones for organic agriculture (Figure S4).

## 3.3 | Barriers and enablers of conservation agriculture

The qualitative expert interviews on the barriers and enablers of conservation agricultural practices yielded reoccurring concepts and arguments that could be structured into five domains: knowledge, policies and economics, bio-physical context, machinery, and ideals. These domains are described hereafter, in the order of decreasing centrality. Concepts with a centrality value lower than 21 were not reported here.

### 3.3.1 | Knowledge

Experts pointed out that conservation agriculture requires particular knowledge, skills, and understanding of the agroecosystem. Knowledge was considered important as conservation agriculture is associated with challenging techniques (e.g., specific machinery operations) and risks (e.g., meteorological impact on seedling emergence). Advisory services were said to support farmers in the adoption of new practices by sharing knowledge and experiences or by organizing field visits. According to the experts, such services were not available to farmers in some countries. In Belgium, the Netherlands, Switzerland, and Sweden, adoption and innovation were said to be driven by peer exchange among farmers. Agricultural research institutions were seldom involved in the promotion of conservation agriculture. However, the mutual exchange between researchers and farmers was seen as an opportunity to address important knowledge gaps, for example in relation to crop diversification or weed management in conservation agriculture.

### 3.3.2 | Policies and economics

Once adopted, conservation agricultural practices were said to be associated with cost savings, in particular by reducing working hours and fuel costs. On the other hand, the adoption of conservation agriculture was reported to be associated with yield reductions and higher financial risks. Subsidies and other financial incentives were reported to cover additional costs (e.g., for machinery or cover crop seeds) and compensate for yield reduction and higher financial risks. Some experts pointed out that subsidies need to be higher than compensatory to provide financial incentives for adoption. The lack of a market for products from conservation agriculture (as opposed to products from organic agriculture that yield premium prices due to certification and labeling) was perceived as a barrier to adoption by some experts. Besides, the ongoing debates concerning herbicides (negatively perceived public opinion) and the risk that some herbicides may be banned (especially glyphosate) have been mentioned to hamper adoption, or even lead to the abandoning of conservation agricultural practices.

### 3.3.3 | Bio-physical context

Clayey soils were said to be a hampering factor to the adoption of conservation agricultural practices, whereas sandy or loamy soils were perceived as enablers. Compared to soils under other management practices, the soil was mentioned to maintain higher water content and lower temperatures in spring, which in turn can delay sowing and crop growth. These effects were said to be more relevant in colder and wetter climatic conditions and may be a limiting factor for conservation agriculture adoption in Northern Europe where the growing season is comparably short. As showcased in our study (see next section), the climate was perceived to limit the adoption of cover cropping, a practice strongly linked to conservation agriculture. On farms that make use of manure, the impossibility of incorporating organic matter into the soil by tillage (typically by mouldboard ploughing) was perceived to be a major barrier to adopting minimum soil disturbance practices.

### 3.3.4 | Machinery

The unavailability of adequate machinery was perceived as a barrier to the adoption of conservation agriculture, as some required equipment (e.g., direct seeding machines) has prohibitive costs, especially for small-scale farms. The availability of contract services that provide conservation agriculture-specific field operations or the availability of shared equipment were said to lower the investment costs and were perceived as an enabler for small farms and for farmers who would like to try out new practices.

#### 3.3.5 | Ideals

Farming traditions, the farmers' perception about the acceptance of the practices by their peers, and the perceived negative public attitude towards herbicide application that might be elevated if conservation agricultural practices are adapted (Nichols et al., 2015), were considered to be barriers. On the other hand, some benefits of adoption such as climate change adaptation and mitigation, were seen as enablers as these effects align with the farmers and the public ideals.

### 3.4 | Estimates of climatic constraints to cover cropping

The climatic conditions for cover cropping after winter wheat were found to be suitable on 54% of all arable land in Europe (Table 1). The share of suitable arable land varied between environmental zones and was estimated to be between 0% (ANA, ALN, see Table 1 for environmental zone abbreviations) and 72% (ATC). Figure 3d shows that the marginally suitable and unsuitable areas were found in high latitudes and high elevations, as well as in the East and the South of Europe. In high latitudes and high elevations (ALN, BOR, NEM, ALS), the low-temperature sums were limiting the cover crop growth (Figure 3b), whereas in the southern environmental zones (PAN, MDM, MDN, MDS, ANA), available water was the limiting factor (Figure 3c). In the continental environmental zone in the east of Europe (CON), a combination of both factors was restricting cover crop growth.

## 4 | DISCUSSION

### 4.1 | Inventory and impacts of soil management practices

Our inventory is a compilation of pre-existing inventories of soil management practices and expands on an earlier EJP SOIL stock take (Paz et al., 2024) that reported 30 soil management practices. The “Catch-C" project (Mallast et al., 2014) had an inventory of 55 management practices but some of these were similar in nature and considered to be the same practice in our inventory. Therefore, our inventory is the most comprehensive and

**TABLE 1** The share of Europe's arable land where the growth of cover crops is limited by climatic conditions for different European environmental zones (Metzger et al., 2005).

| Environmental zones | Arable land (km$^2$) | Unsuitable | Marginally suitable | Suitable |
|---|---|---|---|---|
| ALN - Alpine north | 1′220 | 100% | 0% | 0% |
| BOR - Boreal | 29′847 | 48% | 41% | 11% |
| NEM - Nemoral | 59′275 | 7% | 34% | 58% |
| ATN - Atlantic north | 69′415 | 13% | 19% | 68% |
| ATC - Atlantic central | 182′398 | 3% | 25% | 72% |
| CON - Continental | 312′850 | 15% | 15% | 70% |
| ALS - Alpine south | 6′679 | 11% | 19% | 69% |
| PAN - Pannonian | 184′900 | 58% | 24% | 18% |
| LUS - Lusitanian | 35′494 | 2% | 31% | 67% |
| MDM - Mediterranean mountains | 32′784 | 43% | 15% | 42% |
| MDN - Mediterranean north | 141′678 | 43% | 11% | 46% |
| MDS - Mediterranean south | 59′744 | 27% | 15% | 58% |
| ANA - Anatolian | 12′741 | 100% | 0% | 0% |
| Europe | 1′129′025 | 26% | 20% | 54% |

*Note*: The climate was considered suitable for cover cropping if the temperature sum of days with sufficient available water after winter wheat harvest was higher than 800°C and marginally suitable if the temperature sum was between 650 and 800°C. See main text for a detailed description of the methods.

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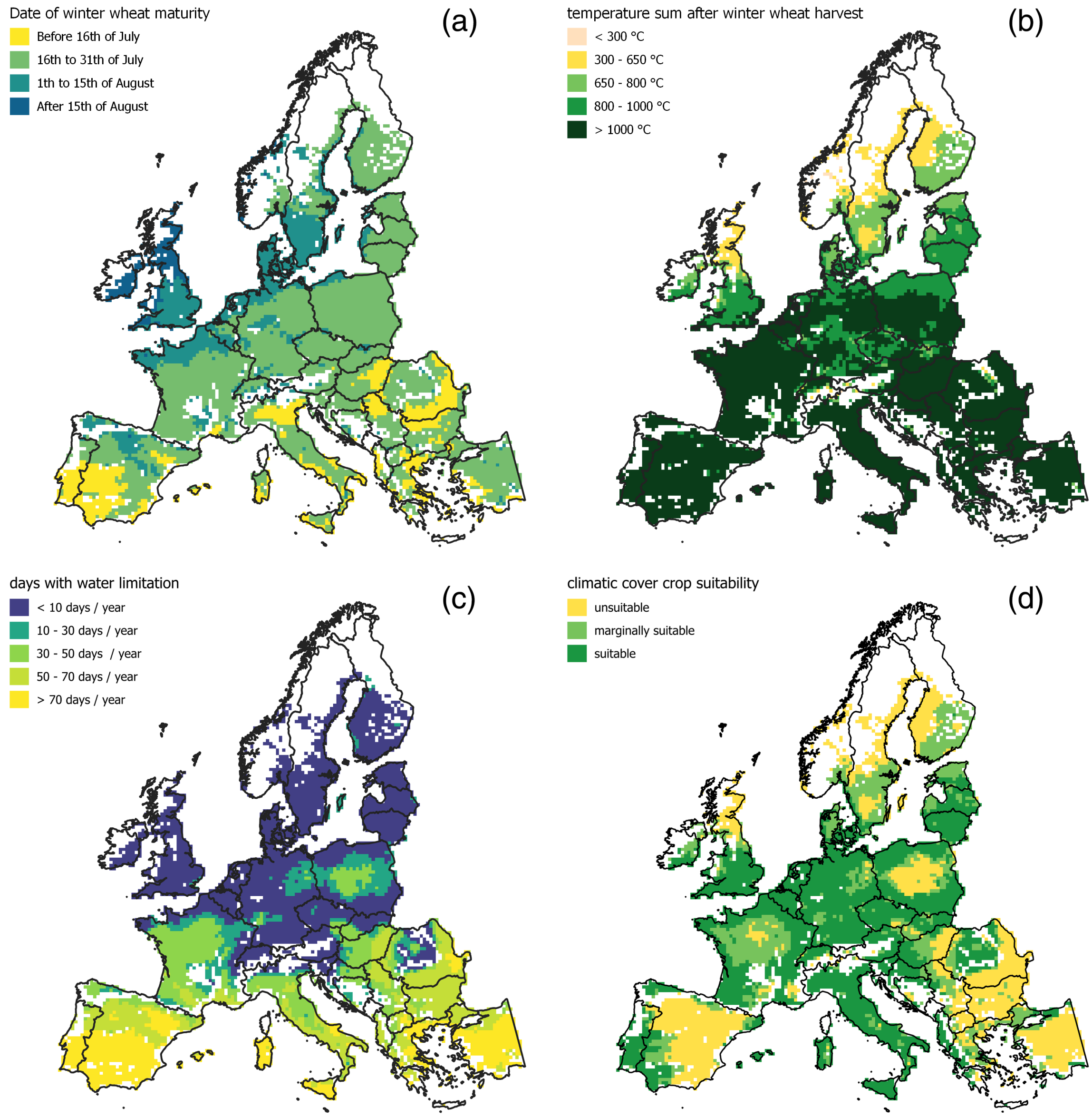


**FIGURE 3** (a) The date of winter wheat harvest, estimated with a model that accounts for daylength and temperature sum (Olesen et al., 2012). (b) The temperature sum (above a base temperature of 4°C) of the days between the winter wheat harvest and the end of the year (not considering water limitation). (c) The number of days after the winter wheat harvest where available water is limiting cover crop growth. (d) Climatic suitability for cover cropping after winter wheat in Europe. The climate was considered suitable if the temperature sum of days with sufficient available water after winter wheat harvest was higher than 800°C and marginally suitable if the temperature sum was between 650 and 800°C. (a–d) Results for grid cells with less than 1% of the land surface covered with arable land are not shown on the maps. See main text for a detailed description of the methods.

up-to-date compilation of scientifically examined soil management practices for European farming systems.

The reported impacts of soil management practices (Supplementary Information II) allowed three key observations to be made: First, a greater number of soil management practices were reported to tackle the more widespread soil challenges (i.e., enhancing nutrient use efficiency and retention, reducing soil erosion, enhancing soil structure, enhancing SOC content, and enhancing water storage capacity) compared to more regional soil challenges. The regional soil challenges were: avoiding soil acidification and salinization, avoiding peat degradation, and avoiding soil sealing (see Thorsøe et al. (2023) and JRC (2015) for the distribution of soil challenges across Europe). Second, the three soil challenges of reducing $N_2O$ and $CH_4$ emissions from soils, reducing soil contamination, and enhancing soil biodiversity were reported to be tackled by relatively few practices (less than 21% of the practices where the impacts were assessed), and many knowledge gaps on impact of soil management practices on these challenges were reported. These soil challenges are particularly complex and site-dependent (Hénault et al., 2012), or generally understudied (Hénault et al., 2012; Tamburini et al., 2020). Third, there seemed to be a bias towards positive effects in the reported impacts. Unlike the impacts that were reported in our study, Guenet et al. (2021) and Grados et al. (2022) reported increased $N_2O$ and $CH_4$ emissions due to organic matter amendments and tillage reduction. Other studies found that measures tackling the identified soil challenges can reduce crop yield or farm profitability (e.g., Rosa-Schleich et al., 2019; Zwetsloot et al., 2021). Hence, trade-offs between tackling different soil challenges and other outcomes (production, farmer income) may be underrepresented in our study. However, these trade-offs (as well as synergies) are important when assessing climate change mitigation potentials and the economic viability of soil management practices (on the topic of trade-off and synergies see Bos et al. (2017), Schröder et al. (2020), Zwetsloot et al. (2021), McGuire et al. (2022), or Morizet-Davis et al. (2023)). Thus, the impacts of soil management practice adoption on the soil and the farms need to be carefully reevaluated in their site-specific context.

## 4.2 | Adoption of soil management practices in Europe

The application of inorganic and organic fertilizers, as well as crop rotation were reported to be common throughout Europe. All other practices had either low or heterogeneous adoption levels, implying room for increased adoption and indicating region-specific limitations. The adoption patterns of some practices could be explained by the occurrence of the soil challenges (JRC, 2015; Thorsøe et al., 2023) that they address. For example, water management practices that avoid or reduce soil salinization were applied in the South of Europe where the warmer and drier climate favour salinization, whereas liming was applied towards higher latitudes where the wetter climate favours soil acidification. However, for many practices, the adoption patterns could not be linked to the occurrence of specific soil challenges, as the adoption levels diverged between neighbouring sub-zones with comparable soil challenges. The adoption levels of conservation agriculture and the two practices that are connected to tillage intensity reduction (reduced tillage and no-till) were reported to have higher adoption levels in southern Europe. This may be explained by the expected yield benefits of conservation agricultural practices in dry climates and yield penalties in humid climates (Pittelkow et al., 2015). However, factors of socio-technical nature, such as the lack of knowledge and adequate machinery, financial risks, and farming traditions, may hamper the adoption of conservation agricultural practices in northern Europe (see Section 4.3). The adoption levels of cover cropping were reported to be highest along the Atlantic coast of Europe, highlighting the effect of climatic constraints linked to cover cropping in other parts of the continent (see Section 4.4).

Overall, the reported levels of adoption matched the data from the available statistics, and the reported spatial patterns (north/south, Atlantic/continental, etc.) matched the spatial pattern in the statistical data (Figures 2 and S2–S4). Thus, on a continental scale, the reported levels of adoption and the resulting patterns seem robust, even though the soil scientists may have over- or underreported the level of adoption in some sub-zones. However, pan-European statistics were only available for cover crops, reduced tillage, no-till, and organic agriculture, and the data for three of these four practices were gathered almost a decade ago (2016) and are therefore not up-to-date anymore. Informed decision-making to foster sustainable soil management requires more detailed information on the levels and trends of practice adoption. We suggest that harmonized and repeated surveys on soil management practices should be carried out across Europe. Such surveys could be based on farmer consultation (e.g., Smit et al., 2019) or remote sensing approaches (e.g., Nowak et al., 2022 or Fendrich et al., 2023).

## 4.3 | Barriers to the adoption of conservation agriculture

Our interviews on conservation agriculture suggested that the most important socio-technical factors that hampered its adoption were related to the availability of knowledge. Morel et al. (2020) assessed the barriers to crop diversification and found similar results as five of their eight most cited barriers to diversification were linked to the lack of knowledge and information. Knowledge availability is dependent on a network of knowledgeable persons accessible to farmers such as other farmers, advisors, researchers and other stakeholders. Some experts mentioned that the integration of the farmer and farm advisor community with the soil research community could be improved to address existing knowledge gaps. This observation aligns with the results of a survey that consulted more than 300 soil-related stakeholders from across Europe (Thorsøe et al., 2023; Vanino et al., 2023). Contrastingly, Strauss et al. (2023) found that lack of knowledge was a less relevant barrier to adopt sustainable soil management practices in Germany.

An economical and political environment that provides financial incentives to adopt conservation agricultural practices seemed to be essential, as conservation agriculture can lead to lower yields (Pittelkow et al., 2015). Similarly, Morel et al. (2020) found that investments and profitability were among the five most mentioned barriers to adopting innovative farming practices. In line with these observations, Strauss et al. (2023) found that in Germany, most barriers to adopt soil management practices were of an economic and technological nature.

Machinery that is adapted to local conditions (farming systems, climate, soil type, etc.) needs to be accessible to farmers to facilitate the adoption of conservation agriculture. Experiences from regions with higher adoption rates suggested that the availability of knowledge and adequate machinery simultaneously increased with the adoption rate. This pointed to the pivotal role that knowledge provision and economic incentives can play in overcoming a locked-in situation where the lack of knowledge and machinery is constraining the adoption of conservation agricultural practices. During our interviews, it was frequently mentioned that conservation agriculture was associated with increased weed pressure, which may lead to increased herbicide application (Nichols et al., 2015) that in turn can be a barrier to adopting conservation agricultural practices (Ghaley et al., 2018).

## 4.4 | Climatic constraints to cover cropping

Our survey revealed heterogeneous adoption levels of cover cropping across Europe (Figure 2b) which is a finding that is well supported by other studies (EUROSTAT, 2022b; Fendrich et al., 2023; Panagos et al., 2015; Smit et al., 2019). In 2016, cover crops were grown on 19% of the European arable land where no winter crop was established, with considerable regional differences, ranging from 0% (North, South and East of Europe) to 92% (Atlantic coast) (Figure 2c; EUROSTAT, 2022b). Farmer surveys by Smit et al. (2019) found that the share of farmers growing cover crops was 11.6% in Castillia y León (Spain), 83.6% in Centre (France), 98.7% in Overijssel (the Netherlands) and 46.1% in South Muntenia (Romania). Noteworthy, the adopters in Spain usually had access to irrigation for their cover crops. Nowak et al. (2022) found that cover crop adoption in France was higher along the Atlantic coast (ATC and LUS) with wetter summers and warmer autumns than in the more continental parts of France (ATC, ALS, CON, MDM) where dryer summers and cooler autumns prevail. This climatic pattern was also confirmed by our approach (Figures 2 and 3) and by Fendrich et al. (2023) who applied a remote-sensing approach to estimating the adoption of cover crops in Europe. Based on our modelling exercise and the studies discussed above, we conjectured that temperature and precipitation limitations explained a large proportion of the observed cover crop adoption levels in Europe. This indicates that bio-physical limitations cannot be neglected when assessing the applicability and potential benefits of soil management practices, such as cover cropping. This is seconded by the review of Rivière et al. (2022) stressing that the introduction of cover crops should consider site-specific environmental conditions. The limited cover crop suitability in some parts of Europe will also affect the adoption and the appearance of conservation agriculture, for which cover crops are an important practice (FAO, 2023).

The discrepancy between the actual application of cover cropping (16% of the arable land in 2016 (EUROSTAT, 2022b)) and our model results (54% of the arable land is suitable) suggest that there is room for increased adoption of cover cropping in Europe despite climatic constraints. Some of this potential may have already been exploited as our survey found higher adoption rates than the EUROSTAT (2022b) investigation from 2016 (Figure 2c). For a more detailed assessment of the bio-physical limits to cover cropping, our modelling approach could be refined and validated with more complex models that better account for water availability to plants and differences between plant species. A regionalization to better represent regional agricultural systems (e.g., Pullens et al. (2021) for Denmark) would further improve the assessment of climatic limitations to cover crops. Furthermore, simulation experiments should explore the implications of climate change for bio-physical limitations to cover cropping, as a changing climate is likely to impact cropping patterns and timing (e.g., IPCC, 2022; Olesen et al., 2012; Sjulgård et al., 2022; Sloat et al., 2020).

## 4.5 | Socio-technical barriers and bio-physical limits are relevant

We have recognized that context-specific socio-technical barriers may slow down or even prevent the adoption of conservation agricultural practices. Additionally, we have explored the climatic constraints that may explain why cover crop adoption is rather low in some regions of Europe. These examples stressed the importance of distinguishing between socio-technical barriers and bio-physical limits to understand current soil management practice adoption patterns and possible potentials to increase the adoption levels (Figure 4). If the socio-technical barriers

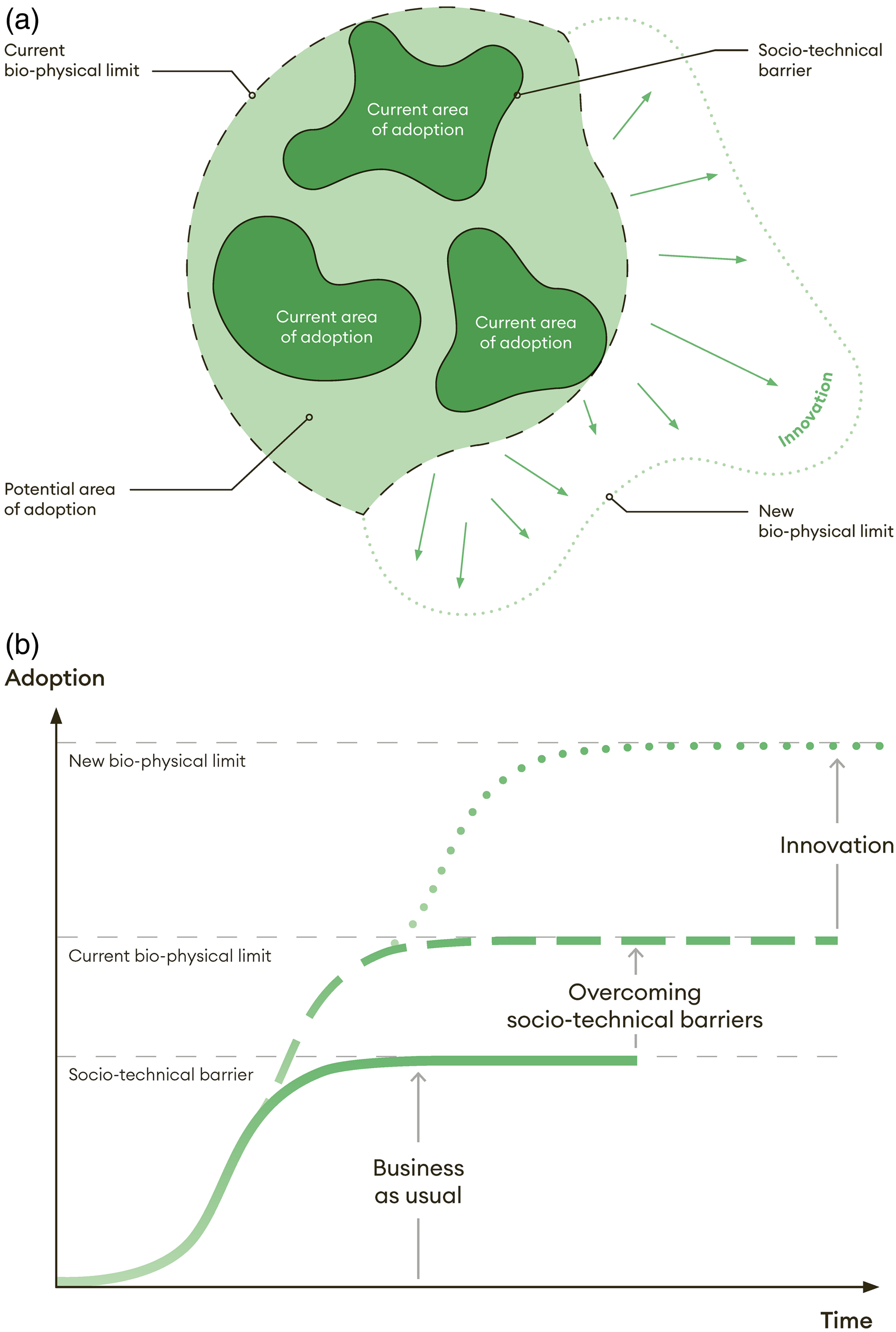


**FIGURE 4** Conceptual illustrations of bio-physical limits and socio-technical barriers that constrain the adoption of a soil management practice. (a) Bio-physical limits restrain the area where a soil management practice can potentially be applied. The current area of adoption is further restricted by socio-technical barriers. (b) The adoption of a practice may increase without specific measures until the further spread of a practice is either hampered by socio-technical barriers or limited by its current bio-physical limits. The socio-economic barriers can be overcome (dashed line) through changes in policies or utilization of other instruments (e.g., provision of knowledge, establishment of networks, increased availability of machinery, or financial incentives). Whereas innovation, research and development (e.g., new cultivars, new implements) are needed to move the bio-physical limits and expand the potential area of adoption to a new bio-physical limit (dotted line).

are the main obstacle for adoption, then changes in the social, political or economical environment of farmers could foster increases in the adoption levels of soil management practices. If, however, bio-physical limits are hindering an increase in the adoption of a soil management practice, innovation, research and development are needed to allow for increases in the adoption levels. Concerning cover cropping, possible innovations that may increase the adoption rates could be the undersowing of cover crops into established main crops to advance the date of cover crop germination (especially relevant in northern Europe; Arlauskienė & Šarūnaitė, 2023), the usage of site-adapted cover crop varieties and mixtures with higher climatic tolerance (Meyer et al., 2020), or where feasible, cover crop irrigation (Smit et al., 2019). Innovation to foster the development and adoption of soil management practices may arise from improving the science-practice interface (Thorsøe et al., 2023), for example, through the proposed network of agroecosystem living labs across Europe (McPhee et al., 2021).

In summary, three aspects were important when soil management practices were evaluated and decisions to foster their adoption were made: (i) synergies and trade-offs between tackling soil challenges, productivity, and profitability; (ii) bio-physical limits; and (iii) socio-technical barriers and enablers for adoption. Thus, the potential benefits of soil management practices are tapped efficiently when: (1) regional soil challenges are identified, (2) promising soil management practices to tackle these soil challenges are identified, (3) the synergies and trade-offs regarding desired outcomes are evaluated in the regional context, (4) the current levels of practice adoption are known and show potential for improvement, (5) both, socio-technical barriers and (6) bio-physical limits for adoption are identified, and finally, (7) appropriate measures to foster regional practice adoption or innovation are taken. With this study, we contributed to (2), (4), (5) and (6), while further efforts by all stakeholders are needed to attain the aspirational goal of sustainable soil management across Europe.

## 5 | CONCLUSIONS

We compiled an inventory of 53 soil management practices that can tackle soil challenges occurring throughout Europe. The adoption level of most soil management practices, despite their documented positive impacts, was reported to be low or heterogeneous. Thus, there is untapped potential to address soil challenges through increased adoption of appropriate soil management practices. The political and economical environment plays a crucial role in increasing the adoption of such practices, as shown here by exploring the factors hampering the adoption of conservation agricultural practices. Additionally, we demonstrated that climatic factors limit the adoption of cover cropping, which is a key practice in conservation agriculture. We argue that the full potential of soil management to tackle soil challenges can only be utilized when socio-technical and bio-physical constraints for soil management practices adoption are considered and, where possible, overcome. To this end, policy frameworks must enable regional and context-specific measures to promote the development and adoption of sustainable soil management practices.

## AUTHOR CONTRIBUTIONS

**Olivier Heller:** Writing – original draft; formal analysis; conceptualization; visualization; funding acquisition; data curation; writing – review and editing. **Claudia Di Bene:** Writing – review and editing; conceptualization; funding acquisition; investigation; data curation. **Pasquale Nino:** Writing – review and editing; conceptualization; funding acquisition; investigation. **Bruno Huygebaert:** Project administration; writing – review and editing; funding acquisition; investigation. **Aušra Arlauskienė:** Writing – review and editing; investigation. **Nádia L. Castanheira:** Investigation; writing – review and editing. **Suzanne Higgins:** Investigation; writing – review and editing. **Agota Horel:** Investigation; writing – review and editing. **Alev Kir:** Investigation; writing – review and editing. **Miriam Kizeková:** Investigation; writing – review and editing. **Marine Lacoste:** Investigation; writing – review and editing. **Lars J. Munkholm:** Investigation; writing – review and editing. **Lilian O'Sullivan:** Investigation; writing – review and editing. **Paweł Radzikowski:** Investigation; writing – review and editing. **M. Sonia Rodríguez-Cruz:** Investigation; writing – review and editing. **Taru Sandén:** Investigation; writing – review and editing. **Lina Šarūnaitė:** Investigation; writing – review and editing. **Felix Seidel:** Investigation; writing – review and editing. **Heide Spiegel:** Investigation; writing – review and editing. **Jarosław Stalenga:** Investigation; writing – review and editing. **Jaana Uusi-Kämppä:** Investigation; writing – review and editing. **Wieke Vervuurt:** Investigation; writing – review and editing. **Thomas Keller:** Investigation; writing – original draft; funding acquisition; supervision; conceptualization; writing – review and editing. **Frédéric Vanwindekens:** Investigation; conceptualization; writing – original draft; software; project administration; writing – review and editing; funding acquisition.

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Institute, Germany), Lisa Makoschitz (AGES, Austria), Rok Mihelič (University of Ljubljana, Slovenia), Paul Pardon (ILVO, Belgium), Mansonia Pulido-Moncada (AU, Denmark), Rachael Ramsay (AFBI, United Kingdom), Endla Reintam (EMU, Estonia), Gareth Ridgway (AFBI, United Kingdom), Greet Ruysschaert (ILVO, Belgium), María Jesús Sánchez-Martín (IRNASA-CSIC, Spain), Maud Seger (INRAE, France), Kamilla Skaalsveen (NIBIO, Norway), Bożena Smreczak (IUNG-PIB, Poland), Jannes Stolte (NIBIO, Norway), Michal Sviček (NPPC, Slovakia), Rafał Wawer (IUNG-PIB, Poland), Lena Weiss (Agroscope, Switzerland), Peter Weisskopf (Agroscope, Switzerland) and Ingrid Wesström (SLU, Sweden) for their contribution in collecting information for the inventory or the level of adoption of soil management practices. This work was funded under the European Joint Program for SOIL (EJP SOIL), which has received funding from the European Union's Horizon 2020 research and innovation programme: Grant agreement No 862695. Open access funding provided by Agroscope.

## CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Zenodo at https://zenodo.org/communities/i-sompe/.

## ORCID

*Olivier Heller* https://orcid.org/0000-0002-5918-4161
*Claudia Di Bene* https://orcid.org/0000-0002-3830-251X
*Pasquale Nino* https://orcid.org/0000-0002-7070-4586
*Bruno Huyghebaert* https://orcid.org/0000-0002-4245-2721
*Aušra Arlauskienė* https://orcid.org/0000-0002-1381-1887
*Nádia L. Castanheira* https://orcid.org/0000-0002-9276-1805
*Suzanne Higgins* https://orcid.org/0000-0001-6116-4410
*Agota Horel* https://orcid.org/0000-0001-9172-9902
*Alev Kir* https://orcid.org/0000-0002-6417-7636
*Miriam Kizeková* https://orcid.org/0000-0003-3025-6704
*Marine Lacoste* https://orcid.org/0000-0002-6635-873X
*Lars J. Munkholm* https://orcid.org/0000-0002-4506-9488
*Lilian O'Sullivan* https://orcid.org/0000-0002-5333-5758
*Paweł Radzikowski* https://orcid.org/0000-0001-8069-8696
*M. Sonia Rodríguez-Cruz* https://orcid.org/0000-0001-6748-3391
*Taru Sandén* https://orcid.org/0000-0002-9542-0117
*Lina Šarūnaitė* https://orcid.org/0000-0002-7080-7454
*Felix Seidel* https://orcid.org/0000-0002-6176-0017
*Heide Spiegel* https://orcid.org/0000-0003-1285-8509
*Jarosław Stalenga* https://orcid.org/0000-0002-3486-0995
*Jaana Uusi-Kämppä* https://orcid.org/0000-0002-3445-7290
*Wieke Vervuurt* https://orcid.org/0000-0002-0474-0597
*Thomas Keller* https://orcid.org/0000-0002-9383-3209
*Frédéric Vanwindekens* https://orcid.org/0000-0002-9117-7543

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## SUPPORTING INFORMATION

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