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Master Thesis

Challenges and opportunities for climate-smart agricultural soil management – a global survey

Submitted by

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Affidavit

I hereby declare that I have authored this master thesis independently, and that I have not used any assistance other than that which is permitted. The work contained herein is my own except where explicitly stated otherwise. All ideas taken in wording or in basic content from unpublished sources or from published literature are duly identified and cited, and the precise references included.

I further declare that this master thesis has not been submitted, in whole or in part, in the same or a similar form, to any other educational institution as part of the requirements for an academic degree.

I hereby confirm that I am familiar with the standards of Scientific Integrity and with the guidelines of Good Scientific Practice, and that this work fully complies with these standards and guidelines.

Vienna, 2021 August 15 Ulises Ramon ESPARZA ROBLES *(manu propria)*

This thesis is dedicated to my mother Mercedes,

my father Miguel,

my siblings Melisa, Iliana, and Jose,

and my niece Miranda.

“Wisdom begins in wonder.”

—Socrates

Preface

This research was conducted in close cooperation with *European Joint Programme Initiative EJP SOIL "Towards climate-smart sustainable management of agricultural soils", GA 862696*, in search for innovative soil management techniques outside Europe. Soil experts from Europe were not targeted as a mechanism to optimize efforts within the program.

EJP SOIL is an initiative aiming to "build a sustainable European integrated research system on agricultural soils and develop and deploy a reference framework on climate-smart sustainable agricultural soil management, to create the enabling environment that will maximize the contribution of agricultural soil to key societal challenges such as food and water security, climate change adaptation and mitigation, biodiversity preservation and human health" (Visser et al., 2019).

The perceptions and agricultural innovations from other regions in the world can provide potential external insights to the reference framework.

Acknowledgements

This thesis would not have been possible without the participation of all soil experts that spent their valuable time in the survey of this research. I thank every one of them.

I would like to thank my supervisors for their support during the elaboration of this master, and especially Dr. Rajasekaran Murugan, who guided me from the beginning of the data collection and enthusiastically advised me on the forms in which I could improve the final output.

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I am profoundly grateful to my parents for all the support they have given me. I could dedicate an entire book to show my gratitude for all the effort they have made to help me succeed. I also thank my siblings, who have always been there for to advise and support me.

I thank my friends back in Mexico, who were always in touch with me on this two-year journey, and the new friends I met during this time, especially my IMSOGLO colleagues.

Finally, I thank Celia for the marvelous moments we spent together during the master's studies and during our visit to Galicia, for all the lessons we learned together, and for her invaluable affection, time, and support. All of it undoubtedly made me enjoy the experience of this master's program even more.

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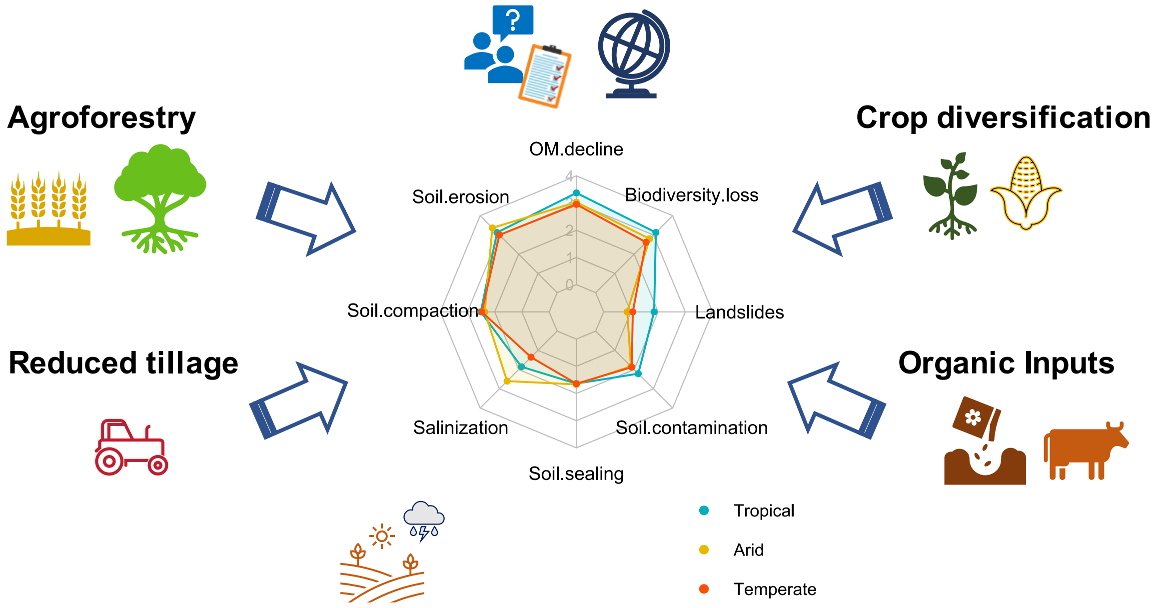
Graphical abstract



Abstract

Population growth coupled with a changing climate exert increasing pressures on food security and soil health across the globe. Climate is a key factor determining the severity of soil threats and the effectiveness of management practices addressing them, establishing the need for site-specific solutions. New strategies developed can be valuable and adaptable to other biophysical and socioeconomic conditions. To compile information on local soil management practices and understand the distribution of soil challenges and effective agricultural practices in different climates, we conducted a global survey to which 162 soil experts in 38 countries contributed. We analyzed the perceptions of the soil experts on soil threats and management practices rated on an importance scale from 1 to 5 in tropical, arid, and temperate climates. From eight selected threats, three received the highest importance across climatic zones: organic matter decline (4.1), soil erosion (4.1), and biodiversity loss (3.9). In tropical climates, a wider use of crop diversification strategies (intercropping, crop rotations) and agroforestry (alley cropping, shade trees) is perceived. Soil experts in temperate climates considered organic inputs less effective than experts from arid or tropical climates. As opportunities for climate-smart farm management, soil experts mentioned innovative techniques: Milpa Interspersed with Fruit Trees (MIAF), Zero-Budget Natural Farming, and Agrivoltaics, which we compared and analyzed for scaling up. This study directly collects the current vision of soil researchers across the globe and highlights concerns about the performance of agricultural soil management practices for mitigating soil threats. Our investigation synthesizes priorities for research in agricultural soil management comparing three major climate groups and highlights some of the new paths towards integral climate-smart soil management.

Keywords: sustainable farming, organic matter decline, soil erosion, farming innovation, soil experts.

Kurzfassung

Das Bevölkerungswachstum in Verbindung mit dem Klimawandel übt weltweit steigenden Druck auf die Ernährungssicherheit und die Bodengesundheit aus. Das Klima ist ein Schlüsselfaktor, der den Schweregrad der Bodenbedrohungen und die Wirksamkeit der Bewirtschaftungsmethoden bestimmt, mit denen diese Bedrohungen gemindert werden sollen. Das begründet die Notwendigkeit standortspezifischer Lösungen. Die für ein bestimmtes Klima neu entwickelten Strategien können unter Umständen an andere biophysikalische und sozioökonomische Bedingungen angepasst werden und dort wertvolle Dienste leisten. Um lokale Bodenbewirtschaftungspraktiken zu erfassen und die klima-spezifische Verteilung von Bodenbedrohungen und effektiven landwirtschaftlichen Praktiken zu verstehen, haben wir eine globale Umfrage durchgeführt, an der 162 Bodenexperten aus 38 Ländern teilnahmen. Wir analysierten die Aussagen von Bodenexperten in tropischen, ariden und gemäßigten Klimazonen und bewerteten sie auf einer Wichtigkeitsskala von 1 bis 5. Von acht ausgewählten Bedrohungen wurden drei in allen Klimagruppen am höchsten bewertet: Rückgang der organischen Substanz (4,1), Bodenerosion (4,1) und Verlust der biologischen Vielfalt (3,9). In tropischen Klimazonen werden Strategien der Anbaudiversifizierung und der Agroforstwirtschaft stärker genutzt. Bodenexperten in gemäßigten Klimazonen halten organische Betriebsmittel für weniger wirksam als in ariden oder tropischen Klimazonen. Als Möglichkeiten für ein klima-freundliches Farmmanagement nannten Bodenexperten mehrere innovative Techniken: Milpa kombiniert mit Obstbäumen (MIAF), Zero-Budget Natural Farming und Agri-Photovoltaik. Diese Methoden haben wir verglichen und im Hinblick auf eine breite Anwendung analysiert. Unsere Untersuchung fasst die Prioritäten für die Forschung im Bereich der landwirtschaftlichen Bodenbewirtschaftung in drei Klimagruppen zusammen und zeigt einige der neuen Wege zu einer ganzheitlichen, klimagerechten Bodenbewirtschaftung auf.

Schlüsselwörter: nachhaltige Landwirtschaft, Rückgang der organischen Substanz, Bodenerosion, landwirtschaftliche Innovation, Bodenexperten.

1. Introduction

The effects of climate change, in dynamic modern times with a rising population and more demanding diets, pressure more than ever food security across countries and climates (Lal, 2013), jeopardizing soil quality and compromising its functions (Rinot et al., 2019). As an effort to understand drivers and interactions of these pressures, a list of soil threats has been identified (Tóth et al., 2008) and modified with time (Stolte et al., 2016), which is essential to establish the most effective mechanisms to mitigate them (Barão et al., 2019). Still, the analyses often fail to associate the role of soil management practices as mitigation strategies and their effect in certain soil indicators. Some of these strategies are climate-smart management practices that bring promising positive effects both for soil resilience and climate mitigation (H. S. Jat et al., 2019; Tadesse et al., 2021; Westermann et al., 2018).

Increasing carbon inputs with residue management (Li et al., 2020), organic amendments (Gross & Glaser, 2021), agroforestry (Stefano & Jacobson, 2018), and crop diversification (including cover crops, intercropping and rotations) (Morugán-Coronado et al., 2020), or minimizing disturbance in tillage practices (Powlson et al., 2016) are some of the widely known strategies to improve soil quality (Z. Bai et al., 2018; Bünemann et al., 2018) and mitigate climate change (Amelung et al., 2020; Ogle et al., 2019). These practices also have the potential to enhance soil biodiversity (H. S. Jat et al., 2019; McDaniel et al., 2014), optimize water management (Kakraliya et al., 2018) and reduce soil erosion (Seitz et al., 2019; Turmel et al., 2015). Notwithstanding the available knowledge, limited information exists on how widely practiced soil management practices are across climatic conditions and their effect on soil threats (Stolte et al., 2016). Additionally, Bai et al. (2019) recognized that methods to evaluate the results after the implementation of climate-smart agricultural management practices to mitigate climate change, either individually or combined, create large uncertainties of their benefits. To tackle this issue, the harmonization of knowledge and methodologies to create and report soil indicators are considered a fundamental step in international soil projects nowadays (Panagos et al., 2020; van Beek et al., 2010; Visser et al., 2019) and a re-assessment of management practices need to be conducted, especially in their potential to store carbon (Chenu et al., 2019).

One of the factors that should always be considered in international or global assessments is the local climate variability, since it plays a crucial role in determining the severity of soil challenges (Le et al., 2018; Murphy et al., 2016; Powlson et al., 2016) and the effect of soil management practices to face them, especially when the socioeconomic conditions also vary (Rufino et al., 2021). Thus, integral local solutions worldwide addressing current needs and challenges (Barrera-Bassols et al., 2009; Pauli et al., 2018; Turrent Fernández et al., 2017) are a prominent source of knowledge and can act as adaptable role models for use in other socioeconomic and biophysical conditions and support the evolution of new strategies and farming systems (Lacombe et al., 2018). Nonetheless, the adoption of new practices is controlled in a certain extent by the paradigms of soil management practices on their use and effectiveness (Dumbrell et al., 2016; Turrent Fernández et al., 2017).

This study aims to synthesize the perceptions of soil researchers outside Europe about the main soil threats, strategies for soil management, needs and knowledge gaps across climatic conditions. In this sense, we have proposed to answer the following research questions: (1) what are the major threats for soils and the most effective soil management practices to mitigate them from the perspective of soil experts in different parts of the world? and (2) which innovative climate-smart soil management practices are known? We hypothesized that: (a) main soil threats and associated management strategies differ among soil experts‘ perceptions with experience in different climate, (b) one of the main concerns of soil researchers worldwide is the soil organic matter decline in agricultural soils and (c) there exist local soil management practices to solve one particular soil challenge or set of soil challenges that could be useful in other regions to create context-adapted innovations for soil management. Identified and described innovative sustainable soil management practices may serve as a potential source of inspiration for developing new strategies within the *European Joint Programme SOIL,* a project aiming to integrate knowledge, tools, and research community focused on the role of agricultural soils in the European Union (Visser et al., 2019). The results of this survey give an intriguing opportunity to share innovative sustainable soil practices that are currently practiced in different areas across the globe and to assess how researchers' perceptions across climates establish priorities to select soil management practices now and in the future.

2. Methodology

2.1. Sources of information

To assess the perceptions of researchers and gather innovative sustainable soil practices that are currently practiced across the globe, we developed an online survey targeted at soil experts with experience in different climates outside Europe as complementary study to activities in the *European Joint Programme SOIL*. The survey was created online using Google Forms and Jot Forms and was accessible in both platforms from 8 February 2021 to 15 April 2021 (full questionnaire available in Appendix A: Questionnaire). A corresponding pilot survey was conducted beforehand to receive feedback on the questionnaire from soil science colleagues. The survey links were sent via individual emails letting the experts chose which platform to use, especially for countries where Google platforms are not used. Research institutes, soil science societies and universities from different countries were a fundamental source of contacts as well as authors of relevant scientific publications (2010-2020) listed in Web of Science using the search terms “soil”, “climate” and the respective country or region, and whose abstracts had a focus on soil management practices within a context of a changing climate.

2.2. Questionnaire

The participants were asked to select a determined region to describe, defining its pedoclimatic conditions inside two categorical items: (1) the Köppen-Geiger climate group and subgroup (Beck et al., 2018; Peel et al., 2007), and (2) the soil order from the 12 defined in the Keys of Soil Taxonomy (Soil Survey Staff, 2014). There was the option to name the soil classification in the World Reference Base for Soil Resources (IUSS Working Group WRB, 2015) to be later transformed into the 12 group classification for simplicity. Subsequently, the first section encompasses the experience of the participant (area of scientific knowledge), and other ancillary questions. Thereafter, the rating questions follow for challenges, soil threats, effectiveness of four groups of soil management practices (crop diversification and vegetative practices, tillage, fertilizer inputs, and agroforestry) and their use in subcategories (see section Use of management practices). There was an explicit question with the purpose to identify the "innovative" or "unique" soil management practices for the area described by the participant. Finally, the questionnaire included a section for the researchers' vision about specific knowledge gaps and other relevant needs. Personal data is not shared and is to be destroyed three months after submitting this master thesis.

2.2.1. Rating questions

The use of a numeric rating system from 1 to 5 ("low" to "high"), classified as an interval scale, allows to quantitatively evaluate the perception of the participants by calculating descriptive statistics and conducting statistical tests between groupings where, depending on the data distribution, parametrical or non-parametrical tests can be used (Harpe, 2015). It is appropriate to calculate arithmetic means from the interval data as a descriptive statistic as well as the standard deviation if the response format contains at least 5 categories, treating the data as continuous variables (Harpe, 2015; Sullivan & Artino, 2013). Categorical data have been used in medical education studies (Harpe, 2015; Sullivan & Artino, 2013) and has also been used to, for example, analyze the adoption of agricultural practices (Van Hulst & Posthumus, 2016).

To avoid misinterpretations in our data, questions only stated the minimum and maximum value, i.e., 1 for "low" and 5 for "high", which creates a mental number line especially important for rating scales (Harpe, 2015) and that otherwise would resemble more to Likert-scale items making it less appropriate to conduct calculations (Jamieson, 2004). To represent the results in a more understandable classification, the coding changes in the charts, transforming the levels from numeric (1 to 5) to categorical levels ("very low", "low", "medium", "high" and" very high"). The recommended graphical display of the results for this type of quantitative surveys are diverging stacked-bar charts (Robbins & Heiberger, 2011), therefore, all the rating questions were plotted as such in this document. To plot the charts we used the packages *ggplot2* (Wickham, 2016), *likert* (Bryer & Speerschneider, 2016) and *HH* (Heiberger, 2020) in RStudio (version 1.4.1106, R version 4.0.5) (R Core Team, 2021; RStudio Team, 2021).

2.2.2. Open questions

Primary challenges, driving factors for selecting a management practice, and their relevance in decision-making, along with existing knowledge gaps and research needs, were identified as open questions and later transformed into more manageable categories to discuss the most mentioned topics and the perspectives' diversity. This step can be done with text mining software (Gupta & Lehal, 2009) to analyze answers. However, the process was done manually to avoid the confusion of similar terms mentioned, since the number of participants was manageable.

2.3. Analysis of global perceptions

183 responses were received, which went through a process of confirmation of the university or institute affiliation and the suitable expertise. After the selection of valid candidates, the number was reduced to 162 participants from institutes and universities distributed in 38 countries in different global regions (more information in Appendix B: Participation by country). Later, the data was organized and transformed into a table format: one row by soil expert, columns for questions and cells for the responses to the questionnaire. The category "zone" was created based on the location of the reported institute or university to which the participant belonged. The participants were allocated in 6 groups: Africa, Asia, Latin America, US&CA (United States and Canada), and A&NZ (Australia and New Zealand). Since 39 participants selected more than one option for the Köppen-Geiger climatic group, the creation of the grouping variable "climate" reduced the number of observations to 120, yielding 3 mutually exclusive groups: Tropical, Arid and Temperate. The other 3 remaining observations selected the climate "Cold", creating a group too small for analysis. Sub-climates specifying the moisture regime were not considered in climate grouping due to the small number of experts per group that this step created. Mutually exclusive grouping variables, like here geographical region (zone) and climate (Table 1), allowed to test for significant differences in the perceptions and disentangle if these variables conditioned soil management. To identify if the change from 162 to 120 soil experts significantly changed the representativity of climate and zones (Table 1), Fisher's Exact Test was used, assuming both samples as independent. Furthermore, the mean of each rating question did not change more than 0.1 units by this reduction of observations, from which 60% keep the same value when rounding to one decimal digit. Therefore, statements made by climate group represent well the general group of all participants. Percentages indicated for comparisons between climate groups or geographical zones in

each figure were calculated by dividing the number of responses of each group by the total responses.

Table 1. Characteristics of the participants that selected only one climate and their representation in the total sample.

	All participants	Those who selected only one climate	p-value[†]
	n=162	n=120	
Climate main groups[‡]			
Tropical	74 (45.7%)	48 (40.0%)	0.341
Arid	59 (36.4%)	30 (25.0%)	**0.041**
Temperate	61 (37.7%)	42 (35.0%)	0.647
Cold	3 (1.8%)	-	-
Geographical zone			
Africa	23 (14.2%)	17 (14.2%)	0.994
Asia	41 (25.3%)	29 (24.2%)	0.826
Australia & NZ[⁋]	7 (4.3%)	5 (4.2%)	0.949
North America	42 (25.9%)	34 (28.3%)	0.652
South America	49 (30.2%)	35 (29.2%)	0.845
Institute			
University	85 (52.5%)	63 (53.3%)	0.996
Non-academic	77 (47.5 %)	57 (47.5%)	0.996

[‡] Köppen-Geiger classification. Some participants selected more than one climate for the zone they described, so percentages–in the column "All participants" are not mutually exclusive and do not sum 100%.

[⁋] NZ: New Zealand

[†] H_0: proportions do not change between grouping of 162 and 120 participants.

The ratings were divided into two categories: higher values (4 and 5) and lower ones (1, 2 and 3). This allows to interpret the result as differences in rating in the Fisher's Exact test of independency of each 2x3 matrix. One matrix corresponds to one question and is created by the two rating categories and the three climate groups. Other possibility is the comparison between the ratings (high or low) and two items (either practices or threats instead of climate groups) to assess whether one practice or threat is rated higher by soil experts across the globe.

Fisher's Exact test, in comparison to the Chi-squared test of independency, has the advantage of dealing with values lower than 1 or lower than 5 in more than one expected frequency of a cell in the matrix (Bewick et al., 2004 cited in Mchugh, 2013), although the former performs better with $N < 300$ observations. This last condition is not a limitation for the analyses made in this study. Results of relation between variables (questions) and groups (climate) are reported with their respective p-value (significance of tests for all ratings questions can be found in Appendix C: Descriptive statistics). Special attention was given to questions where the created diverging stacked-bar charts suggested differences between the climates or zones.

With the aim to monitor the use of climate-smart (or non-conventional) practices, we opted to focus the attention on the rating of certain practices (see Appendix C: Descriptive statistics and Results section). Four main categories (crop diversification and vegetative approaches, tillage, organic inputs, and agroforestry) were presented and practices inside them were rated by the soil experts according to the extent of use inside selected grouping, e.g., in the category "Tillage", three practices were rated: Inversion tillage, No tillage and Reduced tillage. The items within each category also generate a mental comparison between them that is reflected when analyzing their average ratings. A final score of each category was calculated for each participant by averaging ratings of the practices within them (see Results section) from practices considered in this study as "non-conventional" or "climate-smart" (for Tillage, only the last two mentioned earlier), and then tested for normality. Nonetheless, due to the controversies about the use of parametrical tests to analyze interval data (Harpe, 2015; Jamieson, 2004), the final scores were tested from each category using a non-parametric test (Kruskal-Wallis Rank Sum Test). All hypotheses were tested at a 95% of confidence ($\alpha = 0.05$). All statistical analyses were conducted in RStudio (version 1.4.1106, R version 4.0.5) (R Core Team, 2021; RStudio Team, 2021).

2.4. Innovative or unique practices

All answers from the open questions were analyzed to identify possible outstanding innovative or unique practices in the region for each participant. Most mentioned practices or farming systems were identified and categorized. Special attention was given to practices described as successful for the region in economic, social and/or environmental aspects. The categorization of the answers does not mean a sharp division between type of practices but a way to list them according to the benefits they bring or the similarities between them.

3. Results

The three expertise fields of the 162 soil experts were related to soil science (40%), agroecology (18%) or sustainable agricultural management (13%). The number of soil researchers in the three climates were similar (Table 1), with a good sample size for comparisons.

Before starting the central questions, the soil researchers were asked to answer an open question about the "most important challenge in the selected country or region to be described" being as specific as they wanted to. Social, economic, and environmental issues were pointed out such as poverty, political stability, climate variability, land-use change or management-related challenges. Interestingly, from the diverse categories identified for this question, the most frequent concepts were related to soil organic matter (20%), soil erosion (15%) or low fertility levels (13%), as well as achieving sustainable agricultural management (10%). The other most mentioned categories for major challenges can be found in Appendix D: Major challenges. This fact coincided with the selection of major land resource stresses (Eswaran et al., 2005) for their region, where 79% of the participants chose "Low organic matter" (Appendix E: Pedoclimatic conditions), the most frequent selected item followed by "Low moisture and nutrient status" and "Low nutrient holding capacity", stated in a good share especially by soil experts in Africa.

3.1. Soil threats

Among all the participants (n=162), biodiversity loss, soil organic matter decline and soil erosion were the most important soil threats (mean rating [SD] = 3.9 [1.0], 4.1 [1.0] and 4.1 [1.0], respectively) from the eight defined in this study (for all mean and standard deviation [SD] values, see Appendix C: Descriptive statistics). This fact remained for the data grouped by climate (n=120, Figure 1), finding a relation between climate and the rating categories only significant for the organic matter decline (p = .040), where it was perceived with a high importance by 90% of the soil experts in tropical climates (Figure 1). On the other hand, soil erosion (p = .32) and biodiversity loss (p = .08) did not show a significant relation with climate for the threshold define in this study (p< .05).

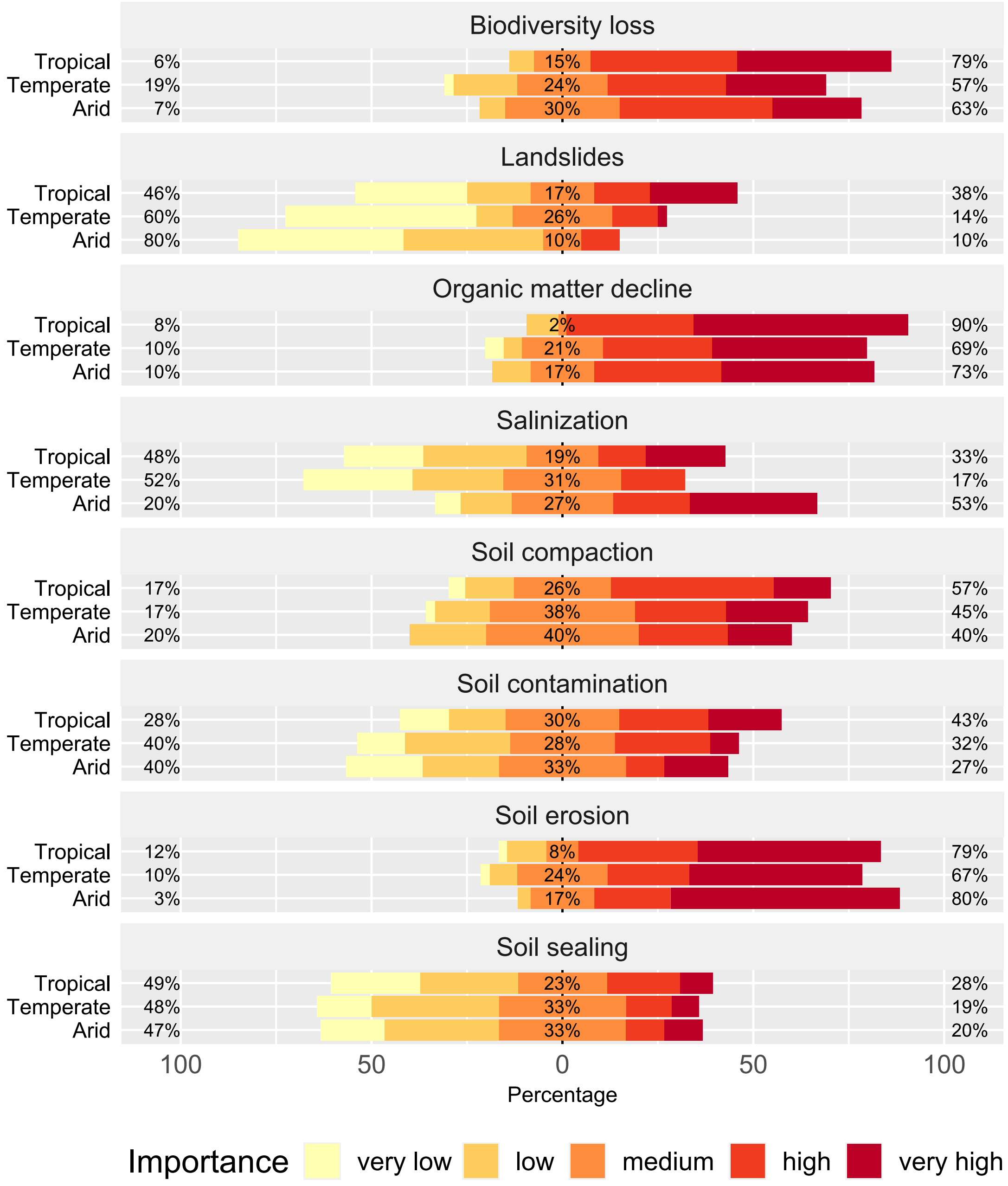


Figure 1. Importance of the eight selected soil threats as perceived by surveyed soil experts (n=120) grouped by climate. The percentages on the left represent the proportion of the two lowest ratings, in the middle that of the medium ratings and on the right side that of the two highest ones.

Although not as higher in importance for the experts as the threats mentioned before, salinization and landslides (mean rating [SD] = 2.9 [1.3] and 2.4 [1.3], respectively) did differ with climate (p = .005 and p = .007, respectively). The relevance for the former was rated higher in arid climates; for the latter, in tropical ones (Figure 1; Appendix C: Descriptive statistics). For the remaining threats, we could not observe a similar phenomenon. Despite the slightly higher rating for soil pollution in tropical climates (Figure 1), the test of independence showed no significant relation between climate and rating for this soil threat ($p = .36$), neither did compaction nor sealing ($p < .28$).

3.2. Management practices

3.2.1. Detrimental practices

From the five detrimental practices for soil among climates and geographical zones (Appendix C: Descriptive statistics; Appendix F: Other stacked-bar charts for rating answers), the lack of organic matter inputs and monocropping systems were considered as major detrimental practices (mean [SD] = 4.1 [1.0] and 4.0 [1.0], respectively) followed by intensive tillage (3.9 [1.1]). This latter together with the use of heavy machinery use and intensive mineral fertilization were not as detrimental to soil experts in Africa and A&NZ (Australia and New Zealand) as for other regions. Nonetheless, the degree of detriment of the five practices mentioned is not perceived differently between the climates ($p > .27$).

3.2.2. Effectiveness of selected practices

As a mechanism to mitigate the threats and minimize the detrimental management practices, a set of strategies was defined (Figure 2), all of which obtained high effectiveness ratings (means from 3.7 to 4.0, n=162). From the five proposed soil management categories, nutrient management and agroforestry were perceived with a higher effectiveness in tropical conditions when compared to other climates ($p < .02$). In contrast, organic inputs were rated lower ($p = .005$) by soil experts with expertise in temperate climates (3.5 [1.2]) than those in tropical (4.0 [1.1]) or arid zones (4.2 [0.9]). On the other hand, the last two categories (tillage and crop diversification) do not present associations between climate with perceived effectiveness ($p > .12$).

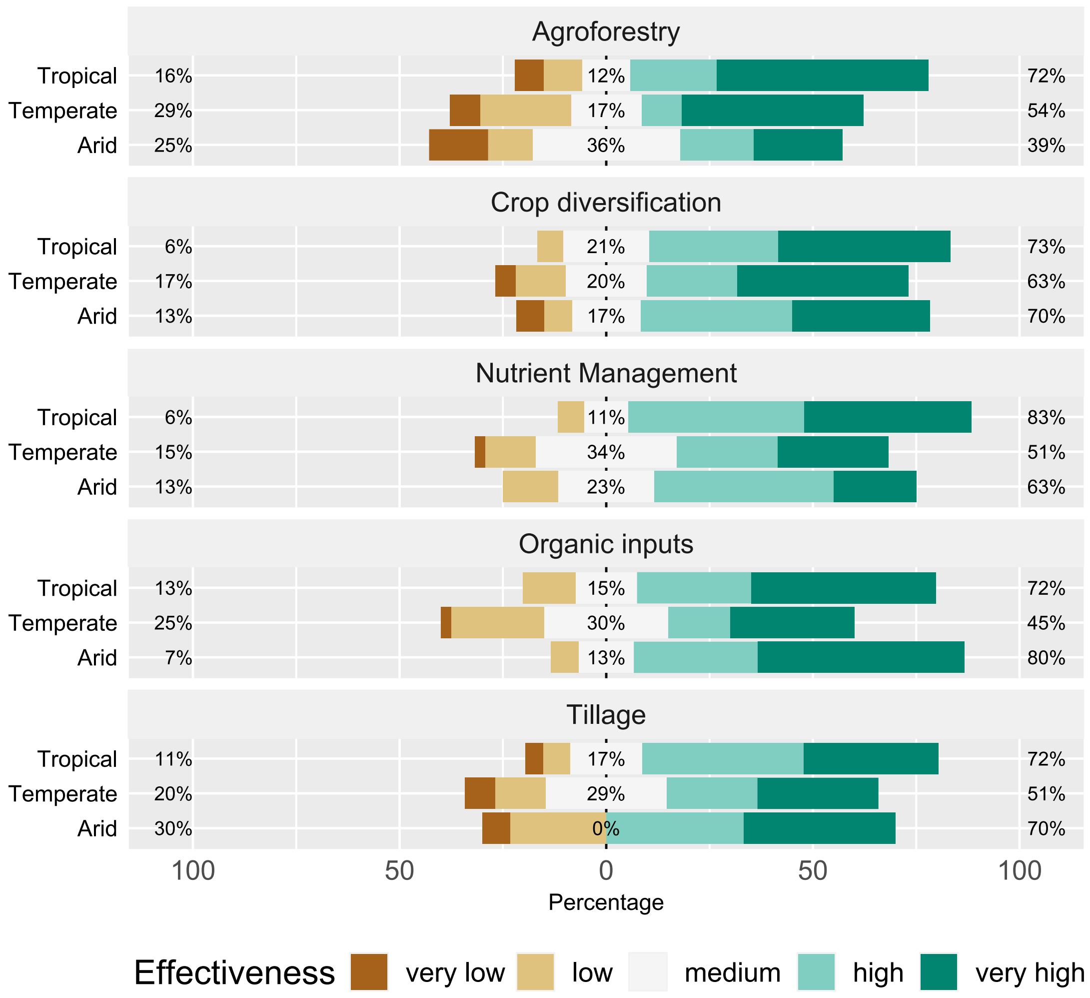


Figure 2. Effectiveness in mitigating soil threats by selected management strategies according to the perception of soil experts (n=120) grouped by climate. The percentages on the left represent the proportion of the two lowest ratings, in the middle that of the medium ratings and on the right side that of the two highest ones.

3.2.3. Use of management practices

The average scores for each grouping of strategies are shown in Table 2 and represent the mean rating of their practices, which are considered in this study as non-conventional or opposed to the detrimental practices mentioned earlier: crop diversification, tillage, organic inputs, and agroforestry.

Table 2.Extent of use of selected management strategies by soil experts (n=120) in different climate groups. Bold rows were calculated from the individual ratings of the practices listed below. Different letters mean significant (α=0.05) differences in the same row (Bonferroni correction).

	Climate			**p-value**[‡]
	Tropical	**Arid**	**Temperate**	
Crop diversification	**3.2 (1.0)[†]a**	**2.6 (0.9)b**	**2.6 (0.7)b**	**0.002**
Crop rotations	3.6 (1.2)	3.1 (1.2)	3.2 (1.2)	
Inter/Mixed cropping	3.2 (1.0)	2.2 (1.3)	1.8 (0.7)	
Cover crops	3.3 (1.0)	2.4 (1.2)	2.0 (1.0)	
Tillage	**2.6 (1.2)a**	**2.6 (1.1)a**	**2.9 (1.2)a**	**0.411**
No tillage	2.4 (1.3)	2.5 (1.3)	3.0 (1.6)	
Reduced tillage	2.9 (1.3)	2.7 (1.3)	2.9 (1.2)	
Organic amendments	**3.1 (1.0)a**	**2.6 (0.8)a**	**2.6 (0.8)a**	**0.026**
Crop residues	3.4 (1.0)	3.2 (1.1)	3.5 (1.3)	
Farmyard manure	3.4 (1.4)	3.2 (1.4)	2.9 (1.3)	
Compost	3.1 (1.3)	2.7 (1.1)	2.3 (1.2)	
Animal dung slurry	2.5 (1.2)	2.1 (1.2)	2.4 (1.2)	
Green manures	2.6 (1.2)	1.7 (0.8)	2.2 (1.1)	
Agroforestry	**2.7 (1.1)a**	**2.0 (0.8)b**	**2.1 (0.9)b**	**0.007**
Alley cropping	2.6 (1.4)	1.5 (0.8)	1.7 (0.8)	
Windbreaks	2.6 (1.4)	2.3 (1.3)	2.6 (1.4)	
Shade trees	2.9 (1.2)	2.0 (1.1)	2.1 (1.2)	
N[⁋]	48	30	42	

[†] Mean (SD). The perception scale for means is: 1 = “low”, 5 = “high”.
[‡] p values from Kruskal-Wallis rank-sum test.
[⁋] Number of participants by climate group

3.2.3.1. Crop diversification and vegetative approaches

In tropical climates, crop diversification and vegetative approaches obtained a higher mean score (3.2) than arid (2.6, *p* = .024) or in temperate climates (2.6, *p* = .007). The main contributors to this difference are the higher use of mixed and intercropping practices (p< .001) and to the slightly higher perception of crop rotations by soil experts in tropical climates (Appendix C: Descriptive statistics; Appendix F: Other stacked-bar charts for rating answers).

3.2.3.2. *Tillage*

It was not the case for tillage, whose practices, no tillage and reduce tillage, are seen with a similar use across climates (*p* = .411). Interestingly, no tillage alone marginally showed to have more presence (*p* = .06) in temperate climates (3.0 [1.6]) than in tropical (2.4 [1.3]) or arid (2.5 [1.3]). Reduced tillage as well as inversion tillage did not differ by climate (*p* > .32).

3.2.3.3. *Organic Inputs*

For the statistical comparisons between mean scores (Table 2), although the tropical climates have a higher mean rating in the use of organic inputs (3.1) than the other two climates (2.6 for both), this was not statistically significant (*p* =0.068) for our confidence threshold. Inside the strategies the option “Mineral fertilizers” was included as comparative measure when asking the perceived frequency for the organic fertilizing practices. According to soil experts’ perceptions (n=162), carbon additions came usually as farmyard manure (3.2 [1.4]) and crop residues (3.4 [1.1]) but are not as frequently used compared with the use of mineral fertilizers (4.3 [1.0]). The use of both carbon inputs does not differ by climate (*p* = .39 and *p* = .23, respectively). On the other hand, green manures as an organic input, obtained very low ratings for use in general (52 to 79% low ratings) and yielded the lowest in arid climates (1.7 [0.8]) with basically no high values, followed by temperate and tropical regions (2.2 and 2.6 [1.1 and 1.2]). The independency test showed a significant relationship between the variables rating and climate (*p* = .007). The least used strategy was biochar (1.6 [0.8]), with low ratings selected (82-97% of soil experts) for the all the climates (see Appendix C: Descriptive statistics and Appendix F: Other stacked-bar charts for rating answers).

3.2.3.4. *Agroforestry*

In comparison to the previous strategies, the agroforestry practices were rated the lowest (Table 2). Nevertheless, their mean score of use is climate dependent (*p* = .007), where the tropical climates lead again the highest use (2.7 [1.1]) between the groupings. In these climates, both alley cropping and shade trees were rated higher than in temperate or arid areas, (*p* = .002 and *p* = .003), respectively. Wind breaks had also low mean ratings (2.6, n=162) but did not differ significantly related with climate for our threshold (*p* = .88).

3.2.4. Soil indicators

When it comes to the soil improvement, the importance of most soil indicators had little discrepancies between the climate groupings (for a separation of ratings into different climate groups see Appendix F: Other stacked-bar charts for rating answers). Three main properties were rated the highest by most soil experts (Figure 3) when selecting soil management practices: soil nutrients, water holding capacity and soil carbon content (mean [SD] = 4.2 [1.0], 4.1 [1.0] and 4.1 [1.1], respectively, n=159). Aggregate stability, pH, porosity, and soil biodiversity were rated lower than the mentioned before (p<.05) and did not get significant different ratings between them. The tests of independency showed that only the rating of soil biodiversity differed with climate (*p* = .002), where soil experts in tropical (3.8 [1.1) and in arid climates (3.6 [1.2]) rated it higher than the ones in temperate regions (2.9 [1.2]). Coincidentally, this awareness pattern by climatic region was comparable to the one for the soil threat Biodiversity loss (Figure 1).

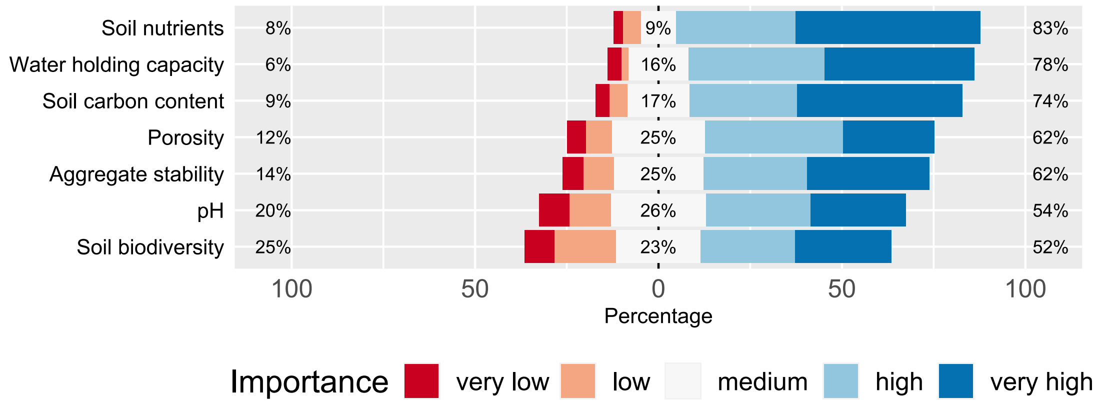


Figure 3. Importance of the soil properties in search of improvement when selecting soil management practices according to the perception of soil experts across the globe (n=162). The percentages on the left represent the proportion of the two lowest ratings, in the middle that of the medium ratings and on the right side that of the two highest ones.

3.3. Innovative soil management practices

3.3.1. Categories

The open question “unique or innovative practices in the selected region” received answers from 71% of soil experts. General comments made emphasis in the reduction of the soil disturbance by tillage and in the increase of carbon additions to restore soil health and biodiversity in diverse manners. Most answers were related to concrete farming systems (Conservation Agriculture (9), Integrated farming systems (9), Precision farming (7), Regenerative agriculture (8)) or to certain management practices (Reduced or no tillage (15), organic inputs (11), nutrient management (10), crop diversification (6) agroforestry (6). A broader list of management practices categories can be found in Appendix G: Unique or innovative practices.

3.3.2. Special practices mentioned

Three special farming systems and their characteristics are summarized in Table 3: (1) Milpa interspersed with fruit trees (MIFT, MIAF for acronym in Spanish), developed in Mexico, (2) the Zero-budget farming system from India (both thought for a smallholder perspective) and (3) Agrivoltaics, for modern mechanized agriculture.

3.4. Needs and perspectives for innovative soil management practices

3.4.1. Areas where strategies need to be developed

When we look at the needs by geographical region, the most important knowledge gap is to find better mechanisms for coordination between researchers and policy makers (highest mean rating = (4.1 [1.0], n=162), especially for Latin America (4.4 [0.8]). The following main areas to improve are the creation of strategies for specific soils (3.8 [1.1]) and studies for cost-effectiveness and applicability (3.8 [1.0]). The lowest mean rating among soil experts was for the development of fertilizer guidelines (3.4 [1.1]), but their development is more important for Latin America (3.7 [1.0]) and Africa (3.7 [1.1]) than for the other regions (3.1 [1.1]) (Figure 4). Mechanisms for knowledge sharing from researchers to farmers is another fundamental element (3.7

Table 3. Innovative or unique agricultural management practices or farming systems mentioned by soil experts.

Strategy	Advantages	Challenges	Carbon benefit	Applicability	References
Milpa interspersed with fruit trees in Mexico	• Carbon sequestration in soil and tree biomass • Soil erosion reduction • Food security: maintaining staple crops in the system • Source of employment • Fruit crops give higher revenue • Land equivalent ratio > 1	• Higher knowledge level needed • Higher labor required • Initial investment needed • Fruits need to be adapted to market conditions	• Pruned branches and residues are placed in the highest retention zone: under the fruit tree • 1.08 to 2.30 % of SOC† increase in at the soil retention area • Organic matter removed by erosion is minimized	• Designed for steep slopes (8-50%) • When used in flatter areas, the distribution of light for the different crops and fruit trees takes more importance	• Turrent-Fernández et al., 2016 • Cortés-Flores et al., 2016 • Duché-García et al. 2021 • Regalado-López et al., 2020
Zero-budget natural farming in India	• Microbial mixture "*jivamrita*" require less time and space than compost • Increase of farm biodiversity • Protection of soil by mulching • Yield increase • Reduction of production costs and need of credit	• Natural inputs can be not enough to reach crop nutrient demands • Specialized knowledge required • Transition from high input systems may reduce the production (mainly due to N supply)	• Rapid stabilization of SOC by addition of "*jimavrita*" • 10-21% potential increase in SOC by mulching • Reduction in fertilizer use decrease about 75% greenhouse gas emission from agricultural soils	• Low-input small farm holdings (<5 ha) • Soil with poor fertility status • Soils prone to degradation • Transition from organic agriculture systems also possible	• Smith et al., 2020 • Khadse & Rosset, 2019 • Veluguri et al., 2021 • Khadse et al., 2018
Agrivoltaic systems	• Provided shadow reduces evapotranspiration and respiration stress, increasing water-use efficiency • Reduction of elevated temperatures by the underlying crop enhances the correct functioning of the panels	• High installation costs (masts, panels, storage, transmission) • Design knowledge is crucial: height and pillar separation for machinery • Shadow reduces yield when water is non-limiting	• Above and below ground biomass yield boosts SOC • CO_2 uptake increased by minimized stress • Increased land productivity by 70% • Lower carbon emissions from energy production	• Areas with sunny weather forecast most days of the year • Areas or countries where cropping land is scarce, but flat • Dry environments avoid the formation of gullies by heavy rainfall	• Dinesh & Pearce, 2016 • Weselek et al., 2019 • Barron-Gafford et al., 2019 • Dupraz et al., 2011 • Amaducci et al., 2018

†SOC: Soil organic carbon

[1.1]), perspective that differed the least between regions (Figure 4). For the countries in our study, the areas US&CA, Asia, and A&NZ similar behavior in rating this question whereas Latin America and Africa obtained similar ratings, generally higher than the former three.

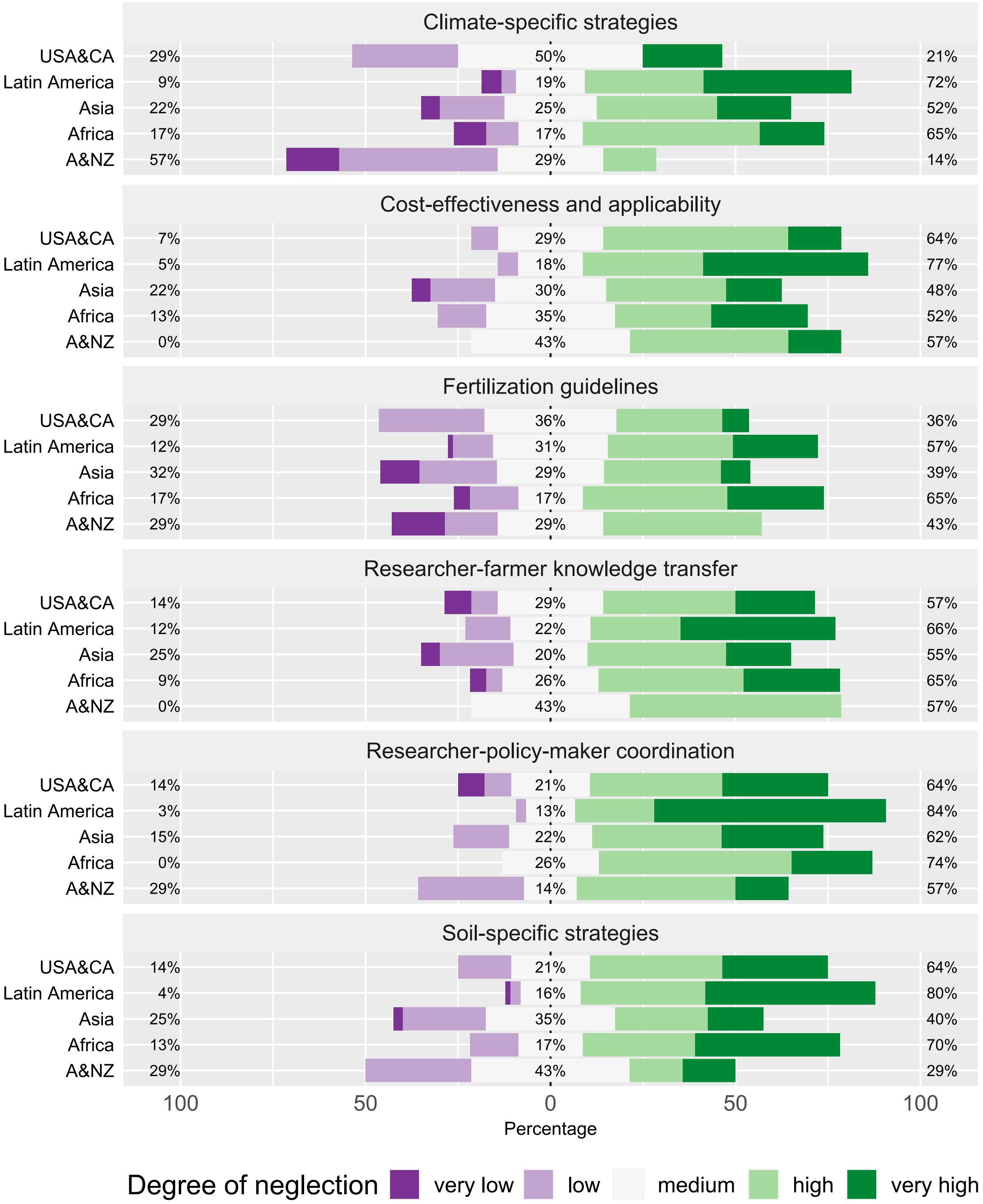


Figure 4. Main neglected areas in research (knowledge gaps) to be addressed for the region and their importance according to the perception of the soil experts (n=162) grouped by geographical region zone (USA&CA: United States and Canada, A&NZ: Australia and New Zealand). The percentages on the left represent the proportion of the two lowest ratings, in the middle that of the medium ratings and on the right side that of the two highest ones.

3.4.2. Needs for farmers

Comparing the five options given (Figure 5), soil data (mean rating [SD]= 3.8 [1.1]) was considered by soil experts (n=159) as the least important need. Nevertheless, there was only one marginal difference between the ratings of soil data and training (p = 0.064). Other comparisons did not show differences with a higher significance. The other four needs for farmers presented high ratings: economic incentives (4.3 [0.9]), field demonstrations (4.2 [0.9]), training (4.2 [1.0]), and knowledge (4.1 [1.1]). An interesting fact was that soil experts in tropical climates considered knowledge as a more important need for stakeholders than those in temperate climates (*p* = .017). For a separation by geographical zones and climates, see Appendix F: Other stacked-bar charts for rating answers.

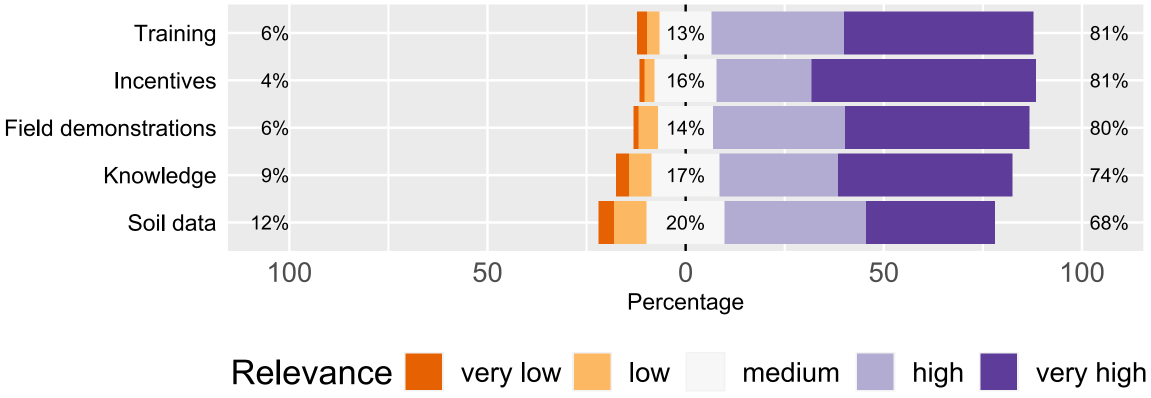


Figure 5. Farmer’s needs and their relevance according to soil experts (n=162). The percentages on the left represent the proportion of the two lowest ratings, in the middle that of the medium ratings and on the right side that of the two highest ones.

4. Discussion

4.1. Climate effect on soil threats

Depending on the temperature and precipitation conditions, soil threats can be either reduced or intensified. Nevertheless, the threats in our survey that showed differences between perceptions of soil experts grouped by climate were only salinization, landslides, and soil organic matter decline (Figure 1). Soils in arid climates are susceptible to suffer not only salinization but also desertification (Okur & Örçen, 2020). On the other hand, the occurrence of landslides in zones with humid-warm tropical climates is commonly associated with strong events of rainfall (Gaidzik et al., 2016). The differences in the awareness of these threats between the three climatic groups were detected by our survey, but other were difficult to notice. In the case of soil experts' main priorities, i.e., organic matter decline, erosion, and biodiversity loss, the awareness of latter two did not vary cross climates. The high ratings of the three soil threats show the high relationship between them (Stolte et al., 2016). This was consistent with the opinion of farmers in China in the study of Barão et al. (2019), who considered soil erosion and soil organic matter decline as two most important threats, but in the study, the awareness of biodiversity loss was not assessed. Stolte et al. (2016) associate the organic matter decline in mineral soils with negative effects to biodiversity and to erosion by both water and wind, and they also associate it as a main cause of desertification. Our results also showed the close relation between the perceived importance of organic matter decline and the high awareness of soil erosion and biodiversity loss.

Some other factors, like the acid nature of some tropical soils (Zhang et al., 2019) and their susceptibility of further acidification by, e.g., nitrogen inputs (Lu et al., 2014), could explain the perceptions of soil contamination. This soil threat, together with compaction and sealing, obtained intermediate values across climates (Figure 1) showing no differences in their awareness. Nevertheless, some researchers in tropical climates strongly made emphasis in that soil acidification should have been considered in the survey as a separate item, not as a possible subsection of contamination, due to the high relevance it has for their region. Soil acidification can reduce the yield of crops (Zu et al., 2014) by affecting the supply and availability of mineral nutrients (IPBES, 2018) like calcium, potassium and magnesium. Despite the allocation of importance in tropical climates, soil research should focus efforts to stopping and reversing soil acidification of agricultural land, especially the one induced by human intervention.

4.2. Climate effect on soil management practices

Heavy machinery, intensive tillage and fertilizer use, monocultures, and the lack of organic input were practices that generated perceived a high detrimental effect that worsen in the long-term the soil organic carbon (SOC) contents and none of them differ in terms of climate. This result was consistent with the meta-analysis of full-inversion tillage systems of Angers & Eriksen-Hamel (2008), where they did not find relation between the accumulation of SOC and to soil properties or climate and rather considered that increases in soil C storage in tillage system comparisons can be attributed to yields and C inputs. Usually management practices based only on the cost-benefit balance of economies of scale (Stolte et al., 2016) lead to unsustainable systems causing or intensifying soil degradation. For example, McDaniel et al. (2014) considered that monocultures are responsible for the soil biodiversity loss when they replace rotations. Other examples are the creation of a hardened layer below the tillage depth (plow pan) that retards water movement (Seo et al., 2016) or the mineral fertilization, when it is not accompanied by organic material (Gram et al., 2020). The substitution or minimization of this detrimental practices for other more sustainable can not only be an option to reduce the risk of soil threats but also increase the productivity and sustainability of agricultural fields (R. S. Jat et al., 2021). Still, the utilization of certain promising soil management practices, as they are sometimes called (Z. Bai et al., 2018), and their effectiveness perception vary depending on the climatic zone where they are applied according to our study.

4.2.1. Crop diversification

The effectiveness of crop diversification strategies was perceived similarly by soil experts in different climates (Figure 2), but not their use (Table 2). McDaniel et al. (2014) found in their meta-analysis comparing 122 studies all over the world in crop rotations and the inclusion of cover crops, that climatic variables (mean annual temperature and precipitation) were correlated with the carbon increase in soils. Their finding differed from the results of our study in terms of effectiveness, at least for SOC increase. In terms of use, the three considered practices in this category (mixed- or intercropping, crop rotations, and cover crops) were perceived with a higher use in tropical climates. The poor integration of intercropping practices and crop rotations in agriculture was reported by Wezel et al. (2014) in their review for temperate regions. This phenomenon can be related to the traditional multiple cropping systems developed in the tropics (Francis & Adipala, 1994), especially for soils with low levels of organic matter and fertility. The increase of crop diversity in such climatic conditions not only reduce the challenging effect of pest and diseases in comparison to monocrops (Afrin et al., 2017) but also diversifies the income in land with low agro-ecological potential (Gatzweiler & von Braun, 2016). Moreover, intercropping makes a better use of the resources (Morugán-Coronado et al., 2020), crop rotations help biodiversity and increase total and microbial SOC (McDaniel et al., 2014), whereas cover crops retain soil and keep nutrients in the topsoil avoiding leaching (Tully & Mcaskill, 2020). All these crop diversification strategies can be combined to maximize their benefits.

4.2.2. Tillage

Differences in tillage were not perceived for either effectiveness or use among climates (Table 3). It has been found that SOC increases by conservation tillage as climate-smart agriculture practice happen only when residues are returned (X. Bai et al., 2019), showing the relevance of this type of C source to soil. It is important to point that the matter of debate when changing tillage systems has been mostly about the distribution of carbon along the profile (Dimassi et al., 2014; Sommer et al., 2018), what may also have an influence on the perceptions. When comparing the no tillage to conventional tillage, Pittelkow et al. (2015) found that aridity index was one of the most important factors influencing crop yield, just after the crop category where the no tillage showed a better performance in rainfed dry climates. This fact was not reflected in the perception of scientists in terms of effectivity. Instead, soil experts in temperate climates were the ones who perceived slightly more implementation of no tillage than other climates (Appendix C: Descriptive statistics; Appendix F: Other stacked-bar charts for rating answers). In terms of yield declines after reducing tillage practices, tropical or subtropical regions suffer them in a larger extent than in more temperate ones (Lundy et al., 2015). Nonetheless, factors other than climate may explain the variations perceived in effectiveness such as slope, where if steep enough, not even conservation tillage helps to reduce the erosion rates and other strategies should be employed (Turrent Fernández et al., 2017).

4.2.3. Organic amendments

Surprisingly, organic inputs were reported less effective in temperate climates in comparison with the tropical or arid climates (Figure 2). This can be explained by the findings of Gross & Glaser (2021) in their study of manure application, in which this amendment practice generates a higher relative increase of SOC for sub-tropical than for non-tropical climates, attributing this response ratio to the lower SOC levels of soils in the tropical and sub-tropical conditions. Nevertheless, the effect of SOC increase in real terms (and not relative) is higher under non-tropical climates than in soils under sub-tropical conditions (Gross & Glaser, 2021).

In terms of use, soil experts in tropical climates reported an average higher score for organic amendments in comparison to arid or temperate climates (Table 3). One of the reasons for this may be their higher temperatures and humidity creating higher microbial activity (Ye et al., 2019) that forces the constant renewal of organic matter in the field by the farmers to avoid as much as possible the otherwise inevitable nutrient mining (Majumdar et al., 2016). Although organic amendments were the category with more diverse practices, the most common types were farmyard manure and crop residues (Table 3; Appendix F: Other stacked-bar charts for rating answers). In conditions where these two types of C inputs are used for other purposes (Lal & Stewart, 2010), the soil can be threatened by further organic matter decline. The least used strategy, biochar application, shows its low adoption levels and therefore, the opportunity to further research and implement this amendment practice across climates.

4.2.4. Agroforestry

Often discussed separately from the previous three categories (X. Bai et al., 2019; Z. Bai et al., 2018; Tully & Mcaskill, 2020) but also a climate-smart practice (Kumar et al., 2020; Tadesse et al., 2021), agroforestry obtained a higher effectiveness and final use score in tropical climates than in temperate or arid ones (Table 2; Figure 2). This might be due to the conception of smallholder farming systems in the tropics that integrate of trees in farmland (Leakey, 2014) reversing some of negative impacts of conventional modern agriculture. Furthermore, agroforestry practices with timber fruit or nut trees have been reported as "poorly integrated" in agriculture for temperate regions by Wezel et al. (2014) in their review. Other aspect is the estimated potential of integrated trees to sequester carbon in aboveground biomass, which is 2×10^8 Mg C a^{-1} higher in tropical than in temperate biomes (Oelbermann et al., 2004). Unfortunately, the SOC increase benefit is lower in the tropics due to the rapid turnover rate despite the higher total organic matter input (Oelbermann et al., 2004). In this sense, the effectiveness perceived might be related to other benefits than purely SOC. Agroforestry has been referred as a “productive and environmentally friendly farming system” not only providing food security but also alleviating poverty aiming for a better balance between agriculture and wildlife (Leakey, 2014), characteristics increasingly threatened in a more severe extent in the tropics nowadays (Cooper et al., 2009; Hirons et al., 2020).

4.3. Prioritization of soil properties by climate

Among our seven selected soil indicators of soil quality, soil nutrients, water holding capacity and SOC were considered highly important regardless of climatic conditions (Figure 3), showing a presumable correlation between them. It has been demonstrated that SOC is responsible in a high extent to water holding capacity (Bhadha et al., 2017) and nutrients like N (Lehtinen et al., 2017), especially in soils with coarse textures. Some authors consider SOC, pH, aggregate stability, yield and earthworms as the main indicators of soil quality (Z. Bai et al., 2018). Soil biodiversity was the only indicator with a lower importance in temperate climates in comparison with arid or tropical climates. An explanation to this can be the effect of climate extremes to soil microorganisms (Bardgett & Caruso, 2020), more noticeable in tropical and arid climates than in temperate ones. The preference to improve certain properties was not explained by the climate groupings defined in our study (Figure 3) and may depend more on the local context, for example, soils with poor drainage preferring an improvement in aggregate stability; acid or alkaline soils affecting nutrient mobility and availability; or soils depleted in organic matter. Soil nutrients, water holding capacity, and SOC were nevertheless the central focus of researchers across climates (Figure 3).

4.4. Other management practices and farming systems

The technique of knowledge harvesting has been applied in other studies involving stakeholders and asking needs and knowledge gaps on soil management in a participatory research project (Bampa et al., 2019). After comparing all answers to the question “unique soil management practices applied in the region”, we consider that the term “innovative” reflected in our results an effect of ambiguity to soil experts since any strategy can be considered “new” if it was never applied before. Nonetheless, we also recognize that innovation happens at local context with owned constraints and the fact that certain answers fitted in our categories (Appendix G: Unique or innovative practices mentioned) does not discredit the innovation local efforts in search of a soil quality improvements. Conservation agriculture, including reduced or no tillage and organic inputs, appeared to be the most used techniques to improve soil quality. Other outstanding systems mentioned were integrated farming systems (Archer et al., 2018) and mixed crop-livestock systems (Ryschawy et al., 2012). The benefit obtained after the application of these strategies may vary from system to system. The so-called best management practices (organic amendments, conservation tillage, cover crops, rotations) increase SOC contents around 18% when comparing systems within organic management (Crystal-Ornelas et al., 2021). However, the SOC benefit actually depends on the type of practice, according to the review of Crystal-Ornelas et al. (2021), with organic amendments having the higher mean benefit but also variation. The variation in the categories obtained can be attributed to the current needs or possibilities in the described region, more than the actual benefit of the practice. The broad list obtained in our survey certainly shows wide diversity of strategies available to apply (Appendix G: Unique or innovative practices mentioned) along with specific farming systems (Table 3). In any case, the application of any farming system must be in a constant monitoring and renovation. New outstanding successful examples should be constantly localized, investigated and shared by and to the scientific community and stakeholders. Therefore, here we mention three potential attractive practices collected in our survey to apply at local level but also to scale-up.

4.4.1.1. Milpa interspersed with fruit trees

It consists of the combination in rows at contour lines of an arable field and an orchard, one providing staple crops and the other giving immense benefits to hillside agriculture. Although silvoarable systems with a similar concept also exist for other regions in the world (Arenas-Corraliza et al., 2018), the space in between the fruit trees, called “milpa”, comprehend a inter/mixed cropping system with maize (*Zea mays* L.) and beans (*Phaseolus vulgaris* L.) (Albino-Garduño, 2014), possibly applicable to any cereal-legume system, obtaining the benefits of better resource utilization, diversity and productivity of intercropping (Lopez-Ridaura et al., 2021). The inclusion of vegetables or the production of ornamentals have also been reported (Albino-Garduño et al., 2018; Lopez-Ridaura et al., 2021; Muñoz-Ruiz et al., 2018) yielding land equivalent ratio higher than 1.0, diversifying diet and income, and promoting biodiversity.

In Mexico, this system was developed for three main reasons (Cortés Flores et al., 2007): (1) maize is the staple food in Mexico and its production is fundamental for food security, but (2) it produces a low revenue reaching even negative values for smallholders, (3) most of which own land in conditions of steep slopes where conservation agriculture practices are not as successful for small farmers with marginal land (Turrent et al., 2012). In this sense, fruit trees planted in contour lines reduce by one third soil erosion by water (Camas Gómez et al., 2012) and serve as an "economic engine" for smallholders (Cadena-Iñiguez et al., 2018). The higher revenue obtained from fruit trees comes with the need of high-quality knowledge and more labor than arable fields (Turrent Fernández et al., 2017) and the fruit has to be adapted to the market (Muñoz-Ruiz et al., 2018). The system has also been consider as a sustainable technique to close the yield gap in the short term applying existing knowledge and technologies with sound support to farmers (Turrent et al., 2012)

Other species can be adapted to a similar model, provided that they generate profit and provide essential regional crops for food security as the traditional milpa (Novotny et al., 2021), especially for subsistence farmers. The main benefit in both soil protection and carbon capture is more visible in the soil under the tree, where crop residues and pruned branches create a filter for water runoff (Arriaga-Vázquez et al., 2020). The trees themselves also increase the total carbon sequestration of the system added to that of the SOC increase (Oelbermann et al., 2004; Stefano & Jacobson, 2018). It is important to consider that SOC increase only occurs in transformations from cropland or pasture to agroforestry systems and not in the transition from forest to agroforestry (Stefano & Jacobson, 2018).

A similar cropping system, resilient to both economic and climate change, is the traditional technique "*metepantle*" with rows of agave plantations (Herrera-Pérez et al., 2017; Viniegra-González, 2021) instead of fruit trees as economic component that also retain the soil and are applicable in drier climates due to the desertic nature of agave plants and their historical, industrial and economical importance in Mexico.

4.4.1.2. Zero-budget natural farming

A farming system that promotes natural and low-cost inputs, multi cropping and mulching (Bishnoi & Bhati, 2017). The strict system differs from organic farming in that it aims to make nutrients available to crops without requiring external inputs like animal manures (Smith et al., 2020). One of the techniques is the application of *Jivamrita*, a semi-liquid microbial inoculum that increases soil biodiversity, soil water-holding capacity and organic matter (Khadse et al., 2018). The rewilding of soil stimulating effective microorganisms by this inoculant also reduces the agrochemical products used, providing nutrients to the system from on-farm made manures and crop protection measures (Khadse et al., 2018). Mulching provides soil protection against erosion and increases the SOC (Veluguri et al., 2021). However, some authors recognized that the N-fixing techniques, manures, inoculum, and residues should still be complemented in supplying the nitrogen demand of crops to achieve food security in the case of India (Smith et al., 2020). The reduction of N fertilizers would assume a decrease in greenhouse gas emissions compared to high-input systems. On the other hand, it has been estimated that SOC increases can reach from 10 up to 21% in soils across India where zero-budget natural farming (ZBNF) is implemented (Smith et al., 2020), even after reducing the inputs from manure or compost. Areas with lower annual temperatures might take a higher advantage of the system.

Studies have been conducted to analyze the adoption of this valuable practice (Veluguri et al., 2021), remarking governance and institutions as a paramount actors to foster adoption. In addition, farmer to farmer knowledge transfer is considered a crucial component of ZBNF (Mier y Terán et al., 2018; Veluguri et al., 2021) especially because this system arises to solve problems of smallholders with low resources, often with important debts. Principles of ZBNF to improve not only agronomic but also socioeconomic benefits can be adapted and transferred to other areas as pilot experiments and even promote cooperation between countries with similar conditions.

4.4.1.3. Agrivoltaics

According to Weselek et al. (2019), it is a system that combines the production of renewable energy and food production. Crops are planted under the shade of solar panel (photovoltaic) infrastructure that can be elevated for harvesting or agronomic practices, keeps the heat during the night and reduces excessive radiation during the day (Barron-Gafford et al., 2019). Photovoltaics alone have inherent disadvantages that can be mitigated by combining it with agriculture: (1) the change of albedo, vegetation, and structure of the terrain to install them (Barron-Gafford et al., 2016), (2) the alteration of the energy flux dynamics of the area by remotion of vegetation and in turn the latent heat fluxes(Barron-

Gafford et al., 2019), (3) although it is a kind of renewable energy, it can be a threat to natural habitats and conservation areas (Kim et al., 2021) due to the extension needed to maximize the sunlight received. To address current challenges, Agrivoltaic systems provide agronomic benefits (Barron-Gafford et al., 2019): (1) the minimization increasingly stressful climate for crops (by heat and drought), (2) the optimization of water-use by irrigation (water-use efficiency). Some authors consider that it combines *green goals* in electricity production and supports rural economy (Proctor et al., 2021) while minimizing the competition of land resources (Dinesh & Pearce, 2016; Dupraz et al., 2011). One example of agronomic benefits shown is the increase in fruit production of the *Solanaceae* plant family and an increased CO_2 uptake by plants (Barron-Gafford et al., 2019), that is transformed into yield and increased water-use efficiency.

On the other hand, there is a synergy in which plants also improve photovoltaics' performance, especially in areas where the hours of sunshine abound. The transpiration from underlying plants decreases the temperature of the solar panels to adequate operation levels for a more efficient functioning (Dinesh & Pearce, 2016). In terms of scalability, dry climates have more potential to implement agrivoltaic systems (Weselek et al., 2019), especially in rainfed fields, provided that the agronomic conditions like soil are also favorable for crops. It is also relevant to consider whether the added shade will be beneficial for the crop. Long-term simulations of the shading effect on maize determined increases in yield when water is a limiting factor, but when it is supplied, the yields are lower in comparison with the non-shaded maize (Amaducci et al., 2018). Simulation programs, pilot trials and design can be useful tools to test the performance of agrivoltaics and evaluate its local suitability since variables like yearly/daily sunshine hours, soil, costs, and crop expertise vary from country to country. More studies are needed to demonstrate if agrivoltaics can significantly enhance the SOC levels by, for example, reducing the organic matter decomposition by the shade they provide, or by the incorporation increased biomass produced to soil.

4.5. Relevant needs

Soil experts recognized that soil data was the least relevant need for stakeholders when compared to others (Figure 5; Appendix F: Other stacked-bar charts for rating answers). Soil data is a crucial element for a sustainable management, but its potential use can be hampered when the knowledge to interpret it and training and tools to make use of it effectively are not available.

From all the responses regarding main policy needs, the most mentioned was need across countries was incentives (Figure 5; Appendix F: Other stacked-bar charts for rating answers), highlighting the need for government support for farmers to foster adoption of beneficial practices, especially those already proven to be effective such as the principles of Conservation Agriculture. Bampa et al. (2019) also recognized incentives as the main need from stakeholders in their study analyzing results from workshops. The second one is the better cooperation between policy makers, researchers, and stakeholders, focusing on knowledge sharing and the application of knowledge. Other less mentioned but still very interesting proposals were the remotion of harmful subsidies to climate and health, such as the use of certain pesticides or the excessive use of mineral fertilizers. Finally, eleven soil experts from different countries urge the creation of a soil protection law by their governments (see Appendix H: Policy needs), arguing that protection mechanisms already exist for water and other natural resources, but there is no specific protection to soil yet like in some European countries where legal frameworks have been developed more than two decades ago (Gunreben, 2005).

5. Conclusions

While the importance of soil threats like salinization and landslides depend more on climate conditions, other threats maintain a similar importance level across climate groups and countries. This holds true for the three main priorities of soil experts across the globe, namely soil organic matter decline, soil erosion and biodiversity loss. Understanding the distribution of main soil challenges in different climates and their hierarchy gives us the opportunity to establish priorities in the selection of effective soil management practices. Likewise, knowing the perspective of soil experts on the effectiveness of soil management practices gives us an external overview to utilize and combine wisely the strategies already applied in certain climates, as well as to explore new techniques. In tropical climates, for example, further research and promotion should focus on the benefits of agroforestry and crop diversification strategies, used more there than in temperate or arid regions, in search for synergies and the minimization of eventual trade-offs. There is a large awareness for the use of climate-smart crop diversification strategies such as crop rotations, mixed cropping, and cover crops in tropical conditions. Their benefits should be explored more in depth as well in other climates with suitable crops and agronomic practices.

The alarming lower use of organic inputs compared to mineral fertilizers across climates shows the current need of finding site-available carbon sources to minimize and reverse the organic matter decline of agricultural soils globally, since crop residues and farmyard manure were the most common types of organic amendments. Soil experts across climates and countries support the use of practices that improve SOC contents together with soil nutrients and water-holding capacity. However, the fact that organic amendments are perceived with less optimism in temperate climates suggests that new techniques need to be developed to increase the benefits of carbon inputs despite the higher actual increase when compared to arid or tropical climates.

Besides climate, topography and the farmers' socioeconomic conditions play a crucial role in the development of new strategies in search of integral solutions. Resources assigned to research, constantly improve, and share the knowledge of innovative integral systems will be spent wisely in the benefit of both climate mitigation and improvement of the farmers' socioeconomic situation. Innovative approaches need to be tested in other potential areas with similar conditions, always adapting them to the local context, expanding the principles of their benefits and enriching the global knowledge of soil management practices. International cooperation to establish pilot experiments and adapt them with time could create further context-adapted management innovations that address the current worrisome decline of organic matter in agricultural soils.

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List of abbreviations

EJP SOIL: *European Joint Programme SOIL*

MIAF: Milpa Interspersed with Fruit Trees (acronym in Spanish)

SD: Standard deviation

SOC: soil organic carbon

ZBNF: Zero-Budget Natural Farming

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Appendix A: Questionnaire

Summary

Table 4. Summary of the questionnaire used in the survey to collect information from and perceptions of soil experts across the globe.

	Question	Type of question	Options
1	Research field, within aims of EJP SOIL	Multiple selection	5 options[1]
2	Expertise in climatic zone(s)	Multiple selection	14 options[2]
3	Expertise in soil groups	Multiple selection	8 options[3]
4	Soil monitoring programs	Ratio (0 to 5)	"Absent" to "excellent"
5	Soil monitoring by the farmers	Ratio (0 to 5)	"Never" to "more than twice per year"
6	Relevance of soil properties in own research	Ratio (0 to 5)	"Possible to do research without them" to "Central focus of research"
7	Major land resource stresses	Multiple selection	24 options[4]
8	Most important challenge	Open	-
9	Significance of 8 soil threats	Interval (1 to 5)	low to high
10	Degree of detriment of 5 inadequate practices	Interval (1 to 5)	low to high
11	Effectiveness of the 5 types of practices to mitigate the threats	Interval (1 to 5)	low to high
12	Rating of 5 crop diversification and vegetative practices	Interval (1 to 5)	seldom to widely use
13	Rating of 3 tillage practices	Interval (1 to 5)	seldom to widely use
14	Rating of 10 types of fertilizers	Interval (1 to 5)	seldom to widely use
15	Rating of 3 agroforestry practices	Interval (1 to 5)	seldom to widely use
16	Rating of 5 selected innovative farming systems	Interval (1 to 5)	seldom to widely use
	From 12 to 16: Other local outstanding practices	Open	-
16a	Innovative or unique practices in the region	Open	-
17	Importance of improvement of properties when selecting practices	Interval (1 to 5)	"not crucial" to "crucial"
18	Specific knowledge gaps for the area	Interval (1 to 5)	"not neglected" to "highly neglected"
19	Causes of the mentioned knowledge gaps	Interval (1 to 5)	"not a reason" to "significant absence"
20	Relevant needs for stake holders	Interval (1 to 5)	low to high
21	Policies that would benefit the area	Open	-

[1] All in interaction with soil: climate mitigation, climate adaptation; sustainable agricultural production, ecosystem services, and land restoration (Visser et al., 2019)

[2] Köppen-Geiger climate classification (Beck et al., 2018; Peel et al., 2007)

[3] Soil Taxonomy (Soil Survey Staff, 2014)

[4] Global Major Land Resource Stresses (Eswaran & Reich, 1999)

Full questions

a. Name, contact details
b. Field of expertise (e.g., Soil Science, sustainable Intensification)
c. Country or region to describe
d. University or institute
e. Position at the institute/University

1. Which research field of agricultural soil management are you more familiar with?
    a. Soil and climate change mitigation
    b. Soil and climate change adaptation
    c. Soils, sustainable agricultural production, and food security
    d. Soils, environment, and ecosystems services
    e. Land and soil restoration, soil fertility, and soil erosion prevention

2. What major climatic zone (World Köppen-Geiger classification) fits best with your expertise? A:Tropical; B: Dry; C: Temperate; D: Continental.
    a. Af Permanent wet
    b. Am Monsoonal
    c. As Dry summer
    d. Aw Dry Winter
    e. BSh Warm semi-arid
    f. BSk Cold semi-arid
    g. BWh Warm fully arid
    h. BWk Cold fully arid
    i. Cf Permanent wet
    j. Cs Dry summer
    k. Cw Dry winter
    l. Df Permanent wet
    m. Ds Dry summer
    n. Dw Dry winter

3. If known, what are the main soils orders (Soil Taxonomy) with which you have had more contact?
    a. Alfisols
    b. Andisols
    c. Aridisols
    d. Entisols
    e. Gelisols
    f. Histosols

   g. Inceptisols
   h. Mollisols
   i. Oxisols
   j. Spodosols
   k. Ultisols
   l. Vertisols
   m. Other: ________

4. How do you rate soil monitoring programs in the selected country/region?

   0-completely lacking
   1-very poor
   2-poor
   3- good
   4-very good
   5-excellent

5. How often do farmers monitor of soil properties in the selected country/region?

   0-never
   1-properties rarely monitored
   2-once every two years
   3-once per year
   4-twice per year
   5-more than twice per year

6. How do you rate the importance of soil properties information in your research?

   0- possible to do research without them
   1-as extra information
   2-to find possible trends
   3- useful
   4- essential
   5-central focus of the research

7. What are the major land resource stresses which you are familiar with?

   a. High shrink/swell potential
   b. Low organic matter
   c. High temperatures
   d. Seasonally excess of water
   e. Minor root restricting layer
   f. Seasonal/continuous low temperatures
   g. Low structural stability
   h. High anion exchange capacity
   i. Impeded drainage

    j. Seasonal/continuous moisture stress
    k. High aluminium
    l. Calcareous, gypseus condition
    m. Excessive nutrient leaching
    n. Low nutrient holding capacity
    o. High retention (nutrients)

8. What do you consider to be the most important challenge for your country or region?

9. What is the importance of the following soil threats in your country or region?
    a. Organic matter decline
    b. Soil erosion
    c. Salinization
    d. Soil contamination
    e. Landslides
    f. Soil sealing
    g. Biodiversity loss
    h. Soil compaction

10. In your opinion, how detrimental are the following practices to SOC sequestration in arable lands the selected country?
    a. Intensive mineral fertilization
    b. Lack of organic matter input
    c. Intensive tillage practices
    d. Monoculture cropping systems
    e. Heavy machinery use
    f. Others

11. What is the performance of the following soil management practices in mitigating the threat(s) the selected country?
    a. Crop diversification
    b. Tillage (no-till/non-inversion...)
    c. Organic amendments (possible to specify)
    d. Nutrient Management
    e. Agroforestry

12. Please, rate use of the following crop diversification practices for the region.
    a. Crop rotation
    b. Cover/catch cropping
    c. Mixed cropping
    d. Inter cropping

e. Green manures

13. To what extent are the following tillage practices used in the region?

    a. No tillage
    b. Reduced/minimum tillage
    c. Inversion tillage

14. What is the popularity of the following organic amendment practices for the region?

    a. Farmyard manure
    b. Compost
    c. Vermicompost
    d. Animal dung slurry
    e. Green manures
    f. Crop residues
    g. Biochar
    h. Biofertilizers
    i. Mineral fertilizers
    j. Integrated fertilizer management

15. When applicable, how popular are the following agroforestry practices in the region?

    a. Alley cropping
    b. Wind breaks/Hedge tree rows
    c. Shade trees

16. How used are the following innovative farming systems are for the selected country or region?

    a. Integrated farming systems (crop-animal model)
    b. Biodynamic farming
    c. Precision farming
    d. Permaculture
    e. Regenerative farming

From 12 to 16: Other outstanding soil management practices (Unique/traditional)

16a. Is there a specific practice or set of farming practices for soil management that you would define as "innovative" or "unique" in the selected country or region?

17. When selecting soil conservation practices in the selected country or region, what is the role of the following properties?
    a. Aggregate stability
    b. Porosity
    c. Water holding capacity
    d. Soil carbon content
    e. Soil nutrients
    f. pH
    g. Soil biodiversity

18. What do you consider as knowledge gaps or main neglected points important for the selected country or region (farmer/policy view)? Lack of...
    a. Climate and region-specific strategies
    b. Soil-specific strategies
    c. Up-to-date fertilization guidelines
    d. Coordination between policy makers and researchers
    e. Knowledge sharing between researchers and farmers
    f. Cost-effectiveness and applicability of soil-improving practices

19. What are the possible causes of the existing knowledge gap in the selected country or region? Lack of...
    a. Scientific papers
    b. Policy advice/briefs
    c. Long-term field sites for research
    d. Advisory services
    e. International cooperation
    f. Stakeholder participation
    g. Soil data acquisition and harmonization
    h. Open soil databases
    i. Standard protocols for soil analyses

20. What are the most relevant needs for stakeholders (farmers) in the selected country or region?
    a. Knowledge
    b. Training
    c. Soil data
    d. Field demonstrations
    e. Incentives

21. In your opinion, what would be the current and future policy needs for the selected country or region?

Appendix B: Participation by country

Table 5. Continents and countries where soil experts' institutes are located. In brackets, the percentage of participants in the area in relation to the total number of survey participants (n=162).

Continent	Countries	
	with >1 participant	**with one participant**
Africa (14.2%)	Ghana (1.8%) Kenya (1.8%) South Africa (1.8%) Uganda (1.2%)	Tunisia Republic of the Congo Niger Mali Ethiopia Burkina Faso Eswatini Malawi
Asia (25.3%)	India (16.6%) Indonesia (1.8%) Vietnam (1.8%)	Nepal China Pakistan Japan Cambodia Bangladesh Taiwan
North America (25.9%)	Mexico (16.0%) United States (6.1%) Canada (2.5%)	Nicaragua El Salvador
South America (30.2%)	Argentina (9.8%) Chile (8.6%) Brazil (4.3%) Peru (1.8%) Paraguay (1.8%) Colombia (1.2%)	Ecuador Venezuela Uruguay
A&NZ (4.3%)	Australia (3.1%) New Zealand (1.2%)	

†Australia and New Zealand

Appendix C: Descriptive statistics

Table 6. Mean and standard deviation of questions with respective subsections rated by soil experts outside Europe (All participants: n=162; Climate: n=120). Numbers shown in bold letters are significant values ($p<0.05$) by the two-sided Fisher's Exact Tests (one 2x3 matrix per question: High-Low ratings in rows and the three climate groups for columns).

Rating question with subsections			Climate†		p-value‡
	All†	Tropical	Arid	Temperate	
Importance of soil threats					
Biodiversity loss	3.9 (1.0)	4.1 (0.9)	3.8 (0.9)	3.6 (1.1)	0.084
Landslides	2.4 (1.3)	2.9 (1.6)	1.9 (1.0)	2.1 (1.2)	**0.007**
Organic matter decline	4.2 (1.0)	4.4 (0.9)	4.0 (1.0)	4.0 (1.1)	**0.040**
Salinization	2.9 (1.3)	2.9 (1.4)	3.6 (1.3)	2.4 (1.1)	**0.005**
Soil compaction	3.4 (1.0)	3.5 (1.0)	3.4 (1.0)	3.5 (1.1)	0.281
Soil erosion	4.1 (1.0)	4.1 (1.1)	4.4 (0.9)	4.0 (1.1)	0.325
Soil contamination	3.0 (1.3)	3.2 (1.3)	2.8 (1.3)	2.9 (1.2)	0.365
Soil sealing	2.6 (1.1)	2.6 (1.3)	2.7 (1.2)	2.6 (1.1)	0.619
Degree of detriment of 5 common practices					
Heavy machinery use	3.3 (1.2)	3.0 (1.2)	3.4 (1.1)	3.5 (0.9)	0.687
Intensive mineral fertilization	3.2 (1.3)	3.4 (1.3)	3.0 (1.3)	3.0 (1.3)	0.287
Intensive tillage practices	3.9 (1.1)	3.8 (1.2)	4.2 (1.1)	4.0 (1.0)	0.311
Lack of organic matter input	4.2 (1.0)	4.1 (1.1)	4.3 (1.1)	4.0 (0.9)	0.289
Monoculture cropping systems	4.0 (1.0)	3.9 (1.1)	4.1 (1.0)	4.1 (0.9)	0.760

†All participants: n=162; Experts selecting one climate: n=120.

‡Two-sided Fisher's Exact Tests. H_0: there is a relationship between the grouping variable climate (Tropical, Arid, Temperate) and the ratings (high, low).

(continuation of Table 6)

Mitigation effectiveness of 5 types of practices					
Agroforestry	3.7 (1.3)	4.0 (1.3)	3.2 (1.3)	3.6 (1.4)	**0.020**
Organic Inputs	3.9 (1.1)	4.0 (1.1)	4.2 (0.9)	3.5 (1.2)	**0.005**
Crop diversification	4.0 (1.1)	4.1 (0.9)	3.8 (1.2)	3.8 (1.2)	0.611
Nutrient Management	3.9 (1.0)	4.2 (0.9)	3.7 (1.0)	3.6 (1.1)	**0.005**
Tillage	3.7 (1.2)	3.9 (1.1)	3.7 (1.4)	3.5 (1.2)	0.119
Rating of 4 crop diversification practices					
Cover crops	2.7 (1.1)	2.6 (1.2)	2.4 (1.2)	2.8 (1.0)	0.960
Crop rotations	3.4 (1.2)	3.6 (1.2)	3.1 (1.2)	3.2 (1.2)	0.225
Inter cropping	2.6 (1.2)	3.2 (1.0)	2.2 (1.3)	1.8 (0.7)	**<0.001**
Mixed cropping	2.7 (1.2)	3.3 (1.0)	2.4 (1.2)	2.0 (1.0)	**0.001**
Rating of 3 tillage practices					
No tillage	2.6 (1.4)	2.4 (1.3)	2.5 (1.3)	3.0 (1.6)	0.060
Reduced tillage	2.8 (1.2)	2.9 (1.3)	2.7 (1.3)	2.9 (1.2)	0.967
Inversion tillage	2.8 (1.4)	2.8 (1.5)	3.1 (1.7)	2.6 (1.4)	0.320
Rating of 10 types of fertilizers					
Animal dung slurry	2.5 (1.2)	2.5 (1.2)	2.1 (1.2)	2.4 (1.2)	0.999
Biochar	1.6 (0.8)	1.7 (0.9)	1.5 (0.6)	1.4 (0.7)	0.999
Biofertilizers	2.3 (1.1)	2.5 (1.1)	2.1 (1.2)	2.1 (0.9)	0.196
Compost	2.8 (1.3)	3.1 (1.3)	2.7 (1.1)	2.3 (1.2)	0.053
Crop residues	3.4 (1.1)	3.4 (1.0)	3.2 (1.1)	3.5 (1.3)	0.229
Farmyard manure	3.2 (1.4)	3.4 (1.4)	3.2 (1.4)	2.9 (1.3)	0.391
Green manures	2.3 (1.1)	2.6 (1.2)	1.7 (0.8)	2.2 (1.1)	**0.007**
Integrated fertilizer management	3.1 (1.1)	3.0 (1.2)	3.0 (1.1)	3.2 (1.2)	0.770
Mineral fertilizers	4.3 (1.0)	4.0 (1.2)	4.6 (0.7)	4.4 (0.9)	0.087
Vermicompost	2.2 (1.2)	2.4 (1.4)	1.9 (1.1)	1.8 (1.0)	0.061

(continuation of Table 6)

Rating of 3 agroforestry practices					
Alley cropping	2.1 (1.2)	2.6 (1.4)	1.5 (0.8)	1.7 (0.8)	**<0.001**
Windbreaks	2.6 (1.3)	2.6 (1.4)	2.3 (1.3)	2.6 (1.4)	0.742
Shade trees	2.6 (1.2)	2.9 (1.2)	2.0 (1.1)	2.1 (1.2)	0.145
Importance of soil indicators					
Aggregate stability	3.8 (1.2)	3.7 (1.4)	3.8 (1.2)	3.9 (0.9)	0.914
pH	3.5 (1.2)	3.5 (1.3)	3.6 (1.4)	3.4 (1.2)	0.298
Porosity	3.7 (1.1)	3.7 (1.2)	3.6 (1.1)	3.8 (1.0)	0.886
Soil biodiversity	3.5 (1.3)	3.8 (1.2)	3.6 (1.2)	2.9 (1.2)	**0.002**
Soil carbon content	4.1 (1.1)	4.2 (1.1)	3.9 (1.2)	4.0 (1.0)	0.437
Soil nutrients	4.2 (1.0)	4.3 (1.0)	4.2 (1.0)	4.0 (1.1)	0.193
Water holding capacity	4.1 (1.0)	4.2 (1.2)	3.9 (1.0)	4.0 (0.8)	0.212
Specific knowledge gaps					
Climate and region-specific policies	3.6 (1.2)	3.6 (1.3)	3.7 (1.2)	3.5 (1.3)	0.707
Researcher-policy-maker coordination	4.1 (1.0)	4.1 (1.0)	4.0 (0.8)	4.1 (1.1)	0.896
Cost-effectiveness and applicability	3.8 (1.0)	3.9 (1.0)	3.7 (1.1)	3.9 (1.0)	0.270
Fertilization guidelines	3.4 (1.1)	3.4 (1.1)	3.7 (1.0)	3.4 (1.0)	0.443
Researcher-farmer knowledge transfer	3.7 (1.1)	3.8 (1.1)	3.5 (1.3)	3.7 (1.1)	0.554
Soil-specific strategies	3.8 (1.1)	3.8 (1.1)	3.8 (1.2)	3.8 (1.1)	0.583
Relevant needs for stake holders					
Field demonstrations	4.2 (0.9)	4.3 (0.9)	4.3 (1.0)	4.0 (0.9)	0.416
Incentives	4.3 (0.9)	4.2 (1.0)	4.1 (1.1)	4.4 (0.8)	0.848
Knowledge	4.1 (1.1)	4.3 (1.2)	4.0 (1.1)	3.8 (0.9)	**0.033**
Soil data	3.8 (1.1)	4.2 (1.0)	4.0 (1.1)	3.7 (1.0)	0.370
Training	4.2 (1.0)	4.4 (1.0)	4.2 (1.0)	4.0 (0.9)	0.132

Appendix D: Major challenges (open question)

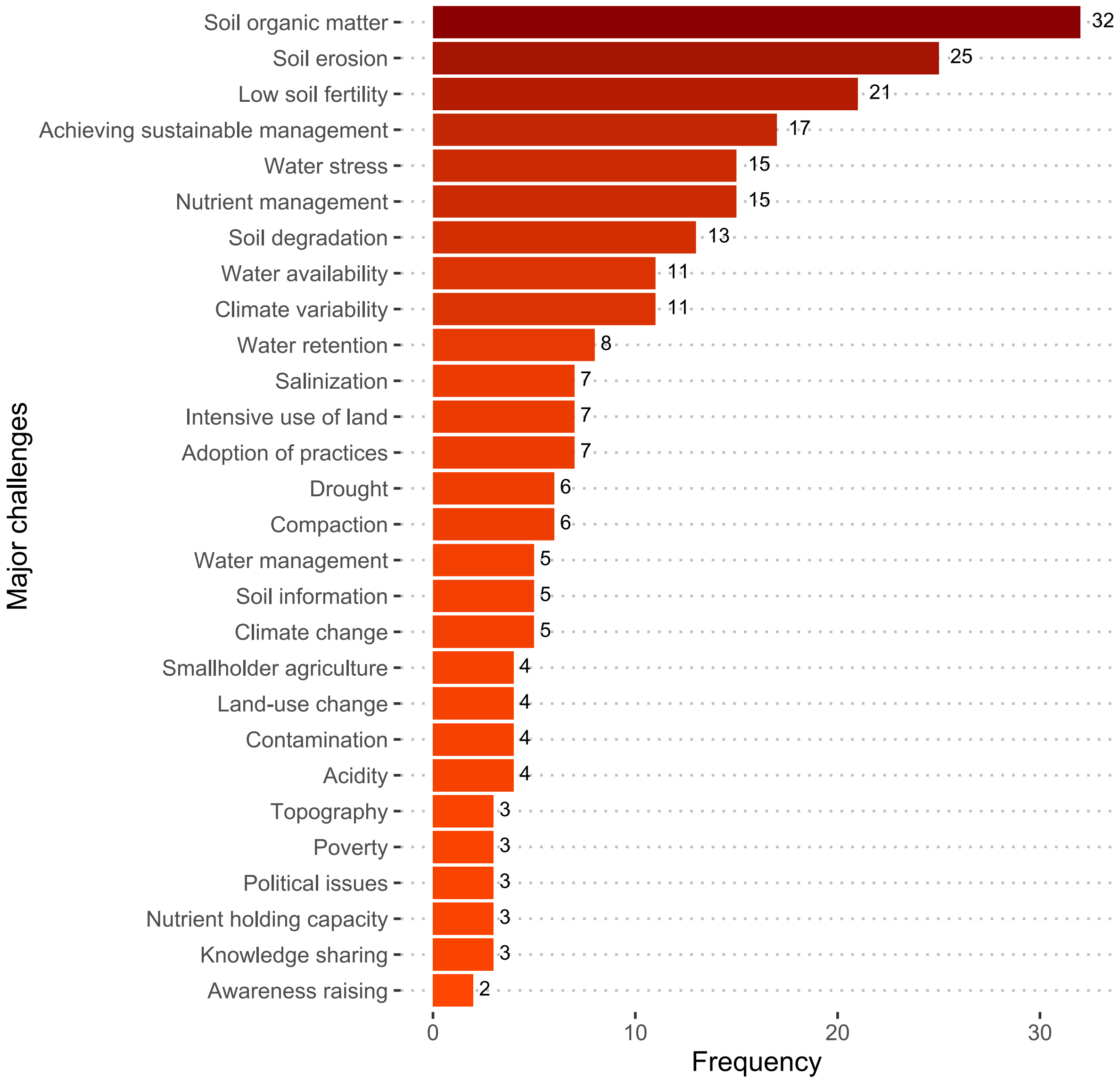

Figure 6. Challenges most mentioned by soil experts outside Europe (n=118). Categories were created from the participants' written answers to the question "major challenge in the described region or country".

Appendix E: Pedoclimatic conditions

Table 7. Pedoclimatic conditions where the participants have more experience (n=162). The percentages show the selection frequency of participants in the same continental area (green intensity shows higher values, and lower values are represented by lighter colors) and are not mutually exclusive.

	Africa	**Asia**	**North America**	**South America**	**A&NZ**[§]
Climate[†]					
Tropical (A)	61%	80%	24%	43%	29%
Arid (B)	57%	34%	43%	14%	27%
Temperate (C)	17%	10%	43%	43%	65%
Major soil groups[‡]					
Alfisols	48%	37%	10%	29%	31%
Andisols	4%	2%	26%	29%	29%
Aridisols	13%	10%	17%	43%	27%
Entisols	9%	27%	14%	14%	33%
Gelisols	0%	2%	0%	0%	0%
Histosols	4%	0%	5%	14%	10%
Inceptisols	13%	41%	12%	29%	35%
Mollisols	4%	7%	33%	14%	45%
Oxisols	43%	7%	10%	43%	24%
Spodosols	0%	2%	2%	29%	4%
Ultisols	35%	20%	12%	29%	31%
Vertisols	48%	37%	10%	29%	31%
Major land stresses[⁋]					
Acid sulfate condition	4%	7%	0%	14%	0%
Calcareous	0%	0%	0%	0%	4%
Excessive nutrient leaching	30%	20%	19%	43%	22%
High aluminum	39%	10%	5%	43%	33%
High anion exchange capacity	9%	7%	2%	0%	8%
High organic matter	0%	5%	5%	0%	16%
High temperatures	48%	34%	40%	29%	18%
Impeded drainage	13%	15%	19%	43%	20%
Low moisture and nutrient status	78%	51%	26%	14%	39%
Low nutrient holding capacity	65%	29%	26%	14%	35%
Low organic matter	100%	76%	74%	29%	84%
Low structural stability	48%	15%	29%	29%	29%
Minor root restricting layer	9%	7%	14%	0%	22%
Seasonally excess of water	22%	37%	19%	29%	22%
Shallow soils	39%	12%	12%	29%	22%
Steep lands	35%	7%	14%	14%	16%
High retention nutrients	0%	0%	7%	29%	12%
Salinity or alkalinity	9%	39%	26%	29%	33%
Number of participants	23	41	42	7	49

[†] Köppen-Geiger climate classification (Beck et al., 2018; Peel et al., 2007)

[‡] Soil Taxonomy (Soil Survey Staff, 2014)

[⁋] Global Major Land Resource Stresses (Eswaran & Reich, 1999)

[§] Australia and New Zealand

Appendix F: Other stacked-bar charts for rating answers

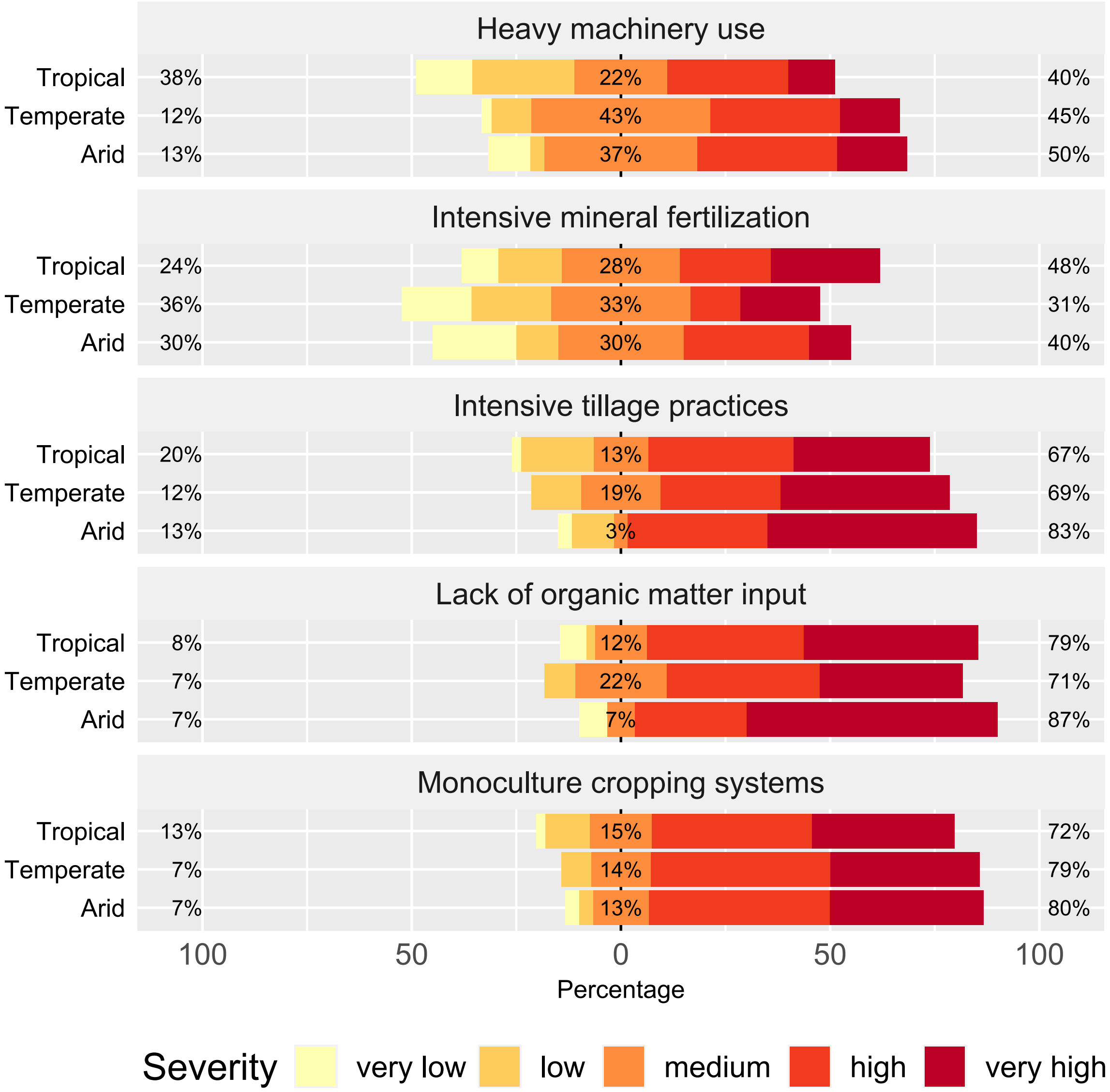

Figure 7. Detrimental practices and their severity as perceived by surveyed soil experts (n=120) grouped by climate. The percentages on the left represent the proportion of the two lowest ratings, in the middle that of the medium ratings and on the right side that of the two highest ones.

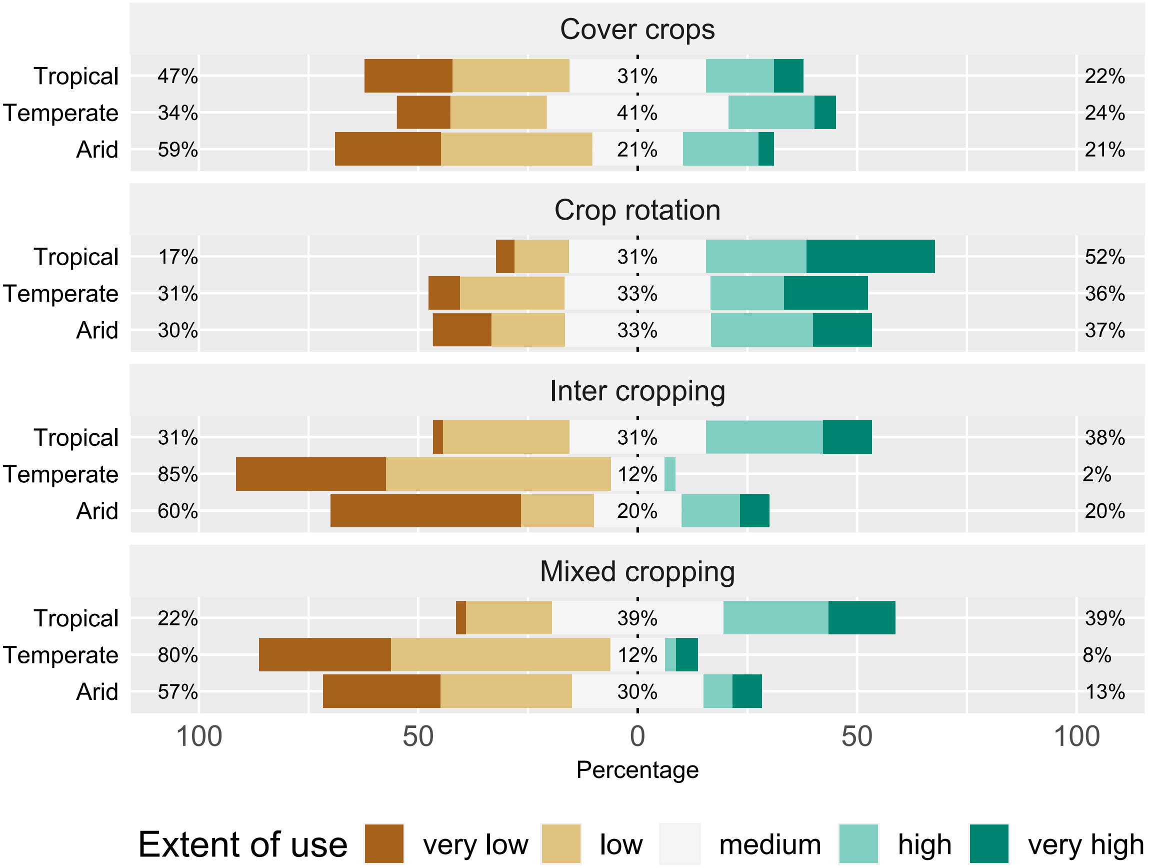

Figure 8. Extent of use of selected crop diversification strategies according to the perception of soil experts (n=120) grouped by climate. The percentages on the left represent the proportion of the two lowest ratings, in the middle that of the medium ratings and on the right side that of the two highest ones.

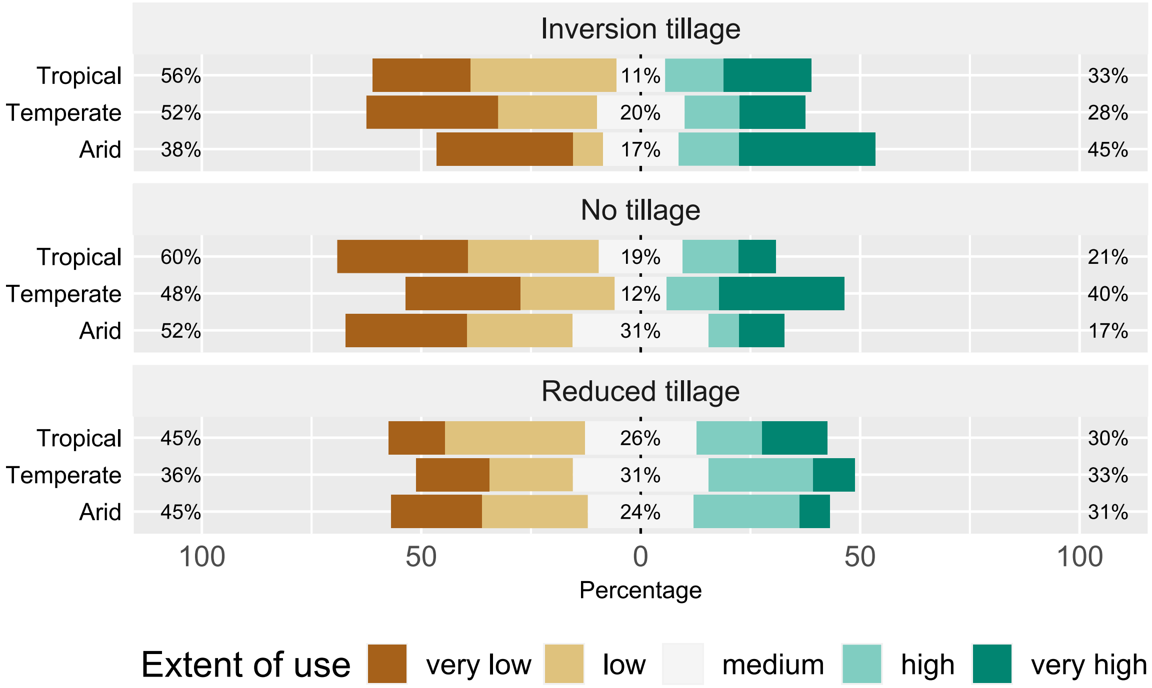

Figure 9. Extent of use of selected tillage strategies according to the perception of soil experts (n=120) grouped by climate. The percentages on the left represent the proportion of the two lowest ratings, in the middle that of the medium ratings and on the right side that of the two highest ones.

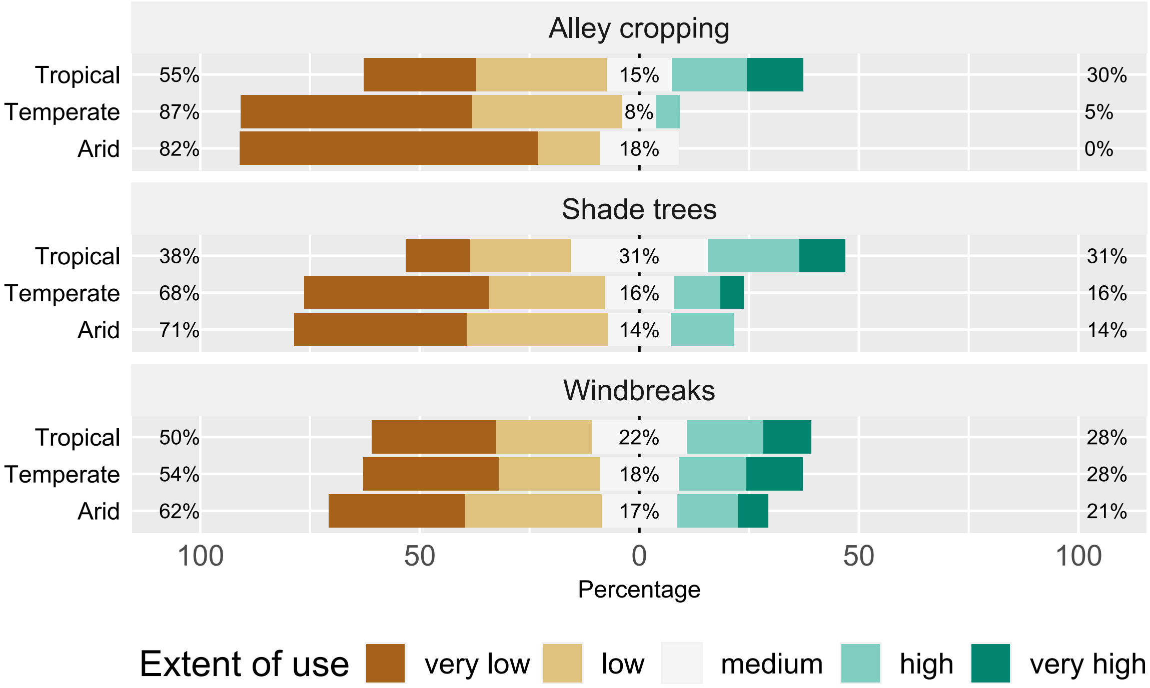

Figure 10. Extent of use of selected agroforestry techniques according to the perception of soil experts (n=120) grouped by climate. The percentages on the left represent the proportion of the two lowest ratings, in the middle that of the medium ratings and on the right side that of the two highest ones.

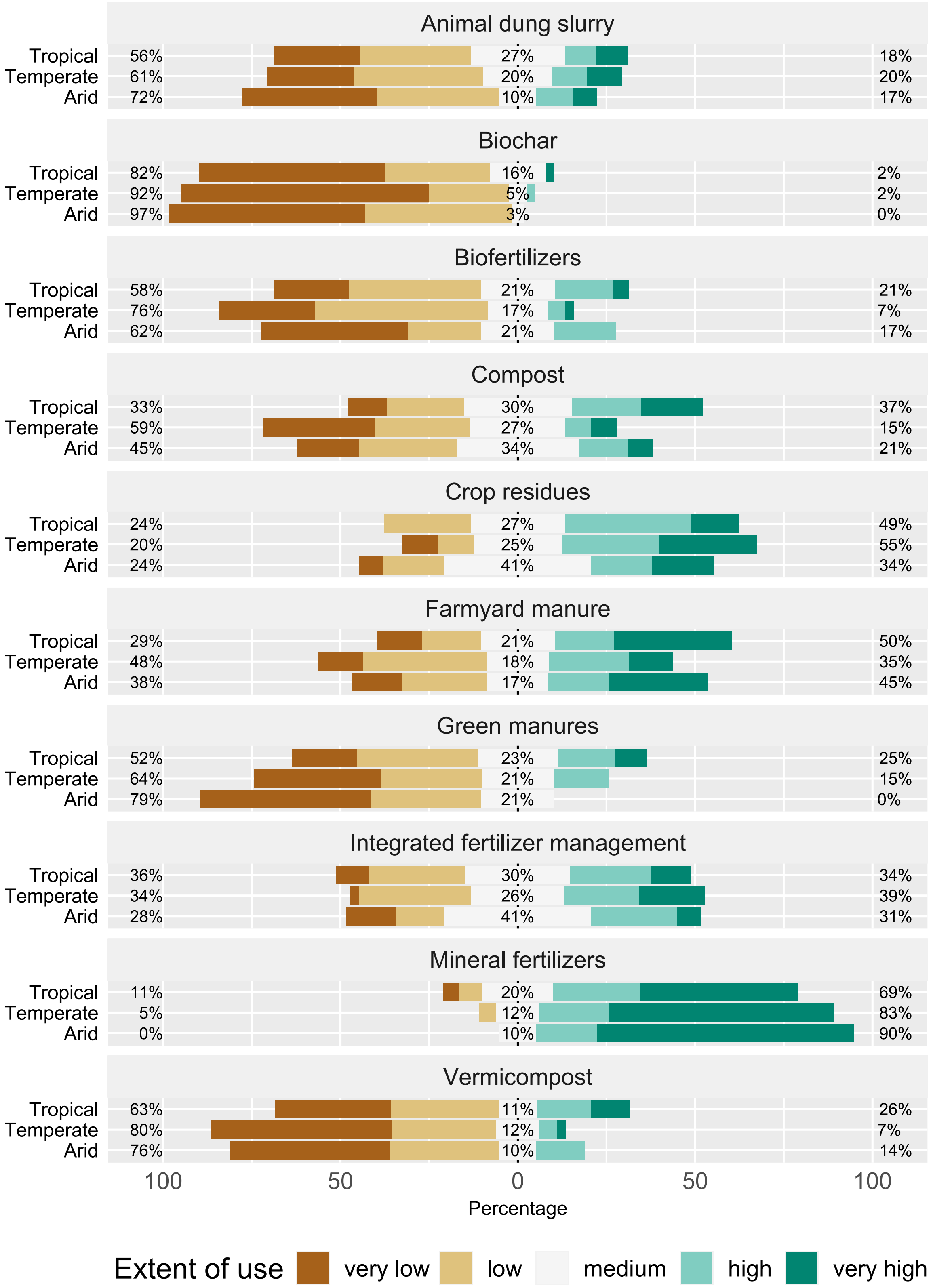

Figure 11. Extent of use of different fertilizers and carbon inputs according to the perception of soil experts (n=120) grouped by climate. The percentages on the left represent the proportion of the two lowest ratings, in the middle that of the medium ratings and on the right side that of the two highest ones.

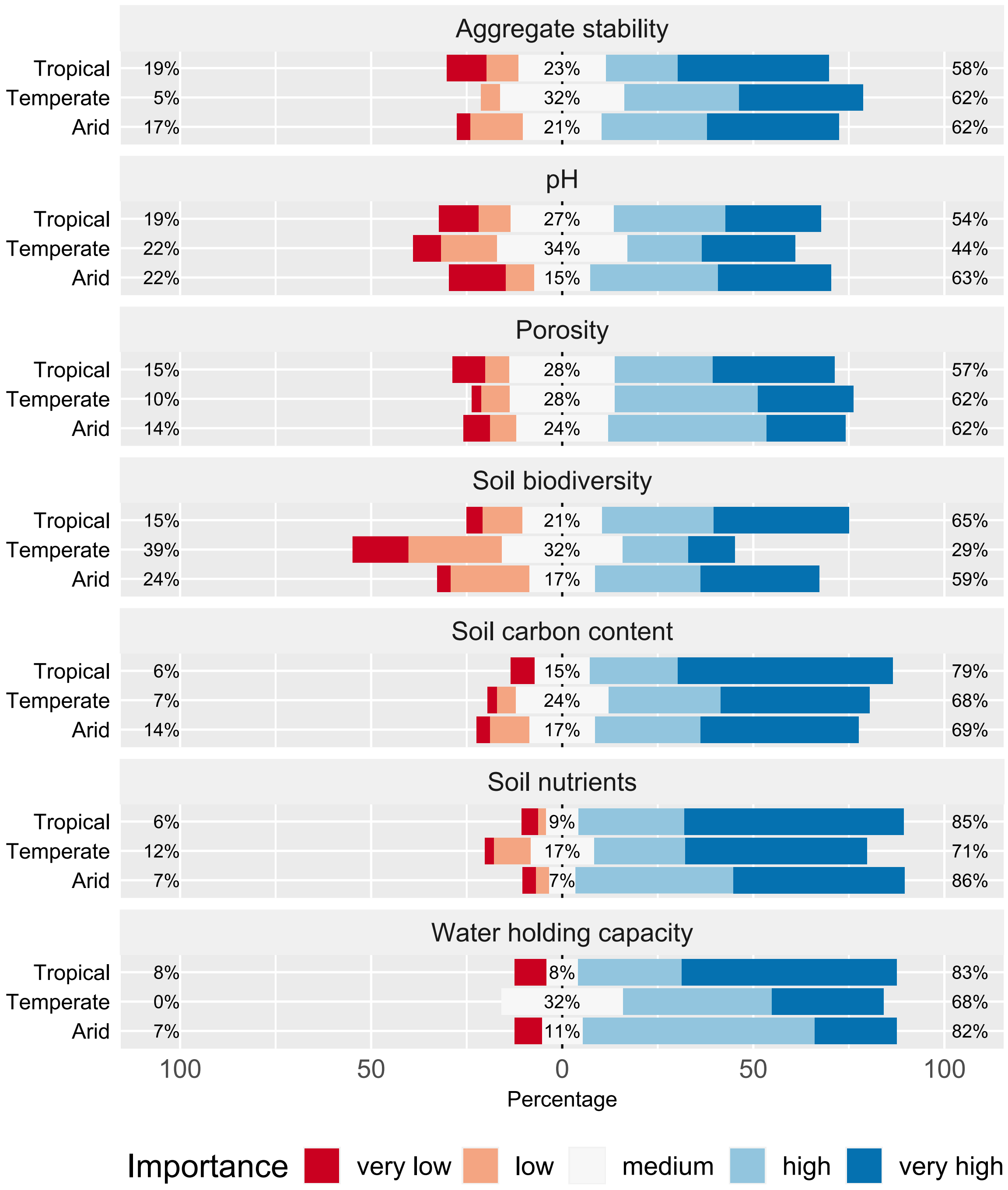

Figure 12. Importance of the soil properties in search of improvement when selecting soil management practices according to the perception of soil experts outside Europe (n=162) grouped by climate. The percentages on the left represent the proportion of the two lowest ratings, in the middle that of the medium ratings and on the right side that of the two highest ones.

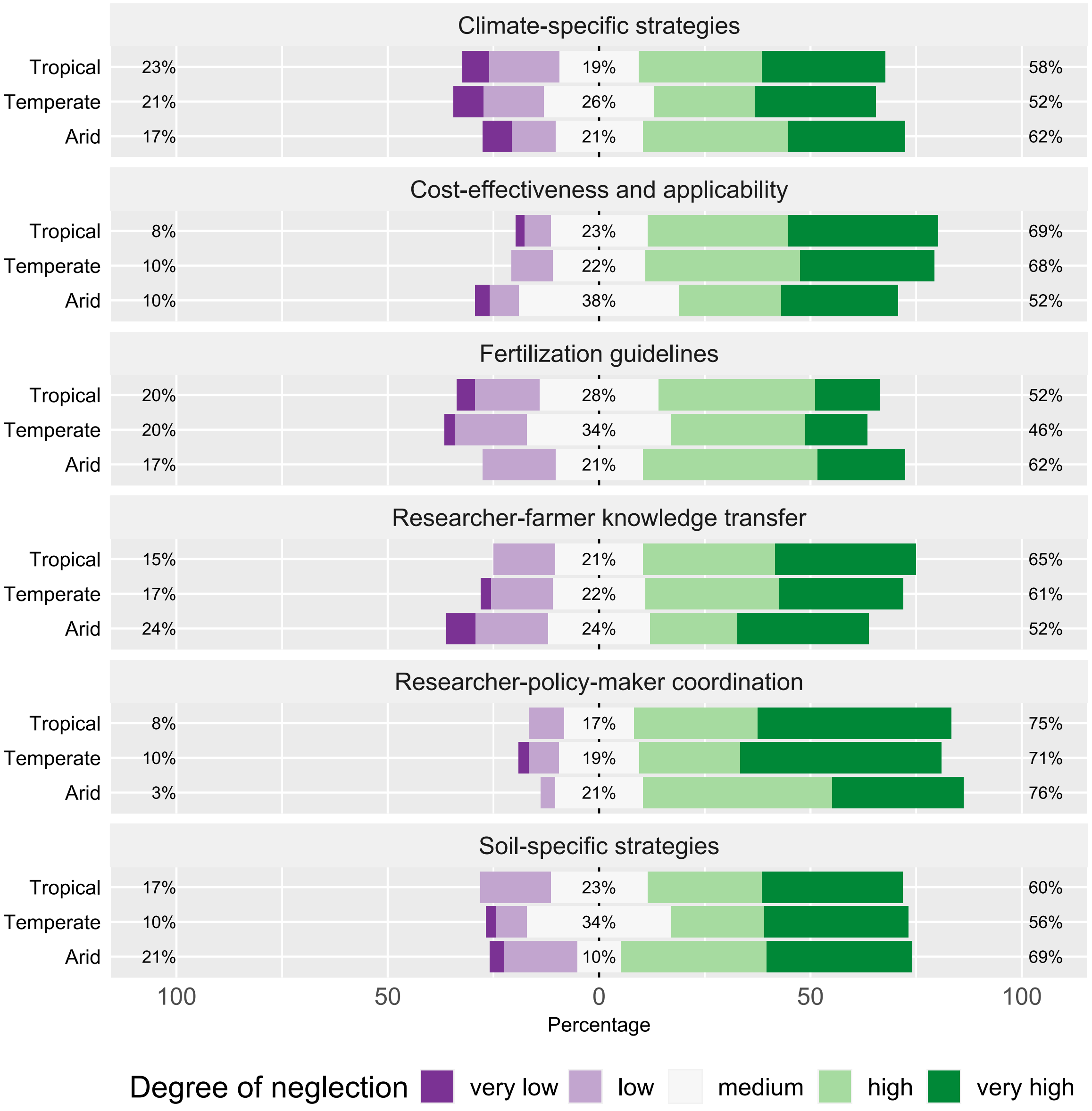

Figure 13. Main neglected areas in research (knowledge gaps) to be addressed for the region and their importance according to the perception of the soil experts (n=162) grouped by climate. The percentages on the left represent the proportion of the two lowest ratings, in the middle that of the medium ratings and on the right side that of the two highest ones.

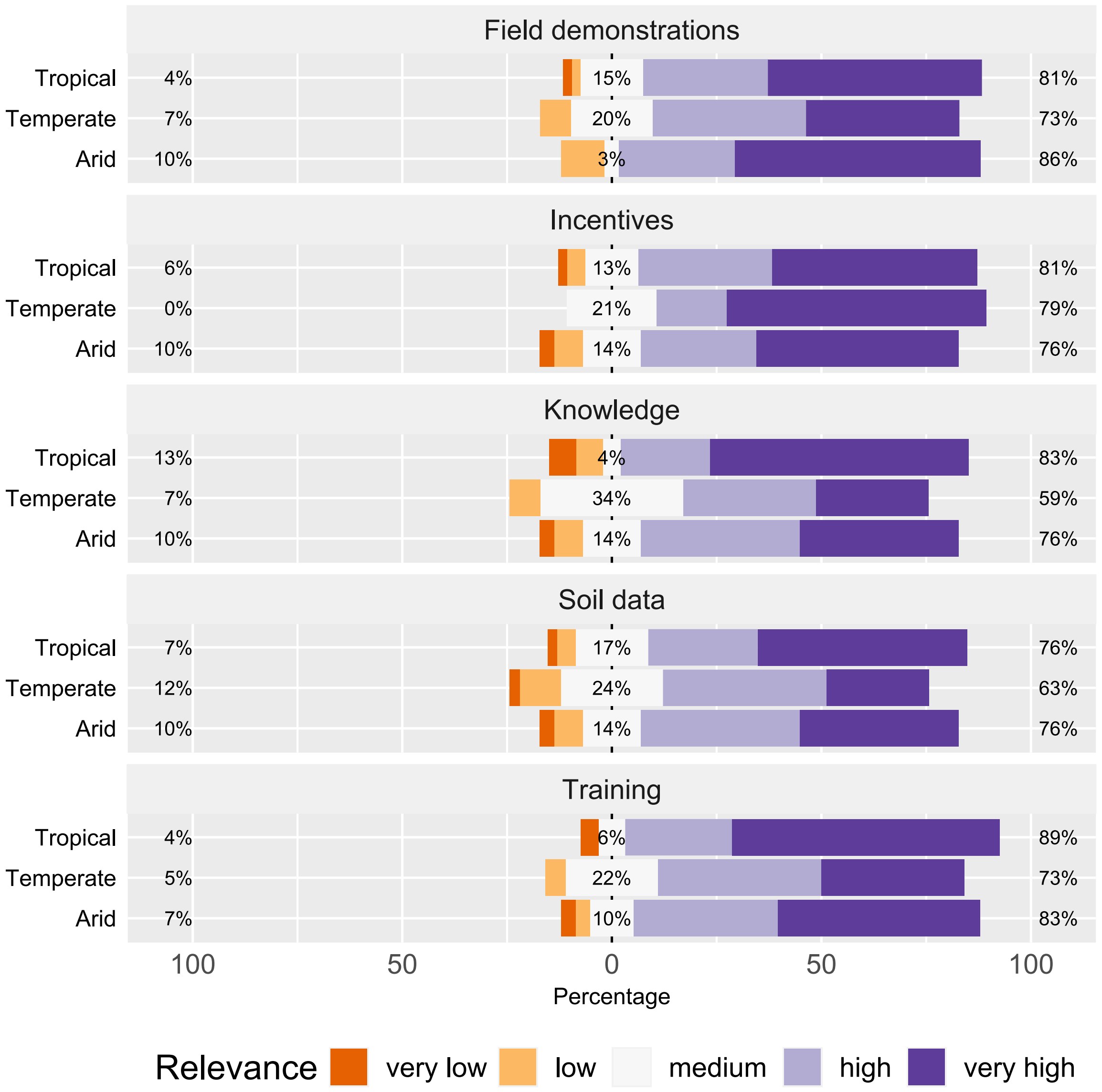

Figure 14. Farmer's needs and their relevance according to soil experts (n=162) by climate. The percentages on the left represent the proportion of the two lowest ratings, in the middle that of the medium ratings and on the right side that of the two highest ones.

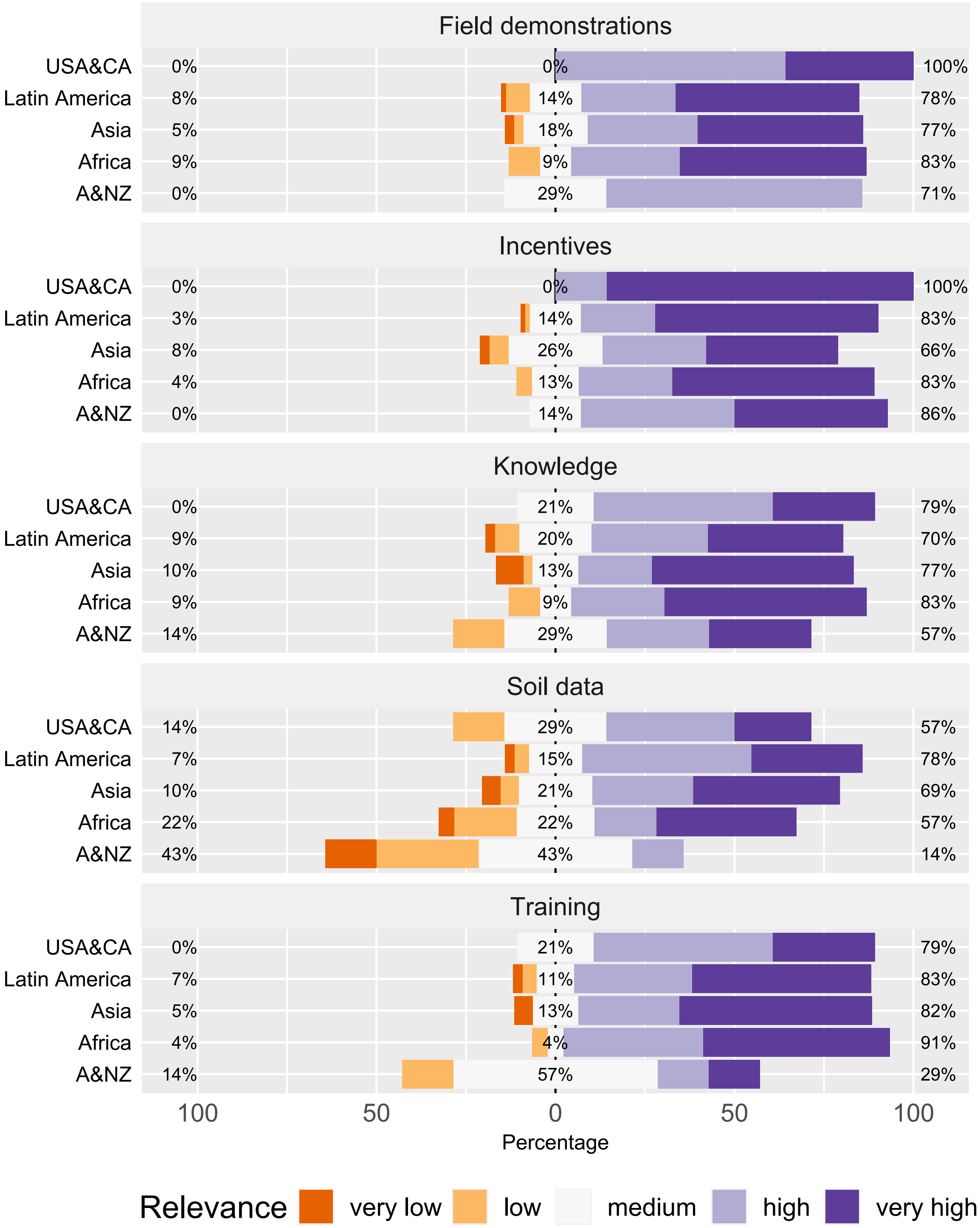

Figure 15. Farmer's needs and their relevance according to soil experts (n=162) by geographical region. The percentages on the left represent the proportion of the two lowest ratings, in the middle that of the medium ratings and on the right side that of the two highest ones.

Appendix G: Unique or innovative practices mentioned

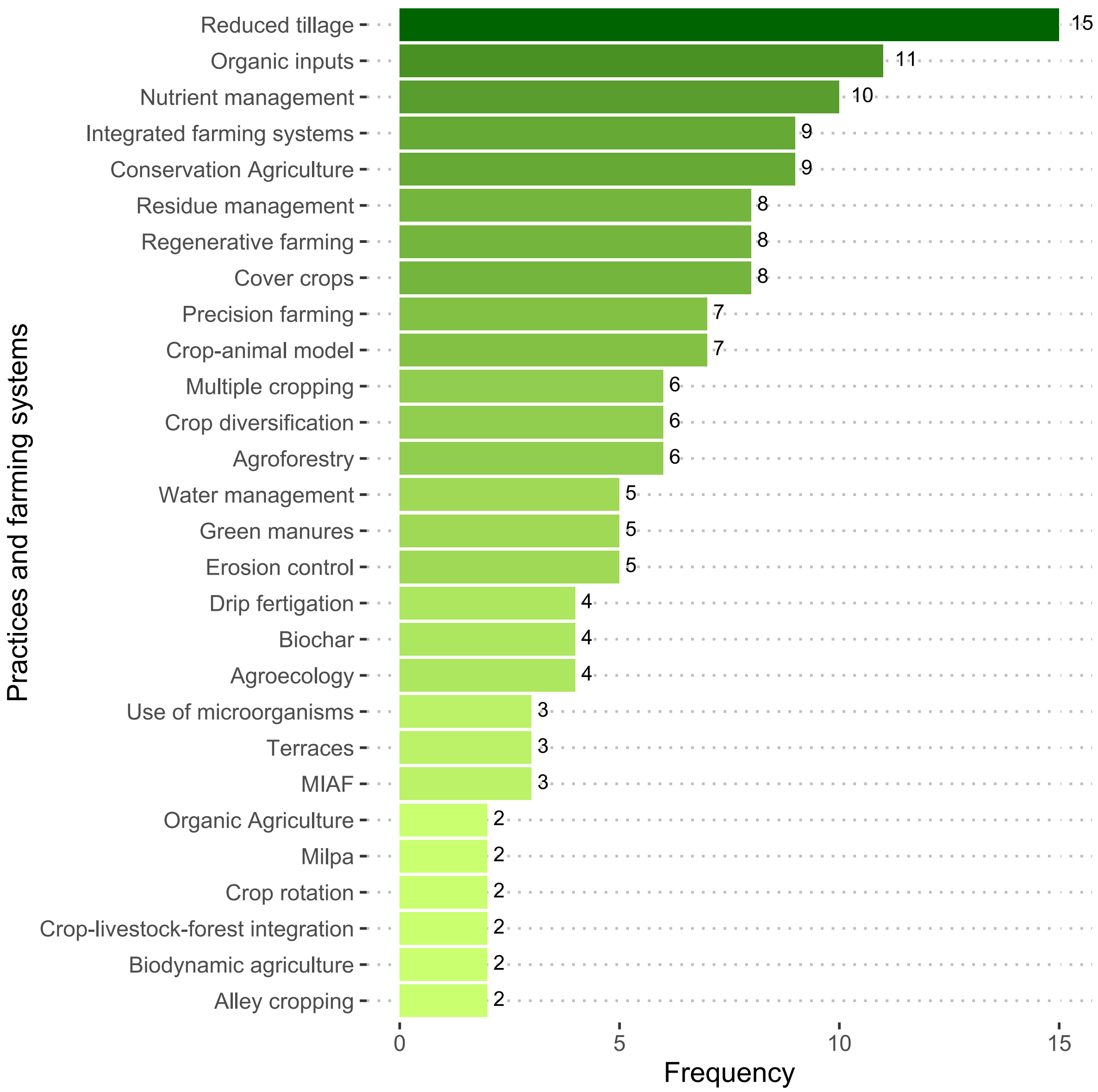

Figure 16. Most mentioned practices or farming systems from the answers to the open question "unique or innovative practices in the region or country described " mentioned by soil experts outside Europe (n=50). The categories were created from the participants' written answers. MIAF: Milpa Interspersed with Fruit Trees.

Appendix H: Policy needs

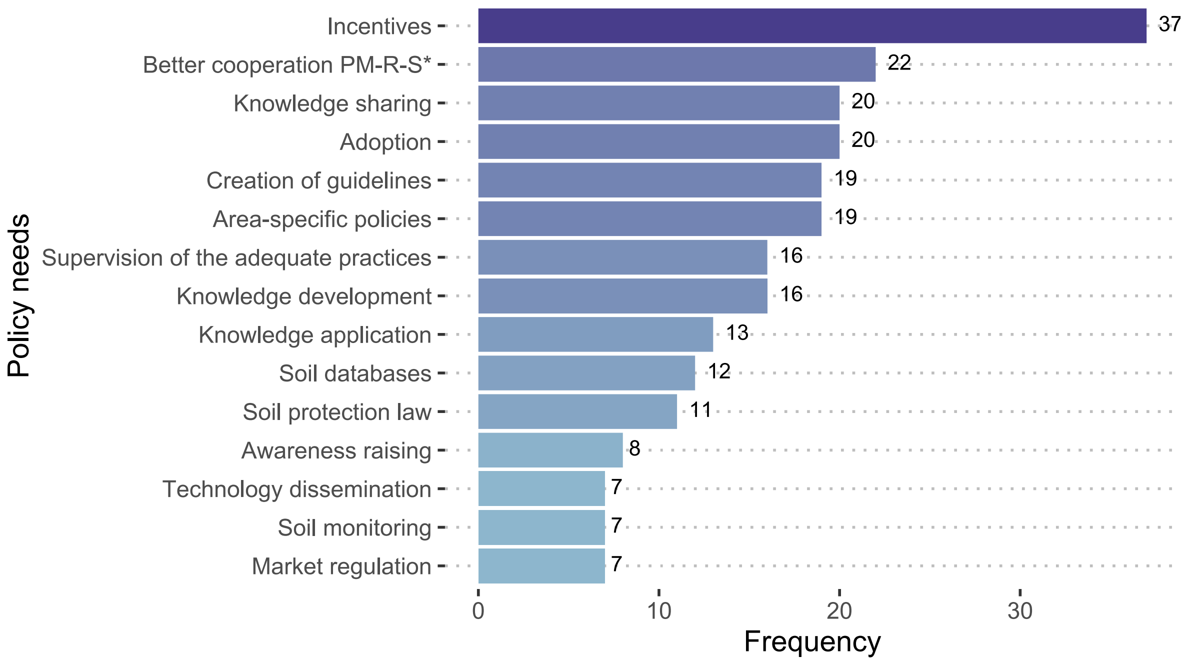

Figure 17. Most mentioned policy needs in the open question "policy needs for the region or country described" answered by soil experts outside Europe (n=124). Categories were created from the participants' written answers. *PM-R-S: Policy makers-researchers-stakeholders.