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Importance of soil fertility for climate-resilient cropping systems: The farmer's perspective

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ABSTRACT

Healthy and productive agricultural soils are the basis for global food security as they are a prerequisite for yield-stable cropping systems under climate change. Despite the expansion of agricultural research activities in this area through field experiments, lab analyses, and modelling frameworks, current empirical insights from farming practice on a more national scale are still rare. For this reason, the agronomic importance of soil fertility for farming practice was the focus of this nationwide empirical study conducted in Germany (winter/spring 2022) with a total sample size of 585. The views and needs of 370 farmers and 215 agricultural institutionalists were evaluated, i.a., regarding the importance of soil fertility and related soil properties, as well as preferred agronomic management strategies and needs for the promotion of soil fertility. The results showed that most farmers and institutionalists consider soil fertility to be very important. Moreover, it was emphasized that the importance of this factor will increase in the future due to changing climatic conditions (e.g., heat/drought stress) and the need for more sustainable land use including the protection of biodiversity. The main motivations for agronomic investments in greater soil fertility were improving the climate resilience and yield stability of cropping systems. In this context, the top soil properties of interest were ranked by the respondents as follows: (1) water storage capacity, (2) rootability, (3) biological activity, and (4) water infiltration rate. To promote soil fertility, farmers mainly considered catch cropping, diversified crop rotations with a positive humus balance, and year-round ground plant cover/mulch as the most useful agronomic measures. In terms of methods for the assessment of soil fertility, soil structure analyses, biological indicators, yield/biomass production, soil nutrient analyses, and field methods were most important, whereas sensor systems and apps/digital tools were of minor importance. For the future improvement of soil fertility promotion in farming practice, simple indicators and reference values for assessing soil fertility as well as 'workshops, field days, and field schools' for training aspects were suggested by the participants. Overall, there were few differences between the perceptions of farmers and agricultural institutionalists. Both groups pointed out the need for improved communication between politics, science, and practice such that agriculture can respond more quickly to changing climatic conditions in the future.

Introduction

Agricultural crop production must increase significantly to keep pace with the increasing food demand of a growing world population. This challenge becomes even more difficult under a background of climate change and related higher agronomic risks for yield failure (Macholdt et al., 2021). Most of our food comes from agricultural managed soils; thus, future food security strongly depends on maintaining soil productivity. Healthy and productive soil (soil fertility), as a finite, non-renewable, and dynamic living ecosystem, is one of the most important strategic resources in global agriculture (Laishram et al., 2012).

From an agronomic view, soil fertility can be described as the soil`s productivity and its capability to provide favourable growing conditions needed by plants for realizing high and stable yields in crop production (Stockdale et al., 2002). In this context, the capacity of the soil to supply crops with a sufficient amount of macro- and micronutrients, which may limit plant growth, is of primary importance (Hartemink, 2006). In

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addition to nutrient supply, a sufficient content of organic matter to retain water and nutrients, water availability, aeration, and plant stability are further essential properties (Estrada-Herrera et al., 2017). Soil fertility is a result of complex interactions between biological, chemical, and physical processes (Stockdale et al., 2002; van Bruggen and Semenov, 2000). Physical soil properties mainly include the soil structure, i.e., the spatial arrangement of solids and voids. Soil structure has a major influence on air and water balance, water and nutrient storage, root penetration, susceptibility to erosion and compaction, and the habitat of soil organisms (Rabot et al., 2018). The chemical reactions that occur in the soil are primarily affected by pH; therefore, pH affects the cation and anion exchange capacity, nutrient and pollutant availability, and organic matter in the soil (Jones and Jacobsen, 2005). Earthworms, microorganisms, fungi, and many other species shape soil life, build up soil organic matter, and are essential for the biological component of soil fertility as they mineralize and mobilize necessary plant nutrients, thereby increasing nutrient and water availability (Chauhan, 2014). Thus, high biodiversity, an intact food web, good internal nutrient cycling, and a high regeneration and buffering capacity are prerequisites for healthy soils in sustainable and climate-resilient crop production (van Bruggen and Semenov, 2000).

Despite the availability of numerous indicators of soil fertility, such as soil pH, soil organic matter content, available nutrient content (e.g., nitrate, phosphate), exchangeable bases (Ca, Mg, K), cation exchange capacity, soil respiration, microbial activity, microbial carbon/nitrogen content, soil life (e.g., the abundance of earth worms), and soil structure (e.g., bulk density), the assessment of soil fertility is still a complex and difficult task for researchers, and even more so for farmers (Estrada-Herrera et al., 2017). In addition to estimating soil structure and nutrient contents (via lab analyses of soil samples), field texture tests (spade test) and odour tests are often applied in farming practice (Rabot et al., 2018). Furthermore, soil analysis data can be collected using different methods (e.g., technical, analytical, sampling depth/intervals) (van Bruggen and Semenov, 2000). This shows that holistic assessment is not yet present in agriculture, as knowledge and methods are not yet united in one practical approach (El Chami et al., 2020). An additional challenge is that most changes in soil fertility need to be analysed from a long-term perspective, and significant changes are rarely observed from one year to the next; moreover, the distinction between the impact of agronomic management measures and environmental factors (e.g., climate, soil type, relief) on soil fertility is a difficult task (Watson et al., 2006).

Soil fertility is of basic relevance for two major points in current crop production: sustainability and climate resilience. In terms of sustainability, a higher soil fertility is associated with higher soil biodiversity and better nutrient recycling and can help to reduce nitrous oxide emissions, the incidence of pests and diseases, and the use of pesticides, fertilisers, and fuel/energy (Watson et al., 2006; Bayu and Li, 2020). With regard to climate change, a higher soil fertility can help to improve the climate resilience (abiotic stress tolerance to hot and drought periods or heavy rainfall events) of plants and entire cropping systems by increasing water availability, which results from increases in soil water storage capacity, rootability, and aggregate stability (Bayu and Li, 2020; Mondal, 2021; Sa et al., 2017; Crane et al., 2011).

Although soil fertility is essential for crop production, most studies dealing with this topic have focused on single factors and mainly used experimental approaches (field/pot trials). However, empirical approaches providing new insights into the complexities of soil fertility in farming practice have been scarcely applied so far (Primbs, 2021). The current empirical study was carried out to help close this gap. The objective of this study was to provide new insights into farming practice with respect to the present and future importance of soil fertility for crop production. Based on the responses collected from farmers and agricultural institutionalists, the main objective of the survey was to answer the following five questions:

(1) What is the importance of soil fertility in agronomy, both now and in the future?
(2) What are the motives for agronomic investments in greater soil fertility?
(3) Which soil properties are expected to be improved from greater soil fertility?
(4) What kind of agronomic measures are recommended and used in practice to promote soil fertility?
(5) What are the demands of farmers for supporting soil fertility promotion in agronomic practice?

Materials and methods

Study area

Half of the total land area in Germany is used for agriculture (16.6 million hectares; 70 % crop production; 28.5 % permanent grassland; 1.5 % vine, fruits, and others). Between 1992 and 2021, a decreasing trend of around 1.38 million hectares was observed, mainly due to an increase in settlement and traffic areas (Statista Number of Agricultural Farms in Germany by 2021). Nearly 10 % of the agricultural area is currently farmed organically, while 90 % is farmed conventionally. The total number of farms decreased from 293,900 in 2011 to 256,900 in 2021, accompanied by a decrease in the number of farms with below 100 hectares of agricultural land and an increase in the number of farms with more than 100 hectares (Genesis Agricultural holdings and Utilised Agricultural Area).

Germany is situated in a temperate climate zone. The consequences of climate change are becoming increasingly apparent in this area: The long-term mean of annual air temperature was 8.2 °C in the 1961–1990 climate reference period and increased to 9.3 °C in the recent reference period (1991–2020) (German Meteorological Service). The long-term mean of annual precipitation was 791 mm (spring: 171 mm; summer: 240 mm; autumn: 190 mm; winter: 190 mm) in the 1991–1920 climate reference period and remained mostly stable (789 mm in the 1961–1990 reference period) with a trend towards higher interannual variability (German Meteorological Service). As observed using the Helmholtz Centre for Environmental Research drought monitor, the intra-annual precipitation distribution shows a trend towards an increase in the winter and a decrease in the summer, which results in more frequent and severe droughts during the main vegetation period for agricultural crops (Markonis et al., 2021).

Data collection and analysis

The nationwide survey was conducted in winter/spring 2022 in Germany and utilized a standardized online questionnaire. The target groups were German farmers and institutionalists, such as agronomic advisors, agricultural scientists, and other stakeholders in the agricultural sector (associations, federal institutions). Farmers and institutionalists with experience in the field of agronomy and soil fertility were invited to participate in the survey by direct e-mails with a personal letter and link to an online version of the questionnaire. The survey was also sent to agricultural and scientific associations to reach potential participants through appropriate mail distribution systems. Many advertisements were also placed in agricultural magazines, on the homepages of agricultural associations, and on online agricultural platforms. In addition, potential participants were contacted directly and invited to participate. The target groups were provided with a direct link to the Q-Set internet portal.

The questionnaire was set up as follows: In the first part, participants were asked to provide personal information about their occupations. If their respective field of work was not included in the suggestions, additional responses could be added in a free-text field. In addition, farmers were asked to provide information about the on-site conditions at their farm (soil quality index or score `from 0 as lowest soil quality up to 100 as highest soil quality' and average sum of annual rainfall). In the main part, three questions addressed the importance of soil fertility (now and in the future), motives for agronomic investments in soil fertility, and related positive agronomic effects and improved soil properties. Furthermore, participants were asked for the criteria or methods that they used to assess the fertility of agricultural soils. In the following section, the participants were asked to provide recommendations of agronomic measures for soil fertility promotion; in addition, farmers were asked if these measures were already implemented on their farms. At the end of the questionnaire, an assessment of demands from science/authorities/advice was included and a closing remark could be made. The questions were primarily multiple-choice, with multiple and single responses, and rating questions based on a three/four-point Likert scale. In addition, five questions included free-text fields for additional comments and remarks. The full questionnaire is provided in Table S1 in the Supplementary Material.

At the end of the study period, the total number of returned questionnaires was 929. Responses were received from individuals belonging to the following professional groups: farmers ($n = 498$), private agricultural consultants ($n = 117$), agricultural office/Ministry of Agriculture/Chamber of Agriculture ($n = 81$), research institutions/universities ($n = 154$), agricultural associations ($n = 24$), and other/not specifies ($n = 55$). The participants were divided into two groups: (1) farmers and (2) agricultural institutionalists, which included all other subject-related occupational groups. After reviewing the questionnaires to assess their reliability, completeness, and coherence, the number of acceptable questionnaires decreased. Reasons for this included the presence of non-plausible answers, unrealistic responses, or incompletely answered questionnaires. This resulted in a final approved sample size of 585 fully answered questionnaires considering the responses of 370 farmers and 215 agricultural institutionalists. This represents a response rate for farmers of < 1 % (0.14 %) based on the number of farms (257 thousand) in Germany. For the directly invited farmers and agricultural institutionalists, a response rate of 64 % could be assumed in relation to the number of invitations sent out (direct mailings).

At the beginning of the survey, the participating farmers were asked to provide some details about their on-farm conditions, including the prevailing soil texture class, soil quality index (or score), and average sum of annual rainfall. The provided information can be summarized and categorized as follows: Regarding the general soil texture class (number of responses $n = 290$), 22 % of the farmers reported having soils with mainly light texture (sandy soils, loam-sandy soils), 69 % with medium/heavy texture (sand-loamy soils, loamy soils), and 9 % with heavy texture (clay-loamy soils, clay soils). The farmers surveyed were also asked to specify the average soil quality index/score of their managed soils (number of responses $n = 351$). The soil quality score, which ranges from 0 to 100 points (highest soil quality), is a measure of long-term soil quality and provides a rough estimate of the local crop yield potential (BGR 2013). Of the total farmers, 28 % graded their soils of poor quality, with a soil quality score range of 18–39 (Ø 31; $n = 100$), while 37 % estimated their soils to be of medium quality within a soil quality score range of 31–49 (Ø 48; $n = 130$). Soils of high quality, with a score range of 60–90 (Ø 71; $n = 121$), were reported by 35 % of farmers. With respect to the average sum of annual rainfall (mm) (number of responses $n = 283$), responses ranged from 242 mm to 1300 mm, where Ø 673 mm was calculated as the annual average precipitation over all farmers. A total of 14 % of respondents stated having less than 500 mm, 48 % reported having 500–700 mm, 26 % responded with 701–800 mm, and 12 % reported having more than 800 mm of annual average precipitation.

Data were prepared descriptively using Excel (2019, version 16.63.1 macOS). Bivariate analyses with Spearman`s correlation were used to describe the dependencies between farmers' ratings/assessments and their on-farm site conditions (two co-variables were included: soil quality index and average sum of precipitation). These analyses were performed using the IBM SPSS Statistics 23 software (IBM Corporation, New York, NY, USA). The analysis of the comments written in the free-text fields is presented in both the results and discussion sections.

The survey was presented exclusively online to achieve a high participation rate and comparability of the results. However, it should be noted that the results include subjective information provided by the respondents and are not generally valid due to limited statistical representativeness. Further critical points of online surveys include testing environments that are not transparent for the interviewer and problems with higher drop-out rates (Couper, 2000). On the other hand, faster processing, lower costs, and the possibility of a more accurate summary of the results are considered positive factors for online surveys. Overall, the advantages of a web-based empirical study reaching a large nationwide target group using a single interviewer and providing a broad dataset outweigh the possible risks mentioned above (Gosling et al., 2004).

Results

Present and future importance of soil fertility in agricultural crop production

The first question on the survey targeted the importance of soil fertility in agricultural crop production. Respondents were asked to distinguish between the importance of soil fertility 'at present' and 'in the future' (Table 1). Almost half of the farmers (49 %) stated that soil fertility was very important at present, while about one-third (31 %) stated that it was important. Similar results were found amongst agricultural institutionalists, with 32 % choosing 'important' and 47 % choosing 'very important'. The similarity of these results between the different occupational groups was confirmed by a significant correlation ($R = 0.72$; $p < 0.05$). None of the farmers and only 1 % of the institutionalists indicated that soil fertility was unimportant, while 8 and 9 %, respectively, abstained from answering (Table 1). When answering this question with respect to the future, a significant increase in the relevance of soil fertility was detected amongst both farmers and institutionalists. amongst farmers, the perception of very high relevance increased to 69 %, while it increased to 66 % amongst institutionalists. A significant correlation ($R = 0.93$; $p < 0.05$) was found for the relationship between the farmers' and institutionalists' ratings of soil fertility importance in the future. The changes in perceptions are shown in a cross table (Table 2), including the ratings from all respondents (farmers and agricultural institutionalists). This comparison underlines the increasing importance of soil fertility as we move into the future. Specifically, 18 % of the respondents changed their ranking from 'important' in the present to 'very important' in the future, while the other ratings (less important, unimportant, and not specified) remained nearly constant (Table 2). In the bivariate analyses, farmers' ratings regarding the present and future importance of soil fertility showed no significant dependence on their stated on-farm conditions, including the soil quality index and average sum of annual rainfall (Table S2 Supplementary material).

Table 1
Ratings of farmers and agricultural institutionalists regarding the present and future importance of soil fertility.

Rating	Present importance of soil fertility		Future importance of soil fertility	
	Farmers (%)	Institutionalists (%)	Farmers (%)	Institutionalists (%)
Very important	49	47	69	66
Important	31	32	13	14
Less important	12	11	10	11
Unimportant	0	1	0	0
Not specified	8	9	8	9

All participants included ($n = 585$, 370 farmers and 215 agricultural institutionalists).

Table 2
Cross table comparing the importance of soil fertility in the present and future.

Present/ Future	Unimportant (%)	Less Important (%)	Important (%)	Very Important (%)
Unimportant	0,2	0	0	0,2
Less Important	0	21	1	1
Important	0,3	0,3	11	18
Very Important	0	0	1	46

All participants included (n = 585, 370 farmers and 215 agricultural institutionalists).

Motives for agronomic investments in greater soil fertility

Although soil fertility was generally considered important, there were differences in the rationale for its importance. Farmers (Fig. 1) and agricultural institutionalists (Fig. 2) were asked about their motives for agronomic investments in greater soil fertility. There were seven motives (or reasons) to choose from, which were rated based on a four-point Likert rating scale (very important, important, less important, and unimportant). For 61 % of the farmers and 66 % of the institutionalists, increasing the climate resilience (abiotic stress tolerance) of cropping systems was found to be most important. The motive of increasing yield stability in crop production ranked second amongst farmers (61 %) and institutionalists (57 %). Contributing to environmental protection and saving chemical-synthetic inputs were also found to be important reasons, receiving votes from 35/36 % of farmers and 40 % of agricultural institutionalists. In comparison, contributions to climate protection, for example by C sequestration, or increasing yield level were rated of less importance by both groups (19–32 %). Overall, 13–15 % of farmers and institutionalists abstained from answering this question. In the bivariate analyses, the farmers' motives for agronomic investments in greater soil fertility showed no significant dependence on their stated on-farm conditions, including soil quality index and the average sum of annual rainfall (Table S3 Supplementary material).

In addition, several participants (n = 64) made comments about other objectives and motives for agronomic investments in greater soil fertility. From this, it became clear that the provision of ecosystem services, such as erosion and flood control, and filtering and buffering functions are especially important for achieving high water quality and soil water storage. The contributions of these factors to the production of healthy, high-quality, and nutrient-rich food and feed as well as the protection of soil biodiversity (including habitat functions and soil organisms) were also given high priority by the respondents (n = 32). Finally, the careful use of finite resources and energy as well as cost savings were mentioned as important motives. These comments can be summarized by the following quote from the survey: 'healthy soil—healthy plant—healthy human'.

Improved soil properties expected from greater soil fertility

To determine which soil properties were expected to be improved as a result of greater soil fertility, eleven soil properties were presented to the respondents. These were also rated based on a four-point Likert scale (very important, important, less important, and unimportant). Over half of the farmers (52 %) found the water holding capacity of the soil to be positively affected by soil fertility promotion (Fig. 3). This was followed in the ranking of effect relevance by rootability (50 %) and soil biological activity (49 %). In comparison, soil air and temperature balance (24 %) and soil workability/trafficability (20 %) were considered to have rather low importance amongst farmers. Overall, a higher number of farmers (27–28 %) abstained from answering this question.

In the bivariate analyses, the farmers' assessment of improved soil properties expected from greater soil fertility showed no significant dependence on their stated on-farm conditions (co-variables: soil quality index and average sum of annual rainfall), except for the water storage capacity and aggregate stability, which were both related to the rainfall co-variable (Table 3). Here, with a lower rainfall amount, the water storage capacity was rated of higher importance by farmers (rho = −0.12; negative correlation). For aggregate stability, a different dependence was observed: the larger the amount of rainfall, the higher the importance of aggregate stability (rho = +0.12; positive correlation).

The agricultural institutionalists gave similar opinions to the farmers, particularly for the top three ranked soil properties (Fig. 4). The water storage capacity of the soil received 59 % of the votes, indicating that it was of highest importance. With 47 % of the votes, soil biological activity came in second, while rootability came in third with 45 %. This was closely followed by the water infiltration capacity, soil organic matter content, plant health, and aggregate stability in the same order as that for farmers. Better soil workability/trafficability (18 %) was also considered the soil property with the least importance by the institutionalists. A total of 20–21 % of the institutionalists abstained from answering this question.

The participants were given the opportunity to add additional soil properties that they expected to increase with greater soil fertility. In the comments (n = 24), soil structure and crumb stability were emphasized above other factors in terms of preventing erosion and thus the loss of soil as an essential natural resource. Additionally, the respondents stated that biological soil components and the promotion of soil biodiversity

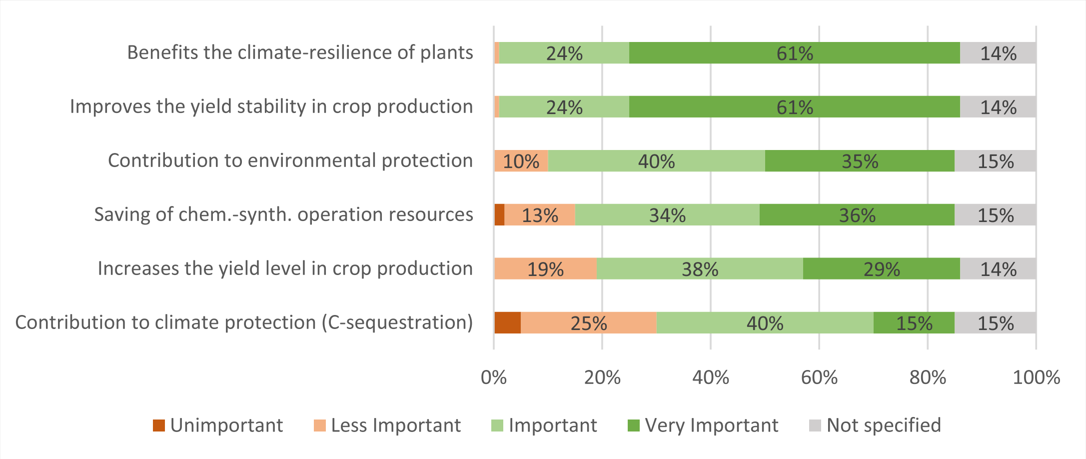

Fig. 1. Evaluation of farmers' motives for agronomic investments in greater soil fertility (n = 370).

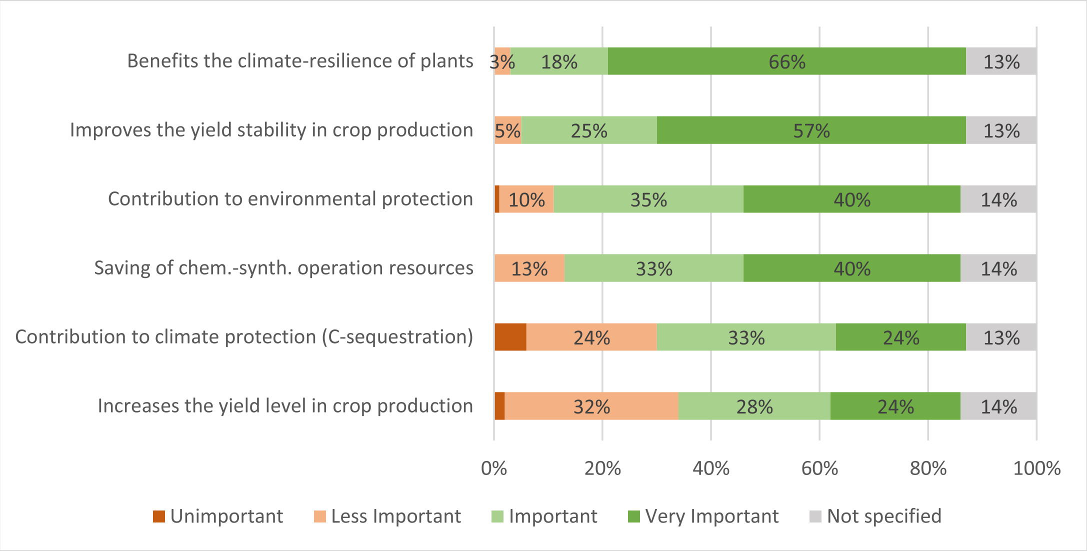

Fig. 2. Evaluation of institutionalists' motives for agronomic investments in greater soil fertility ($n = 215$).

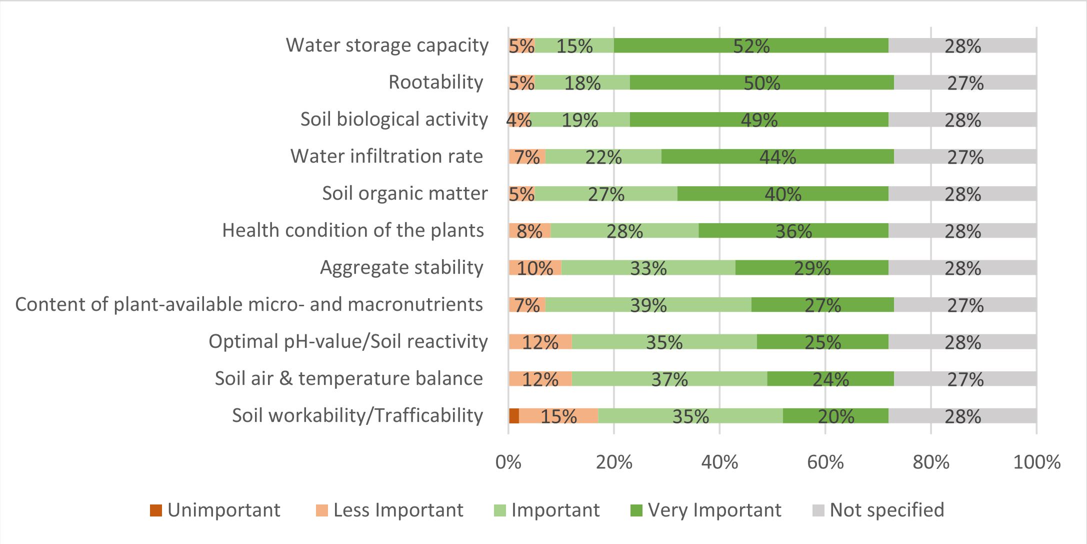

Fig. 3. Positive effects on selected soil properties due to increased soil fertility expected by farmers ($n = 370$).

Table 3
Farmers' assessment of positive effects on selected soil properties of increased soil fertility depending on their stated on-farm conditions (co-variables: soil quality index and average sum of annual rainfall).

Response option	**1. Co-variable: Soil quality index**		**2. Co-variable: Average sum of annual rainfall**	
	rho	**p**	**rho**	**p**
Water storage capacity	+0.02	0.81	**−0.12***	**0.04**
Rootability	−0.05	0.37	−0.05	0.39
Soil biological activity	−0.09	0.14	+0.05	0.39
Water infiltration rate	+0.10	0.11	−0.08	0.17
Soil organic matter	−0.01	0.90	+0.06	0.41
Health condition of plants	+0.04	0.54	−0.06	0.36
Aggregate stability	+0.05	0.38	**+0.12***	**0.04**
Content of plant-available nutrients	−0.03	0.64	−0.03	0.60
Optimal pH-value/soil reactivity	+0.02	0.72	+0.03	0.68
Soil air and temperature balance	+0.02	0.78	−0.02	0.76
Soil workability/trafficability	+0.11	0.07	−0.04	0.54

* significant at $p < 0.05$; $n = 272$ farmers.

should be given greatest importance ($n = 21$). Understanding and restoring matter fluxes and nutrient cycles instead of resource consumption is also a point that was mentioned frequently ($n = 19$). Lastly, one respondent stated that 'all these factors are equally important for a functioning soil ecosystem' (quote from the survey).

In addition, farmers and institutionalists were asked about the methods that they use to assess the fertility of agricultural soil (Fig. 5). In this study, eleven different methods were presented to the respondents. Multiple answers were possible. Soil structure analyses (e.g., examining the soil coarseness) were found to be of the highest importance to farmers (75 %) and agricultural institutionalists (82 %). The following criteria were ranked in descending order: biological indicators (e.g., earthworms and their loss), yield/biomass production, soil nutrient analyses (e.g., Kinsey), and field methods such as the spade test. Criteria including plant health, visual and olfactory impressions (e.g., soil colour, odour), soil trafficability, and expert assessments (e.g., consultants) tended to play subordinate roles. Farmers and institutionalists reported significantly lower use of sensor systems and apps or digital tools. Only 4 % of farmers and 6 % of institutionalists used or

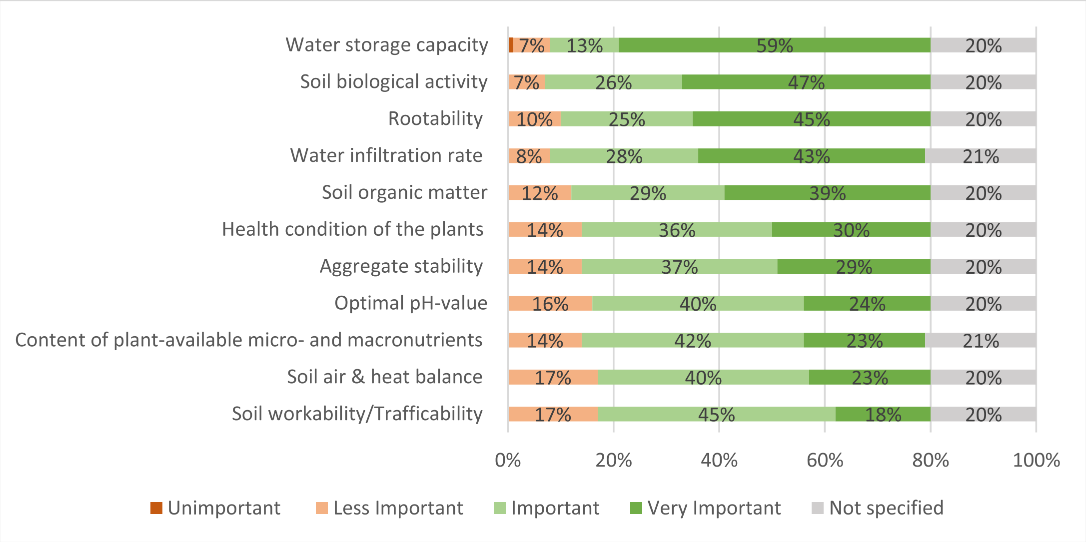

Fig. 4. Positive effects on selected soil properties due to increased soil fertility expected by agricultural institutionalists (n = 215).

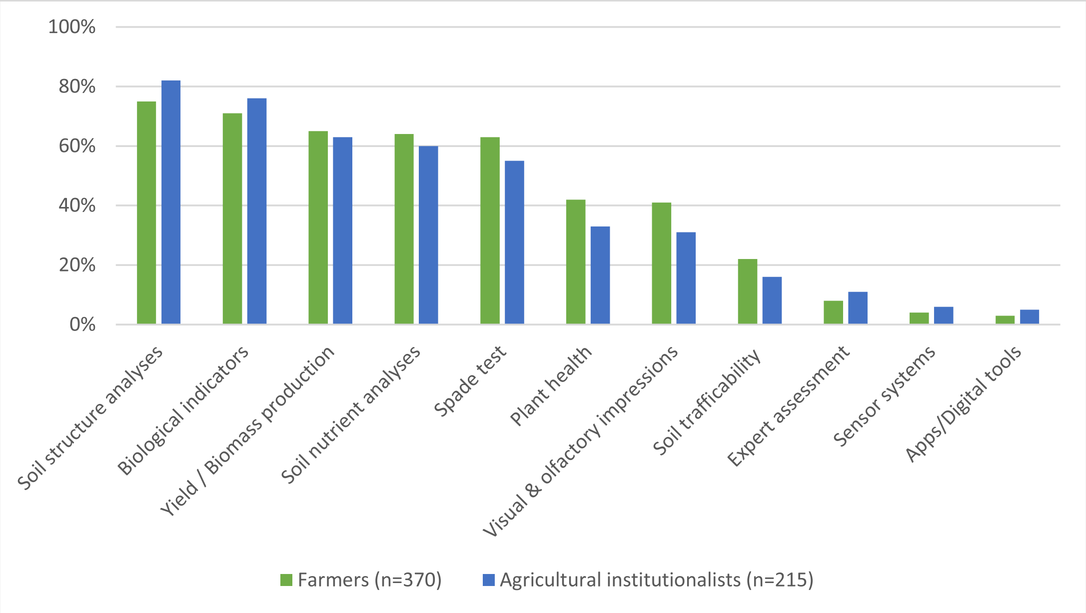

Fig. 5. Evaluation methods for soil fertility used by farmers and agricultural institutionalists (multiple answers allowed).

recommended sensor systems, while apps and digital tools were considered by only 3 % of farmers and 5 % of institutionalists (Fig. 5). Although sensor systems and apps/digital tools for assessing soil fertility are not yet considered as the standard, some examples were still mentioned by respondents in the free-text fields. Based on the comments, soil sensors were mostly used to measure moisture, temperature, pH, nitrogen content, electrical conductivity, and structural stability (n = 10). Field structure approaches (n = 9), remote sensing systems (e.g., satellites, aerial imagery, and drones) (n = 7), and soil maps (n = 5) were also employed. amongst apps, 'OneSoil', 'Field structure', 'My Farm 24′, 'CropSat', and 'Farmblick' were mentioned several times by respondents.

Agronomic management practices for promoting soil fertility

Agronomic management practices can have positive impacts on soil fertility. To determine which sets of measures were recommended and used by farmers, the participants were given 20 agronomic measures on this topic. The farmers (Table 4) and agricultural institutionalists (Table 6) were asked to rate the importance of the measures based on a three-point Likert scale (high, intermediate, and low).

According to the farmers' assessment of the management measures used to promote soil fertility (Table 4), diversified crop rotations with a positive humus balance (45 %), catch cropping (45 %), and year-round ground cover (41 %) were rated as having the greatest benefit. Undersowing, balanced nutrient balances, and mulch seeding with conservation tillage were ranked in the medium impact range. Meanwhile, the farmers reported that biostimulants, soil amendments/biostimulants (e. g., biochar), and agroforestry systems have a low impact on promoting soil fertility. A total of 37–42 % of the farmers abstained from answering this question.

Regarding the farmers' implementation of agronomic management practices (last column in Table 4), the cultivation of catch crops (57 %), balanced nutrient supply (56 %), leaving crop residues on the field (55

Table 4
Farmers' assessment of the impact of agronomic management measures on the promotion of soil fertility and their on-farm implementation.

Response option	Impact (%) High	Intermediate	Low	Not specified	Implemented on-farm (%)
Catch cropping	45	14	2	39	57
Diversified crop rotation with positive humus balance	45	14	3	38	43
Year-round soil cover	41	16	6	37	40
Leaving crop residues on the field	36	22	4	38	55
Cultivation of crops that improve soil structure	36	23	2	39	47
Organic fertilisation	32	27	2	39	55
Cultivation of legumes	29	27	5	39	37
Conservation tillage with mulch sowing	26	30	5	39	49
Regular liming	24	27	10	39	55
Balanced nutrient supply	22	30	8	40	56
No tillage with direct sowing	22	21	17	40	16
Undersowing	14	32	14	40	16
Mixed cropping	11	29	20	40	17
Green fallow	10	27	22	41	11
Agroforestry systems	7	21	30	42	2
Structural elements/ conservation headlands	7	27	25	41	37
Precision farming	7	22	29	42	28
Soil additives/ biostimulants	5	18	35	42	11

$n = 370$ farmers.

Table 5
Farmers' assessment of agronomic management measures for promoting soil fertility depending on their reported on-farm conditions (co-variables: soil quality index and average sum of annual rainfall).

Response option	1. Co-variable: Soil quality index rho	p	N	2. Co-variable: Average sum of annual rainfall rho	p	N
Catch cropping	−0.08	0.23	238	**+0.20****	**0.00**	238
Diversified crop rotation with positive humus balance	+0.11	0.09	244	−0.04	0.49	244
Year-round soil cover	−0.09	0.15	241	**+0.21****	**0.00**	241
Leaving crop residues on the field	**+0.20****	**0.00**	246	−0.12*	0.03	246
Cultivation of crops that improve soil structure	+0.07	0.26	241	+0.01	0.85	241
Organic fertilisation	**−0.24****	**0.00**	243	**+0.14***	**0.02**	243
Cultivation of legumes	−0.07	0.26	239	+0.03	0.62	239
Conservation tillage with mulch sowing	−0.04	0.56	238	+0.04	0.57	238
Regular liming	**−0.12***	**0.03**	248	**+0.14***	**0.02**	248
Balanced nutrient supply	+0.09	0.14	243	−0.02	0.76	243
No tillage with direct sowing	+0.01	0.89	229	+0.04	0.57	229
Undersowing	**−0.13***	**0.03**	233	+0.07	0.29	233
Mixed cropping	−0.06	0.34	231	+0.03	0.65	231
Green fallow	+0.06	0.41	226	+0.08	0.23	226
Agroforestry systems	−0.02	0.82	228	−0.71	0.24	228
Structural elements/ conservation headlands	+0.09	0.19	233	−0.05	0.41	233
Precision farming	+0.01	0.84	228	+0.01	0.89	228
Soil additives/ biostimulants	−0.06	0.40	228	−0.07	0.33	228

** significant at $p < 0.01$; * significant at $p < 0.05$.

%), regular liming (55 %), and organic fertilisation (55 %) were the most commonly used. Further measures including diversified crop rotations (43 %), year-round soil cover (40 %), and the cultivation of crops that improve soil structure (47 %) were less frequently implemented in farming practice, although their potential positive impact on soil fertility were rated as high by the farmers. In contrast, structural elements/conservation headlands and precision farming were rated as measures with intermediate or rather low impacts on soil fertility, but their on-farm implementation rate was comparatively high (37 %, 28 % respectively). However, some measures were neither commonly recommended nor implemented by farmers, including soil additives/biostimulants (11 %), green fallow (11 %), and agroforestry (2 %).

In the bivariate analyses, the on-farm implementation of management measures used to promote soil fertility was tested for significant dependence on the farmers' stated on-farm conditions (co-variables: soil quality index and average sum of annual rainfall; Table 5). In eight cases, a significant dependency was found. The `soil quality index' co-variable was positively correlated ($p < 0.01$) with leaving crop residues on the field (rho = +0.20) and negatively correlated ($p < 0.05$) with organic fertilisation (rho = −0.24), regular liming (rho = −0.12), and undersowing (rho = −0.13). That is, farmers who reported having agricultural soils of higher quality left crop residues on the field more often as a measure for promoting soil fertility. Farmers who reported having agricultural soils of lower quality tended to implement measures such as organic fertilisation, liming, and undersowing. The `rainfall' co-variable was positively correlated ($p < 0.05$) with catch cropping (rho = +0.20), year-round soil cover (rho = +0.21), organic fertilisation (rho = +0.14), and regular liming (rho = +0.14). This can be interpreted as follows: farmers who reported larger amounts of rainfall implemented these measures for promoting soil fertility.

Compared to the farmers' assessment of the management measures used to promote soil fertility, a similar breakdown was seen amongst the agricultural institutionalists (Table 6). They also rated diversified crop rotations (47 %), catch cropping (45 %), and year-round ground cover (44 %) as the top three measures with the greatest positive impact on soil fertility. These measures were followed by the practices of organic fertilisation (41 %), the cultivation of legumes (38 %) or crops that improve soil structure (33 %), and leaving crop residues on the field (32 %), which were also highly recommended by around one-third of respondents. Measures such as precision farming (32 %), mixed cropping (33 %), and undersowing (37 %) were mainly assessed by institutionalists as having an intermediate impact on the promotion of soil fertility. The importance of structural elements/conservation headlands (16 %) and agroforestry systems (10 %) was considered to be higher by institutionalists, meaning that they perceived them to have a slightly greater impact on soil fertility promotion than the farmers did (both 7 %, see Table 4). The impact of soil additives/biostimulants on soil fertility was considered to be very low by 42 % of the institutionalists, which is in line with the low ratings given by farmers (35 %, see Table 4). A total of 36–41 % of the agricultural institutionalists abstained from answering this question (Table 6).

In addition, some comments on further agronomic management measures were made by respondents. To reduce soil pressure and compaction, many farmers referred to the practices of keeping wheel loads as low as possible, lowering tire pressure, paying attention to soil passability, tilling the soil only at the right time with respect to soil moisture, using tramline systems (e.g., controlled traffic farming), and reducing the contact surface pressure and the number of passes ($n = 24$). The following erosion prevention measures were also recommended to

Table 6
Institutionalists' assessment of the impact of agronomic management measures on the promotion of soil fertility.

Response Option	High (%)	Inter-mediate (%)	Low (%)	Not specified (%)
Diversified crop rotation with positive humus balance	47	13	2	38
Catch cropping	45	16	2	37
Year-round soil cover	44	18	1	37
Organic fertilisation	41	21	0	38
Cultivation of legumes	38	23	1	38
Cultivation of crops that improve soil structure	33	26	5	36
Leaving crop residues on the field	32	27	2	39
Balanced nutrient supply	29	27	7	37
Regular liming	24	32	7	37
Green fallow	21	22	16	41
No tillage with direct sowing	20	22	17	41
Conservation tillage with mulch sowing	17	33	9	40
Structural elements/ conservation headlands	16	23	22	39
Agroforestry systems	10	24	23	43
Precision farming	8	32	20	40
Mixed cropping	7	33	20	40
Undersowing	7	37	15	41
Soil additives/ biostimulants	2	16	42	40

$n = 215$ agricultural institutionalists.

maintain soil fertility: year-round ground cover and active plant cover, no-till systems, tillage parallel to contour lines, field subdivision, and the establishment of hedgerows and structural elements to minimize potential erosion routes ($n = 10$). The integration of catch crops into crop rotations was also recommended, as they can increase the climate resilience of crop production systems ($n = 14$). However, some participants pointed out that catch crops are only useful if they can become well established and form sufficient biomass (e.g., difficult in dryland areas) without depriving the subsequent main crops of water ($n = 4$). Furthermore, the positive impacts of biodynamic supplements, fermentation preparations (e.g., compost tea), and reductive composting (e.g., microbial carbonization) were mentioned several times ($n = 14$). This was supplemented by the recommended avoidance of synthetic chemical pesticides with potentially negative effects on soil edaphon. Two opinions from the free-text field clearly showed that care should be taken to ensure that a recommendation of the appropriate measures is only made after considering the specific site conditions and all relevant cultivation factors ($n = 4$). In addition, a differentiated consideration at the farm level is required before new measures are introduced ($n = 3$).

Demands for supporting soil fertility promotion in farming practice

In order to reveal concrete demands for supporting the promotion of soil fertility in farming practice, the participants were asked to choose from nine options (Fig. 6). From the survey, simple indicators (41/56 %) and reference values (38/44 %) for assessing soil fertility as well as 'workshops, field days, and field schools' (38/45 %) for training aspects were the most commonly requested by respondents (farmers and agricultural institutionalists, respectively). In addition, around one-third of both groups of respondents demanded more 'on-farm research and funding programs' as well as the provision of sufficient 'information material/publications' as important tools to make knowledge transfer faster and easier for handling the complex task of soil fertility promotion. Farmers did not place increased value on 'videos/podcasts/TV/radio contributions' (14 %), 'state monitoring of soil fertility' (14 %), or 'apps/online tools' (13 %). Agricultural institutionalists showed the same low interest in 'videos/podcasts/TV/radio contributions' (15 %), while a higher demand for 'state monitoring of soil fertility' (27 %) and 'apps/online tools' (24 %) was found (Fig. 6). Fig. 6 shows a comparison of both respondent groups, with agricultural institutionalists (blue bars) showing an overall higher demand for soil fertility promotion than farmers (green bars).

In the additional free-text fields, farmers primarily expressed the

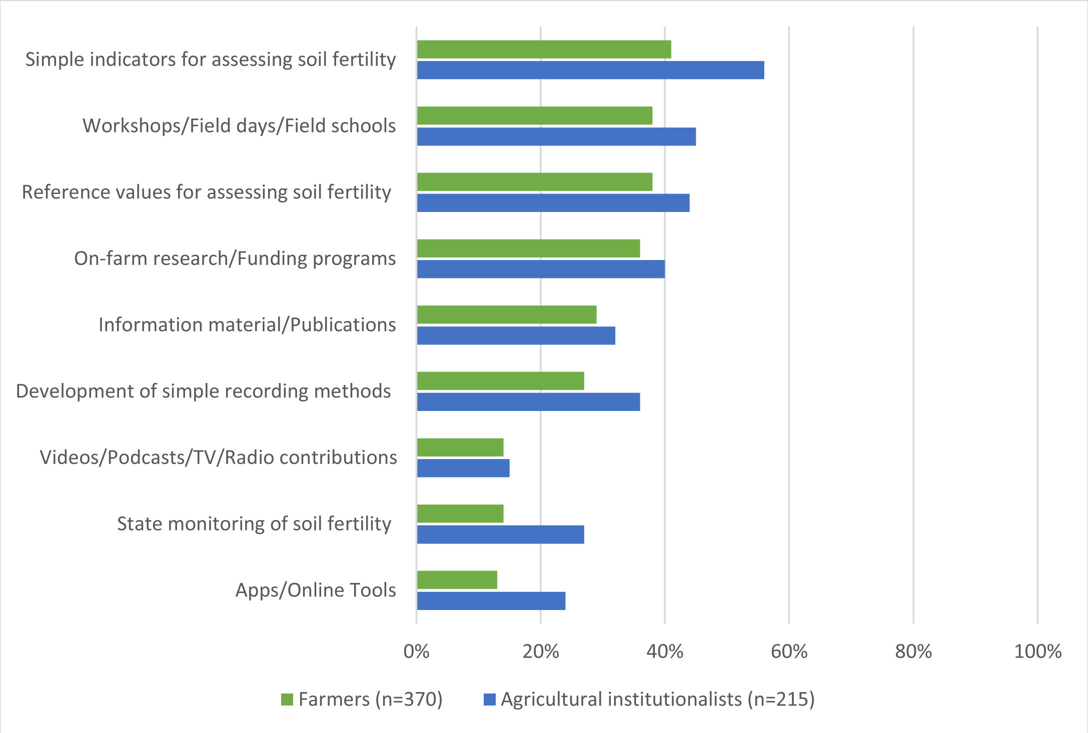

Fig. 6. Demands for supporting soil fertility promotion in farming practice.

desire to increase joint work between research and practice (e.g., on-farm research networks) and thus expand knowledge transfer into practice, including evidence-based and site-specific recommendations ($n = 52$). For this purpose, workshops, field days, and 'peer-to-peer learning groups' were mentioned several times ($n = 25$). Participants also expressed their desire for more lighthouse farms, on-farm research networks, and national soil biology monitoring programs to fully integrate any lessons learned into practice ($n = 9$). Finally, the issue of agricultural education in terms of increasing teachings about soil fertility was highlighted several times ($n = 16$). Two quotes from the survey aptly described the call for greater attention to soil fertility: (1) 'the importance of healthy soil and how it should be treated definitely needs to be taught more in agricultural education! Curriculum/training/courses need to be completely revised to teach soil fertility as one of the most important tasks in crop production' and (2) 'those who do not know what to protect will only protect what they know'.

Discussion

Soil is the one of the most important strategic resources in crop production. Agronomically relevant soil parameters include nutrient and water availability, biological activity, rootability, and air and heat balance; these parameters are responsible for plant health and thus high and stable yields (Ellis and Foth, 1997; Troeh and Thompson, 2005). However, in addition to natural environmental conditions, all human-controlled interventions and actions can have consequences for the condition of agricultural soils and their productivity. Although this study did not present experimental data, the empirical insights into farming practice gained here provide unique information about soil fertility based on the broad and detailed experiences of the farmers and agricultural institutionalists surveyed. Considering that empirical approaches are relatively unconventional in agronomic research, this study should be seen as an extension of possibilities and may stimulate scientific discussion and future experimental research, particularly on-farm research.

The majority of respondents stated that soil fertility was of great importance at present and would become even more relevant in the future. Climate change, which will introduce new dynamics and uncertainties for agricultural production, may be one of the most important reasons for this increase in the importance of soil fertility (Bayu and Li, 2020; Crane et al., 2011; Abid et al., 2016). Depending on region- and specific site-conditions, the predicted shift in the distribution of annual precipitation (from summer to winter) and overall increase in air temperature will aggravate deficits in climatic water balance and drought stress during the main vegetation period, resulting in negative impacts on plant physiology and the soil moisture regime—and thus the nutrient and water supply of plants—as well as on soil life (Markonis et al., 2021; Altieri et al., 2015; Ebrahimi et al., 2016; Shelia et al., 2019). In light of this, adapting agriculture to climate change is essential. Accordingly, increasing the climate resilience and related yield stability of cropping systems through soil fertility improvement was shown to be the most important issue for respondents. This is in line with the top-ranked soil properties that were expected to be improved with greater soil fertility: (1) water storage capacity, (2) soil biological activity, (3) rootability, and (4) water infiltration rate. As water is often a limiting factor under climate change, the soil's capability to take up and store water is crucial; in addition, having plants with a deep root system is desired as they can reach water in deeper soil layers. This is in line with the results of the bivariate analyses, which showed a significant negative correlation between the desired soil property 'water storage capacity' and the environmental co-variable 'annual average sum of precipitation' at the farm sites (range 242–1300 mm, Ø 673 mm). This indicates that farmers working on drier sites are more interested in the soil's water storage capacity than farmers on sites with higher amounts of precipitation. Here, the support of soil microorganisms (e.g., mycorrhiza) comes into play, as they can act as 'water and nutrient miners' for plants and increase their drought tolerance, which can also promote the climate resilience and yield stability of cropping systems (Williams et al., 2018; Zhang et al., 2019; Vlček and Pohanka, 2020; Hoang et al., 2022; Renwick et al., 2021). In addition to the higher risk of drought stress under climate change, projections also show an increase in the frequency of extreme weather events, such as storms or heavy rainfall events, which greatly amplify the risk of soil erosion and floods and significantly increase production risk for farmers (Ray et al., 2015; Ray et al., 2019; Várallyay, 2010; Wilcox et al., 2017; Smith et al., 2020). This was also reflected in the respondents' answers as a significant negative correlation (bivariate analysis) between the soil property of interest ('aggregate stability') and the environmental co-variable 'annual average sum of precipitation' on the farm sites. The farmers who reported more rainfall had greater interest in the aggregate stability of their soils, i.a., to prevent soil erosion due to heavy rainfall events and sustain soil fertility in the long term (stated in the free-text fields of the survey). Appropriately, the top-rated agronomic measure was 'year-round soil cover', which is well supported within conservation agriculture as it helps to reduce the risk of soil erosion and soil evaporation (unproductive water losses) while supporting soil biology and improving the water infiltration rate (Williams et al., 2018; Michler et al., 2019; Giller et al., 2015).

As a clear outcome of this study, yield stability—or rather reducing the production risk (probability that the yield will fall below a crucial level)—is one of the most important aspects under climate change and is even more important than the absolute yield amount, especially with regard to climate change (as stated by the farmers surveyed). This can be entirely confirmed by the results of a recent empirical study by Macholdt et al. (2017) focusing on wheat in German crop production (Macholdt and Honermeier, 2017). In both studies, the surveyed farmers underlined that they are not interested in achieving the maximum yield—instead, they will tolerate somewhat lower yields in the case of better yield stability or lower production risk.

Appropriate management measures can be used with the aim of improving soil fertility and related soil properties; these measures also support the climate resilience and yield stability of cropping systems. Catch cropping, diversified crop rotations with a positive humus balance, and year-round soil cover were rated by respondents to have the highest positive impact on soil fertility. This finding is also reflected in the results of many recent studies that addressed the functional and agronomic benefits of rotational crop diversity including catch cropping, especially in relation to the development of more sustainable agriculture practices under climate change (Furey and Tilman, 2021; Maitra, 2019; Shah et al., 2021; Triberti et al., 2016; Borase et al., 2020). Catch cropping and diversified crop rotation design were given nearly the same level of importance by the farmers and agricultural institutionalists surveyed. This may also be due to the fact that integrating catch crops is part of a favourable crop rotation design. All crop species differ in their capabilities; thus, crop choice can have a critical effect on soil properties. Similar to diversified crop rotations, catch cropping affects the physical, chemical, and biological properties of soil (Scavo et al., 2022; Kirkegaard et al., 2008). Catch cropping and crop selection exploit the potential of plants to improve the structure and thus the physical properties of soil; in addition, the easily degradable organic matter of catch crop residuals has an important function as a nutrient source (Bodner et al., 2007; Meike and Jürgen, 2018). Crop species with a long taproot, such as alfalfa and rye, allow soil loosening and, at the same time, compaction around the root. This root penetration allows for the formation of macropores, which are responsible for better water infiltration. At the same time, aggregates are formed in the soil due to root penetration. The stability of these aggregates is achieved primarily by the root exudates of the plants but also by decomposing plant residues and polysaccharides excreted by bacteria (Angers and Caron, 1998). In addition, the improved macroporosity and the opening of the soil by the roots provide greater water infiltration and rootability, which was also highly supported by the respondents. The influence of cultivating crops that improve soil structure was considered of high importance by more than one third of the farmers and institutionalists surveyed, and as many as 47 % of the farmers stated that they already implemented this measure on their farms. In particular, radish species (e.g., oil radish) are known to improve soil cohesion and break up soil compaction (Büchi et al., 2018). Having a good aggregate structure and macroporosity are prerequisites for rootability and a high air and water balance (Bodner et al., 2007). Diverse crop rotations, including catch cropping, can also help to increase soil organic matter and soil organic carbon contents, which are of great importance for stabilizing the soil structure and thereby improving water storage capacity and rootability (Shah et al., 2021; Triberti et al., 2016; Seitz et al., 2022; Karlen et al., 2013; Van Eerd et al., 2014). These were the top-ranked soil properties for farmers in this study and are important for the climate resilience and yield stability of cropping systems; they represent what the farmers desire to improve, as they use diverse rotations and catch cropping primarily "to maintain humus formation and [improve] water retention in the soil" (quote from the survey). Further comments from the respondents focused on positive soil organic matter balances (e.g., achieved by leaving crop residues on the field) and organic-matter-amplifying crops, such as legumes, in the context of diversified crop rotations. All these agronomic measures result in dynamic soil structuring, higher organic matter content, higher soil moisture, and the release of root exudates, which lead to an increase in soil microbial activity (Niewiadomska et al., 2020; Gentsch et al., 2020). The organic matter serves as food for both micro- and macrofauna in the soil, increasing microbial activity. As a result, higher soil enzyme activity has been demonstrated, which results in greater levels of plant-available nutrients (Borase et al., 2020). This stimulation of soil biology was found to be highly desired by respondents in this study and reflects the mobilization of plant-available nutrients for nutrient carry over, particularly using catch crop mixtures and crop rotational diversity (Borase et al., 2020; Piotrowska-Długosz and Wilczewski, 2020; Heuermann et al., 2022). This leads to less dependence on external inputs, such as fertiliser, and higher sustainability in terms of the circular principle. The increase in soil enzyme activity can also have a disease-inhibiting effect, which increases plant health and the resilience of cropping systems to biotic stresses (Stomph et al., 2020; Thakur et al., 2021). Lastly, the use of diverse crop rotations including cover cropping with deep-rooting mycorrhizal plants can promote arbuscular mycorrhizal fungi, which provide root system extension and aggregation to support the water and nutrient supply of plants (Plenchette et al., 2005; Sosa-Hernandez et al., 2019). In addition, different plants have different nutrient requirements. Thus, if they do not compete for the same ecological niche and the soil is not depleted, yield increases can result (Giller et al., 2015; Maitra, 2019). Furthermore, the bioavailability of nutrients such as phosphorus, iron, zinc, and manganese can be increased because different crop species have different abilities to mobilize the soluble inorganic forms of nutrients (Piotrowska-Długosz and Wilczewski, 2020; Stomph et al., 2020). Overall, promoting soil fertility through the use of diverse crop rotations, including catch cropping, can help to increase the climate resilience and yield stability of cropping systems, especially in the face of ongoing climate change, as highlighted by the respondents.

However, according to the farmers' comments (in the free-text fields of this survey), it is becoming increasingly difficult to expand and diversify crop rotations. The reasons for this are unfavourable economic conditions, a lack of recommendations and financial incentives, increasing lease prices, and higher costs. This shows that there is a high potential for future agriculture in this area, but it cannot be exploited today; a similar situation is observed for catch cropping. The area under catch crops is currently relatively low; however, it has increased from just under 1.2 million hectares in 2010 to almost 2 million hectares in 2020 (in relation to 11.6 million hectares of total German crop production area), confirming the fact that catch crop cultivation is continuing to gain importance in Germany (Destatis 2022). This is also evident from the responses to our survey, as farmers and agricultural institutionalists ranked the positive impact of catch cropping as the most important for the promotion of soil fertility. However, only 57 % of the farmers surveyed indicated that they already used catch crops. According to Seitz et al., only one-third of winter fallow is used for cover crops, which means that cultivation and thus the return of organic matter could be tripled (Layek et al., 2018). Reasons for not cultivating catch crops were stated by farmers in free-text comments. For example, the lack of a legal framework and non-existent financial support were mentioned as being part of the problem. In addition, some farmers would like to see more official catch cropping and undersowing (e.g., rank legumes and corn as a support crop) field trials, the reliable results of which should be communicated more to encourage the spread of these systems. Furthermore, new perspectives should be emphasized, such as the grazing of catch crops, since in this way "no track damage by harvesting vehicles [occurs] and high-quality organic fertiliser for soil organisms […] [is] distributed reasonably evenly even without ruts." (quote from the survey). A broad uncertainty stated by farmers in this study was the water consumption of catch crops (transpiration losses > evaporation reduction) resulting in a lack of water for the following main crop (Bodner et al., 2007). This is in line with the results of the bivariate analyses, which showed a significant correlation between more farmers using catch crops on sites with a higher annual precipitation, and vice versa (less catch cropping on drier sites with < 500 mm annual precipitation).

In this study, the respondents highlighted that sufficient organic matter return together with nutrient balance are important factors for sustaining soil fertility and consequently yield stability in the long term, which is in line with long-term analyses on cropping system perspectives (Macholdt et al., 2021; J. Macholdt et al., 2020; J. Macholdt et al., 2020; Faye et al., 2023; Reckling et al., 2016; Reckling et al., 2019). These studies recommended cultivating legumes and leaving crop residues on the field (green manure, return of organic matter, positive humus balance), in addition to adequate organic/mineral fertilisation. A quote from the survey echoes this: “having sufficient and thus proper fertilisation of the crop [is important] to prevent mineralization of the usually already scarce humus content by plant growth”. The use of organic fertilisers can help to offset the reduction in synthetic fertilisers (Ye et al., 2020), increase soil fertility while maintaining yield expectations, and allow management in a closed-loop system (Herencia et al., 2007). The addition of organic fertiliser, particularly manure, can increase soil fertility by enriching organic matter. Accordingly, this significant increase in organic matter may also lead to increased nutrient availability. Higher levels of major nutrients, such as nitrogen, phosphorus, and potassium, and essential micronutrients can be assumed (Herencia et al., 2007). The improved physical and chemical soil properties and enhanced soil microbial community resulting from organic fertiliser application can further support the pH, air, and water balance of the soil (Ye et al., 2020; Han et al., 2021; Kumar et al., 2019). Despite all the benefits of organic fertilisation, the potential toxicity from heavy metals and naturally contained pathogens should also be addressed (Kumar et al., 2019). Furthermore, nutrient availability strongly depends on soil pH; thus, liming is also a relevant measure for soil fertility and crucial for a range of physical, chemical, and biological soil parameters, such as optimal nutrient supply and organic matter build-up (Haynes and Naidu, 1998; Olego et al., 2021; Bossolani et al., 2021). Accordingly, more than half of the farmers indicated that they used liming as a common measure, suggesting that it is considered to have as much value as fertilisation. The farmers surveyed reported using organic fertilisation and liming more often for agricultural soils of lower quality (significant negative correlation; bivariate analyses); on soils of higher quality, they tended to use these measures somewhat less often (range of soil quality index as stated by farmers: 28 % of soils with 18–39; 37 % of soils with 31–49; 35 % of soils with 60–90). Thus, the willingness and motivation of farmers to invest in soil fertility also depend on their soil`s quality. If the soil has a higher demand, improvements are often more noticeable and observable, for example, a payoff in yield or improvements in certain soil properties, such as trafficability. If the soil is of higher quality, the amortization of investments is not as easy to recognize, and a payoff, e.g., in yield, often requires more time and efforts.

Tillage also has a major impact on soil fertility. In this study, the respondents mainly recommended and preferred reduced tillage and conservation tillage for promoting soil fertility instead of conventional tillage practices such as ploughing. Conservation tillage has been shown to improve the physical, chemical, and biological properties of soil (Michler et al., 2019; Giller et al., 2015; Busari et al., 2015; Peigné et al., 2018; Palm et al., 2014), including water infiltration/storage capacity and biodiversity, which were rated of high interest for climate-resilient and yield-stable cropping systems by the farmers surveyed. For this reason, conservation agriculture measures are becoming increasingly prominent. This is also reflected in the fact that 49 % of the farmers who participated in the survey already implement conservation tillage with mulch sowing on their farms. The three associated basic principles, which play important roles in the conservation agriculture system, are permanent ground cover, crop rotation diversification, and minimal soil disturbance (Busari et al., 2015). Permanent soil cover with crop residues or mulch primarily protects soil aggregates from mechanical destruction by raindrops (more water-stable aggregates in the upper soil layer), reducing wind and water erosion as well as evaporation (unproductive water losses from the soil) (Giller et al., 2015; Busari et al., 2015; Peigné et al., 2018; Palm et al., 2014). The absence or minimization of soil disturbance increases the activity and diversity of soil organisms. Bacteria, fungi, and especially earthworms have significant impacts on the pore system and thus on the air and water supply to plant roots (Peigné et al., 2018; Palm et al., 2014; Techen and Helming, 2017). All these aspects can help to increase the climate resilience of agricultural soils and consequently yield-stable crop production as extreme weather events (heavy rainfall events, storms, drought, and heat stress) are predicted to become more frequent (Várallyay, 2010). Despite these benefits, conservation tillage can also have some negative effects, including a higher weed pressure, soil organic carbon accumulation in the uppermost soil layer and a decrease in the deeper layers, in some cases a higher bulk density, and yield decreases in the first years of system conversion, reaching a dynamic equilibrium only after more than 10 years (Giller et al., 2015; Busari et al., 2015; Peigné et al., 2018; Palm et al., 2014). However, conservation tillage has been scientifically proven to be advantageous in dry climates, showing its potential for use in the future in regions affected by climate change (Michler et al., 2019). Nevertheless, it is important that long-term trials are carried out and that no blanket recommendations for measures are made, as it is essential to carry out differentiated consideration at the site and farm level beforehand. In addition, farmers are seeking greater recognition and promotion for soil-conserving tillage techniques and would like more financial and practical support in the form of recommendations and advice (as stated in comments of this survey). Only this will enable farmers to give more consideration to the promotion and maintenance of soil fertility through conservation tillage.

In contrast to soil tillage, agroforestry was one of the agronomic measures that the respondents clearly rated as having a lower impact on soil fertility, where only 2 % of farmers had integrated agroforestry systems into their operations, and only 7 % of these had seen a positive impact on the promotion of soil fertility. Agroforestry is considered to have a positive impact on soil-related ecological services and soil fertility as it results in improved physical, chemical, and biological soil properties (e.g., buffers moisture, enhances biodiversity, and reduces erosion) while also providing food, wood, and fodder (Fahad et al., 2022; Jose, 2009; Wilson and Lovell, 2016). Thus, agroforestry is a way to decrease risk for farmers through the growth and use of multiple products to generate short-term as well as long-term income streams. However, the high investment costs, delayed gains, and large amounts of time and knowledge required for management discourage many farmers from adopting agroforestry practices (Wilson and Lovell, 2016). In addition to a lack of farmer experience and a lack of demonstrations or on-farm trials, conversion to agroforestry involves permanent land alterations and has legal and economic implications. An equally important issue for farmers is the regulatory space for agroforestry systems. However, agroforestry systems will be eligible for funding through the German agricultural policy from 2023 forward, which could significantly change farmers' attitudes and interest towards their on-farm implementation.

The impact of biostimulants or soil amendments, such as biochar, was considered to be extremely small, resulting in low levels of recommendation and implementation for these practices by farmers as well as institutionalists in this study. This result clearly contradicts the goals of the EU Commission and the German government to achieve drastic reductions in the use of chemical-synthetic fertilisers and pesticides (especially glyphosate) through, i.a., biologicals (biocontrol), soil additives, and biostimulants. The aim is to use these kinds of bio-based products to increase soil quality, crop productivity, tolerance to biotic/abiotic stresses, and the effective use of water and nutrient resources (Van Oosten et al., 2017; Abhilash et al., 2016; Franzoni et al., 2022). Despite the growing economic sector and the fact that biostimulants are being used in agricultural practice more frequently, it is clear from this survey that neither German farmers nor agricultural institutionalists give high value to these agronomic management measures thus far. Reasons for this could be a lack of valid information and personal on-farm experiences, as the comments of respondents indicated a demand for more scientific research on biostimulants/soil amendments as well as reliable recommendations for their on-farm application and the fast transfer of knowledge from research to agronomic practice. Many of the complex interactions between biostimulants/soil amendments and the agronomic system ('soil x climate x crop') have still not been clarified. These gaps in knowledge, poor shelf life (e.g., microbial-based biostimulants), and susceptibility to photo-, thermo-, hydro-, and biolability could be further reasons for the low appreciation and application of these substances thus far (Van Oosten et al., 2017; Abhilash et al., 2016; Franzoni et al., 2022; Rouphael et al., 2015). To characterize these biological agents for farmers and to allow them to integrate these tools into practice, collaboration between scientists, farmers, and industry is required.

Conclusions

In farming practice there is a high awareness of the importance of soil fertility for climate-resilient and yield-stable cropping systems, especially when considering the increasing production risk due to ongoing climate change. Based on the survey results, our five initial research questions can be answered as follows:

(1) Soil fertility for agricultural crop production was rated as being of high to very high importance now and even more so in the future.
(2) The main motives for agronomic investments in greater soil fertility were improving the climate resilience and yield stability of cropping systems.
(3) The main soil properties of interest that were expected to be improved with greater soil fertility were water storage capacity, rootability, biological activity, and water infiltration rate.
(4) The three highest ranked agronomic management practices with the greatest estimated positive impact on soil fertility were catch cropping, diversified crop rotations with a positive humus balance, and year-round soil cover.
(5) For future improvement, in terms of supporting the promotion of soil fertility in farming practice, simple indicators and reference values for assessing soil fertility as well as 'workshops, field days and field schools' for training aspects are required.

In terms of methods for the assessment of soil fertility, soil structure analyses, biological indicators, yield/biomass production, soil nutrient analyses, and field methods were found to be the most important, whereas sensor systems and apps or digital tools were of minor importance. Overall, there were few differences between the perceptions of farmers and agricultural institutionalists. Both groups pointed out the need for improved communication between politics, science, and practice so agriculture can respond more quickly to changing environmental conditions in the future. However, soil fertility is a complex issue that must be addressed using an agronomic systems approach considering the interaction effects of environmental (soil × climate) and management factors. This can best be assessed using long-term field experiments at multiple sites combined with agroecosystem modelling approaches, such as process-based soil models considering abiotic and biotic factors. Although environmental impacts are uncontrollable, appropriate management measures can be used with the aim of promoting soil fertility over the medium to long term. Nevertheless, the concrete establishment of these measures in farming practice is a difficult task due to, i.a., various site conditions, farm structures, and financial constraints. Therefore, further research, knowledge transfer, and specific funding instruments (political support and incentives) are needed. It is necessary to expand technical advice to farmers by establishing on-farm research networks and demonstration trials and providing opportunities for internal exchange between farmers accordingly. Establishing more on-farm experimental networks with appropriate and site-adapted management strategies could help better identify their potential for future use. Decision-support tools could also make an important contribution. In addition, more research should be carried out on smart technologies and digital tools that can be used by farmers to measure soil fertility based on reference values. This could make it easier for farmers to make the right decisions with respect to the aim of promoting soil fertility.

Author contributions

J.M. and M.W. conceived and designed the study; J.M. and M.W. performed the study; J.M. and M.K.W. analysed the data; M.K.W., J.M., and M.W. discussed the results; and J.M. and M.K.W. wrote the original manuscript draft; J.M., M.W., and M.K.W. contributed to the final manuscript version (review and editing). All authors have read and agreed to the published version of the manuscript.

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Data availability statement

Not applicable.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.soisec.2023.100119.

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