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Assessing criteria for adopting sustainable subsoil management practices: an application of multinomial logit model

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Abstract. Subsoil management practices are crucial for improving agricultural sustainability by enhancing resource use efficiency and soil health. This study focuses on two key methods: (a) the cultivation of deep-rooted crops like alfalfa, which enhances the accessibility of subsoil resources for subsequent crops, and (b) strip-wise loosening of the subsoil combined with compost addition (UEK)[1], which is being developed and tested within the framework of the Soil³ project. A comprehensive model is developed to assess factors influencing the adoption of these practices using a Multinomial Logit model and survey data from stakeholders in Anhalt-Bitterfeld, Rhein-Sieg-Kreis, and Teltow-Fläming in Germany. Stakeholder responses are categorized into four groups: stakeholder characteristics, adoption factors, alfalfa cultivation and UEK method features. Statistical and econometric analyses reveal three critical factors: insufficient soil water storage capacity, business orientation, and ownership relationships. Through the identification of marginal effects, it appears that 'business orientation' is more influential in the adoption of the alfalfa cultivation method compared to the UEK method, whereas 'ownership relationships' have a greater marginal effect in the UEK method compared to alfalfa cultivation. Findings suggest that policy interventions should address method-specific barriers, promoting business incentives for alfalfa cultivation and resolving land ownership issues for the UEK method. Tailored, region-specific approaches are essential for promoting subsoil management practices, contributing to resilient and resource-efficient farming systems.

Key words: deep-rooted crop method, econometric analysis, Germany, marginal effects, strip-wise loosening method.

INTRODUCTION

With a growing global population and climate change impacts placing greater pressure on food production, the need for yield stability (Guedioura et al., 2023) and effective soil management practices have become increasingly important (Ahrends et al., 2021; Botta et al., 2024). The subsoil, often neglected by policy makers and other social

[1] UEK is used here as an abbreviation for strip-wise loosening of the subsoil combined with compost addition. However, in general, this method is known in Germany as the Soil³ method or technology.

stakeholders, holds substantial reserves of water and nutrients, which could play a crucial role in enhancing crop yields, particularly during dry seasons (Kautz et al., 2013, Schneider at al., 2017, Frelih-Larsen et al., 2018).

Notably, subsoil amelioration has a long history (Schneider et al., 2017). Techniques such as deep ploughing and mechanical subsoiling have been employed for many years. Deep ploughing involves turning the soil at depths of 50 cm or more, which inverts the soil profile by bringing subsoil to the surface and burying the topsoil (Gailis et al., 2017). This method aims to break up compacted layers and improve crop growing conditions but requires considerable energy and heavy machinery (Alcántara et al., 2016). Recent advancements have focused on optimizing the operational efficiency of tillage machinery to address these high energy requirements. For instance, (Askari et al., 2021) applied the Response Surface Methodology (RSM) to model and predict key tractive performance parameters of agricultural tractors during semi-deep tillage. By systematically varying factors such as tractor speed, tillage depth, and loading, the study developed accurate predictive models of draft force and tractive efficiency. This approach enables identification of optimal operating conditions that minimize wheel slip and fuel consumption while maintaining effective soil loosening. Such modeling contributes to improving the energy efficiency and sustainability of mechanical subsoil management practices. Mechanical subsoil loosening, also known as subsoiling or deep ripping, focuses on alleviating subsoil compaction without turning the soil (Frelih-Larsen et al., 2018). By allowing deeper and wider root growth, this technique enhances water infiltration and nutrient uptake, ultimately aiming to boost crop yields (Cai et al., 2014). Moreover, differences in tillage systems have been shown to substantially affect soil moisture distribution and crop productivity. Conservation-oriented systems, such as subsoiling with ridgers or chisel-rotary combinations, generally preserve more soil moisture in both the topsoil and deeper profiles compared to conventional plough tillage, especially during dry periods. These practices enhance root development, reduce runoff losses, and improve overall water availability, resulting in higher and more stable yields (Abo-habaga et al., 2022).

Since both techniques mentioned above have certain limitations, such as being too labor-intensive and highly disruptive methods, and even reducing soil fertility in the long term (Frelih-Larsen et al., 2018), a new approach has been developed and tested as part of the Soil³ project[2]. The suggested new method involves subsoil loosening combined with the incorporation of organic matter into the loosened subsoil. This approach is more effective when applied in alternating furrows (e.g., spaced one meter apart) and when the topsoil and subsoil layers remain undisturbed and are not mixed or turned (Schmittmann et al., 2021; Bauke et al., 2024).

In addition to mechanical methods, cultivating deep-rooting plants, such as alfalfa, provides a biological approach to subsoil amelioration. This method uses deep-rooting crops like alfalfa to create vertical root channels (bio pores) in the subsoil, improving access to water and nutrients for subsequent crops (Lynch & Wojciechowski, 2015) and was also further tested in the context of the Soil³ project.

As subsoil amelioration needs to be region-specific, it is important to identify regions within Germany that can benefit most from both subsoil management measures

[2] For more details about the Soil³ project, see 'www.soil3.de'

tested in the frame of the Soil³ project. As part of the project, the identification of suitable regions was based on the consideration of a) favorable geogenic, pedogenic and climatic factors and b) socio-economic and political factors. With regard to the first set of factors, (Schneider, 2020) found that mechanical amelioration is most suitable for relatively dry regions with sandy soils in Northeastern Germany. In contrast, biological amelioration can have the strongest positive effects in Central and Southern Germany (Fig. 1).

From a socio-economic and political point of view, a number of region-specific factors may facilitate the uptake of subsoil management measures such as business orientation, regional compost availability, number of mixed farms in a certain region, and others (Hinzmann et al., 2021).

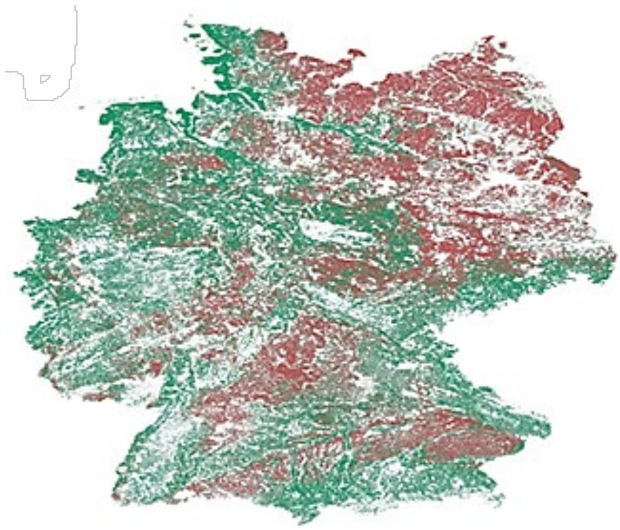

Figure 1. Map of Germany showing the need for subsoil amelioration. Green areas show that there is no need for subsoil amelioration. Red areas show that there is a need of subsoil amelioration (Schneider et al., 2024).

While subsoil management practices have been widely studied, existing research often lacks a comprehensive comparison between biological and mechanical amelioration methods in terms of their practical implementation, stakeholder preferences, and perceived barriers. Most studies focus on subsoil, frequently in connection with issues of subsoil compaction (e.g., Schjønning et al., 2015), carbon storage and sequestration (e.g. Rumpel et al., 2012), the role of subsoil in plant nutrition (Gaiser et al., 2012, Kautz et al., 2013; Lynch & Wojciechowski, 2015; Schneider & Don, 2019a, 2019b) but pay limited attention to the socio-economic factors influencing adoption of subsoil management techniques. While recent research has begun to examine stakeholders' perceptions of subsoil amelioration, identifying relevant factors like biophysical conditions, economic feasibility, and barriers to implementation (Frelih-Larsen et al., 2018, Hinzmann et al., 2021; Schneider et al., 2024), it is important to employ targeted qualitative and quantitative statistical methods to gain a deeper understanding of how these perceptions align with diverse agricultural and socio-economic contexts. To address this, our study utilizes the Multinomial Logit Model to answer two main questions: (1) What are the key factors influencing the adoption of biological versus mechanical subsoil management practices, and how do these factors vary across different agricultural contexts? (2) How do stakeholders perceive and prefer these methods, and what barriers hinder their implementation?

In line with the context of stakeholders' decision-making processes, we use data collected from a survey conducted between March and June 2023. A Multinomial Logit model is applied to analyse how stakeholders differ in their perceptions and preferences regarding subsoil management methods.

MATERIALS AND METHODS

Analytical framework of the study

The analytical framework employed in this study serves as the foundation for analysing and interpreting the research data, allowing for a comprehensive exploration of the key variables and their interrelationships. By delineating the structure and methodology of our analysis, this framework establishes a clear roadmap for understanding the intricate aspects of the research topic and drawing meaningful conclusions (Fig. 2).

Data source and study site

This study examines data from an online survey conducted between March and June 2023, focusing on German stakeholders' perspectives regarding subsoil management and deep-rooting practices, particularly the use of the Soil³ technology and alfalfa cultivation. The Soil³ technique, developed by (Schmittmann et al., 2021) involves the strategic opening of subsoil layers and the placement of organic material to enhance nutrient capacity. As part of the implementation of this technology, it is crucial to understand the perspectives of stakeholders, especially stakeholders, who may be directly impacted by its adoption. Additionally, the long-standing practice of deep-rooting crops, particularly alfalfa, was analysed to assess its potential for supporting sustainable soil management. In particular, the survey aimed to gather insights on factors influencing the adoption of both subsoil amelioration practices, such as financial resources of the farm, land ownership structure, business orientation, availability and quality of compost in the region, and soil properties. The surveys also explored the willingness of farmers and stakeholders to adopt these techniques, as well as the interest in integrating policy incentives, such as humus-building premiums, into agricultural practices.

While other subsoil amelioration techniques exist, the focus of the Soil3 project was on improving subsoil properties in central field studies through the combined growth of deep-rooting pre-crops (alfalfa cultivation) and technical subsoil heterogenization via rotary cutters and economic organic matter injection (UEK). Both techniques were considered to be highly suitable solutions that provide attractive options for plants to invest into roots, thereby elevating nutrient and water uptake from the subsoil.

The survey was administered using the open-source application LimeSurvey Cloud Version 6.6.5. Major agricultural organizations and local stakeholder associations across Germany were contacted by email and asked to distribute the survey link to their members.

The survey distribution targeted the federal states of North Rhine-Westphalia, Brandenburg, and Saxony-Anhalt. The final respondent distribution in regions was as follows: 6 from Rhein-Sieg-Kreis (14.63%), 14 from Teltow-Fläming (34.15%), 8 from Anhalt-Bitterfeld (19.51%), and 13 from other regions (31.71%). These regions were selected due to their proximity to field experiments and demonstration farming sites for the Soil³ technology. It was expected that stakeholders in these areas, having practical experience with the Soil³ technique, would offer valuable insights into its effectiveness.

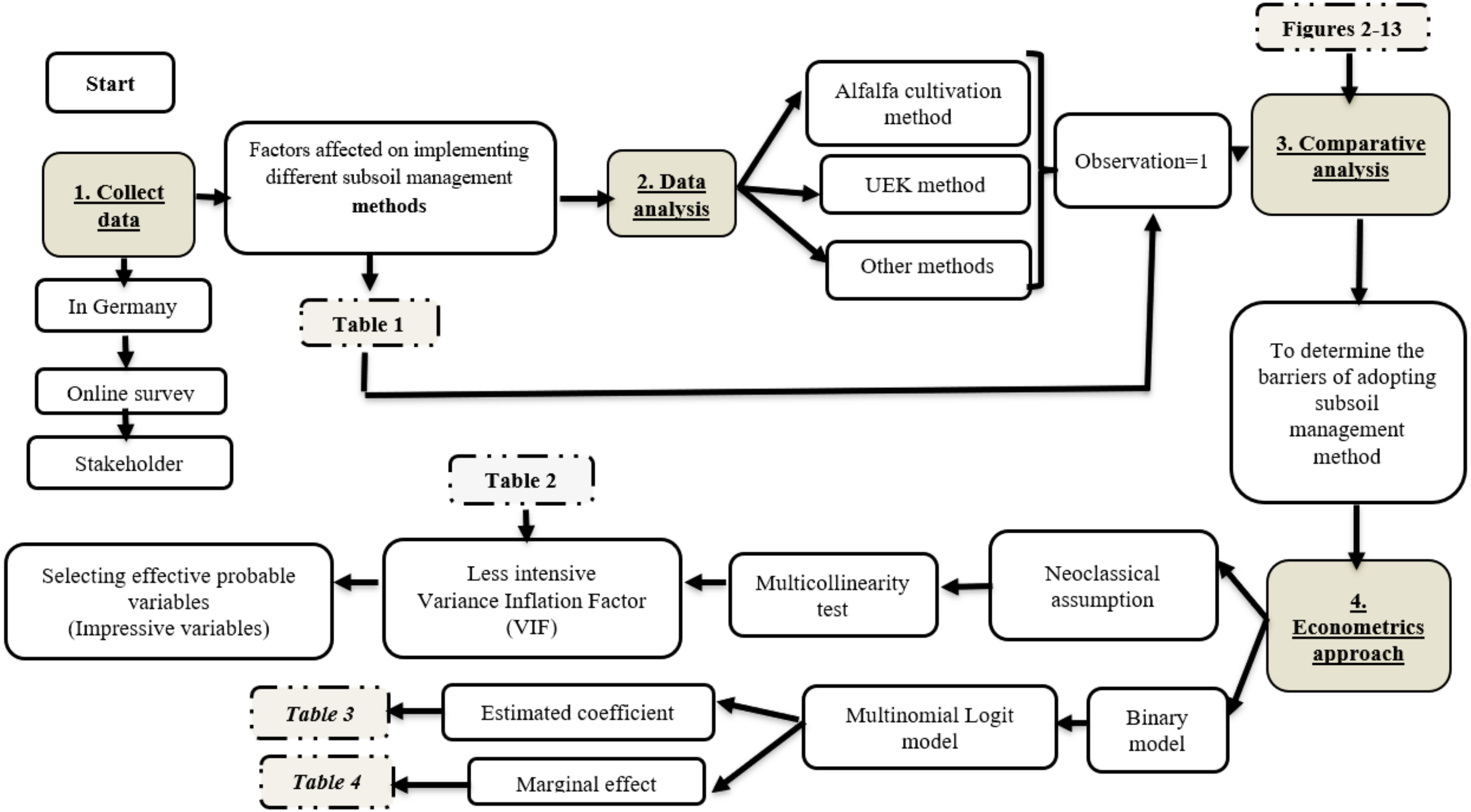

Figure 2. Analytical framework of the study.

The survey was organized into four main groups of questions. The first group focused on stakeholder characteristics, gathering demographic and professional information about the respondents. The second group aimed to identify and analyze the key factors that differentiate the implementation of subsoil management practices. The third group examined the features of the alfalfa cultivation method, investigating its implementation and impact. The fourth group explored the details of the UEK method, including its application and outcomes (see Table 1 for details).

Since the focus shifts to assessing and identifying factors that either facilitate or act as barriers to the adoption and implementation of subsoil management methods, attention was given to a second group of factors related to the specific influences on the implementation of these methods, namely, the Alfalfa cultivation method and the UEK method. Forty-one stakeholders were initially asked separate questions regarding Alfalfa cultivation and the UEK method. Responses were collected independently for each method. These responses were then pooled (82 answers), enabling the definition of independent variables for model estimations.

To assess the most impactful factors influencing the implementation of different subsoil management techniques, an econometric model is required. Given that the data collected from stakeholders is quantitative and discrete, a suitable approach for estimation is the binary model, such as the Logit model. However, since there are multiple implementation scenarios-specifically the Alfalfa and UEK methods - multinomial logit model is more appropriate.

The initial step in modelling involves defining the dependent and independent variables. The dependent variable in this analysis is categorized into two methods: Alfalfa cultivation and the UEK method. Five key elements define this variable: low yield levels, insufficient soil water storage capacity, existing soil compaction, financial resources of the farm, and business orientation (e.g., arable farming, horticulture, fodder farming, livestock farming, mixed business), along with farming form (organic vs. conventional) and ownership relationships (e.g., lease agreements, land ownership). Each element is rated on a five-point scale from ‘not relevant’ to ‘very relevant,’ with values ranging from 1 to 4 and 0 for ‘no opinion.’ The summation of these values for each respondent creates a new scale ranging from 0 (all variables rated as ‘not relevant’) to 35 (all variables rated as ‘very relevant’), reflecting their likelihood of adopting different subsoil management techniques. To convert these continuous values into discrete groups, thresholds are established based on average scores: 23 for the Alfalfa method and 24 for the UEK method. Respondents scoring above these thresholds are categorized into the respective groups, while those scoring below are placed in a third group. It should be noted that other groups are not related to the subsoil management methods not considered in this study. These groups are associated with stakeholders who provided lower scale values (primarily selecting 'not relevant') for most of the factors in both the Alfalfa cultivation and UEK methods. As a result, their responses fall below the defined threshold based on the average scale values. This indicates that these stakeholders did not perceive most factors as effective or influential enough to distinguish between the implementation of the Alfalfa cultivation method and the UEK method.

Table 1. Stakeholder survey: categorization of inquired variables

Group	Variables	Variable name
First Group: Stakeholder characteristics	Which group of actors would you place yourself in? (Stakeholder, Chambers of agriculture, Local politics, Environmental association, Other)	Actor_Group
	How do you manage your business? (Conventional, Organic, Tillage-plough, Conventional/Tillage-plough, Organic/Tillage-plough, Conventional/organic/tillage, No answer)	Business_Type
	Which region do you work in? (Teltow-Fläming, Rhein-Sieg-Kreis, Anhalt-Bitterfeld, Others)	Region_Work
	Which groups would you assign yourself to? (Group1, Group2, Group3)[3]	Assigned_Groups
	How can politics facilitate the practical application of knowledge in subsoil management? (Financing information campaigns for stakeholders and agricultural advisors (Info_Campaigns_Stakeholders), Financing information campaigns to educate the general public (Info_Campaigns_Public), Promoting the exchange of experiences between stakeholders/agricultural advisors (Experience_Exchange_Stakeholders), Promotion of consulting services (Consulting_Services_Promotion), Promoting the exchange of knowledge among stakeholders (e.g. field schools, field days) (Knowledge_Exchange_Stakeholders), Establishment of region-specific test areas under real conditions, Additional (Regional_Test_Areas), targeted and long-term research funding (Research_Funding_Targeted), Other)	Politics_Knowledge_Application
	Do humus-building bonuses provide incentives for adopting mechanical or biological subsoil management practices? (Yes, No)	Humus_Bonus_Incentive
	How would you evaluate stakeholder s' interest in implementing humus-building bonuses in agriculture within your region? (Very low, Low, Neutral, High, very high, No opinion)	Stakeholder_Interest_Humus_Bonus

[3] Group 1: The subsoil should be improved to reduce yield fluctuations. I support UEK, especially for low-yield or degraded soils, and have few concerns about its practical application. I also believe biological methods like growing alfalfa are effective for subsoil enhancement.Group 2: To reduce yield fluctuations, the subsoil should be utilized and improved. I am convinced of new measures like UEK only if backed by reliable research. Generally, stakeholder s will adopt measures only if they offer a favorable cost-benefit ratio, including organic practices such as growing alfalfa. Group 3: Subsoil should be incorporated into agricultural management under certain conditions. I favor biological methods, such as alfalfa cultivation, over mechanical approaches like UEK. I believe that organic measures offer long-term benefits and can achieve similar results without compromising soil health.

Table 1 (continued)

Group	Variables	Variable name
	How would you evaluate the interest of local politicians in introducing humus-building bonuses for agriculture in your region? (Very low, Low, Neutral, High, very high, No opinion)	Politician_Interest_Humus_Bonus
	How would you assess civil society's interest in the introduction of humus-building bonuses for agriculture in your region? (Very low, Low, Neutral, High, very high, No opinion)	Civil_Society_Interest_Humus_Bonus
Second Group: What factors influence the implementation of subsoil management; Alfalfa cultivation method & UEK method (Not relevant, hardly relevant, neutral, relevant, very relevant, no opinion)	Low yield level of the area	Low_Yield_Level
	Insufficient water storage capacity of the soil	Water_Storage_Capacity
	Existing soil compaction in the subsoil	Soil_Compaction
	Financial resources of the company	Financial_Resources
	Orientation of the business (e.g., Arable farming, horticulture, fodder farming, livestock farming, mixed business)	Business_Orientation
	Form of farming (organic, conventional)	Farming_Form
	Ownership relationships (term of lease agreements, land ownership)	Ownership_Relationships
Third Group: The features of the alfalfa cultivation method	Readiness to grow Alfalfa (Very low, Low, Neutral, High, very high, No opinion)	Alfalfa_Readiness
	How should politics promote the cultivation of alfalfa? (Increased support for the cultivation of alfalfa, e.g. B. via the Common Agricultural Policy (CAP) (Alfalfa_CAP_Support), Integration of alfalfa cultivation into contractual nature conservation (Alfalfa_Nature_Conservation), Promote the development of local marketing initiatives for alfalfa-based feed (Alfalfa_Local_Marketing), Promote feeding strategies (particularly soy replacement) for ruminants, pigs, poultry and horses based on alfalfa (Alfalfa_Feeding_Strategy), Promote fertilizer production based on alfalfa (Alfalfa_Fertilizer_Production), Funding of experimental facilities for protein production from alfalfa(Alfalfa_Protein_Facilities), Promotion of biogas substrate from alfalfa through premiums) (Alfalfa_Biogas_Premium)	Politics_Alfalfa_Support

Table 1 (continued)

Group	Variables	Variable name
Fourth group: The features of the UEK cultivation method How do you assess the availability and quality of compost for the implementation of UEK in your district? (Very low, Low, Neutral, High, very high, No opinion)	Available quantity-farm own compost	Farm_Own_Compost_Quantity
	Available quantity-purchase from compost plants	Compost_Plant_Quantity
	Compost quality based on the pollutants contained -farm own compost	Farm_Own_Compost_Quality
	Compost quality based on the pollutants contained purchase from compost plants	Compost_Plant_Quality
	Stakeholder s' openness in implementing technical innovations such as UEK	Stakeholder_Openness_UEK

This approach results in three distinct groups: 34 stakeholder s implementing the Alfalfa method (41.46%), 37 stakeholder s using the UEK method (45.12%), and 11 stakeholder s employing other methods (13.42%). Based on this definition of the dependent variables and the main categories for the subsoil management methods, the following section reports the percentage contributions of each variable, while maintaining them within their respective subsoil management groups.

Data analysis

In this study, the independent variables are binary (coded as 1 and 0), meaning the calculation of mean and standard deviation does not provide meaningful insights for such data. Additionally, the dependent variable is discrete, with more than two possible values (1, 2, and 3). Given these characteristics, we opted for a Multinomial Logit Model, which is specifically designed to handle discrete dependent variables with more than two categories. This approach allows us to appropriately model the relationship between the independent variables and the likelihood of adopting different subsoil management methods. Therefore, in this section, we focus on figures to better illustrate the distribution of independent variables (factors) across the different categories of the dependent variable (subsoil methods), providing a clearer understanding of how these factors influence adoption decisions.

Factors perceived as barriers or influencers for adopting each method are detailed in Table 1. Additionally, Fig. 3 through 14 provide a visual representation of the percentage distribution of these factors across the different subsoil management methods. This detailed breakdown highlights the distinct considerations and barriers associated with each method, based on the respondents' feedback.

The analysis of respondent distribution identified five categories: stakeholders, chambers of agriculture, local politicians, environmental associations, and others. The results revealed that stakeholders constituted the majority group, accounting for 71% of all respondents. Among these, 68% reported considering the alfalfa cultivation method, while 70% indicated interest in the Soil³ technique. The second largest group, classified as others, represented 19% of the sample, with 21% showing adoption tendencies for both the alfalfa and UEK methods. The chambers of agriculture ranked third, comprising 10% of the respondents, of which 12% applied the alfalfa method and 8% employed the UEK method. Local political actors and environmental associations did not contribute responses to the survey (Fig. 3).

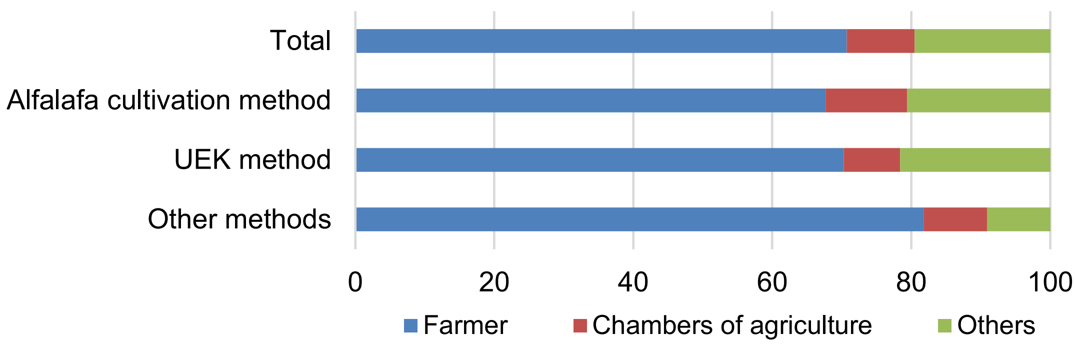

Figure 3. The first group: Stakeholder characteristics: Which group of actors would you place yourself in? (Actor_Group).

The analysis of farming system types among respondents revealed that conventional systems represented the predominant category, accounting for 27% of all respondents. Within this group, 23% were associated with the alfalfa cultivation method and 27% with the UEK method. The conventional/tillage plough system followed closely, comprising 24% overall, with 26% corresponding to the alfalfa method and 24% to the UEK method. Respondents who did not specify their farming system constituted approximately 31% of the total sample. The remaining categories, including organic, tillage/plough, organic/tillage plough, and conventional/organic/tillage systems, each accounted for less than 10% across all methods (Fig. 4).

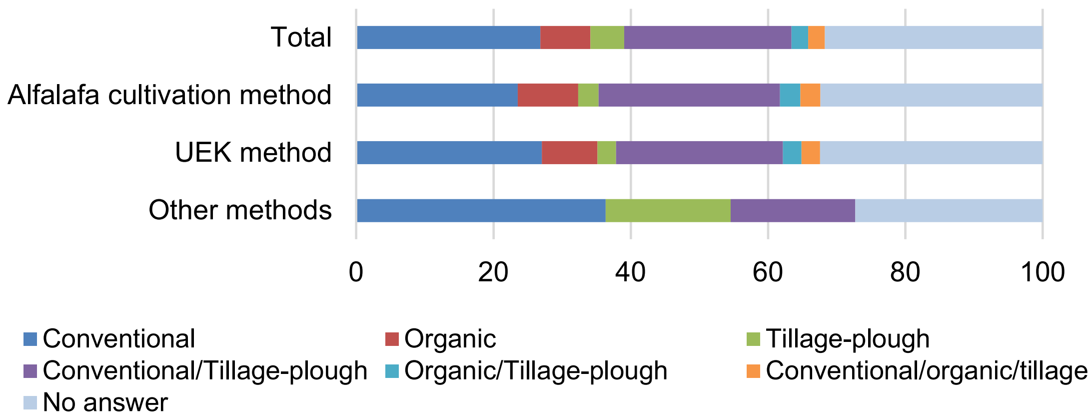

Figure 4. The first group: Stakeholder‘s feature: How do you manage your business? (Business_Type).

The regional analysis identified Teltow-Fläming as the leading area, representing 34% of the total distribution. Within this region, the alfalfa cultivation method accounted for 35%, while the UEK method comprised 30%. Anhalt-Bitterfeld and Rhein-Sieg-Kreis emerged as the second and third most represented regions overall and specifically for the UEK method. In contrast, for the alfalfa cultivation method, both regions exhibited percentage shares below 15%, with no significant difference observed between them (Fig. 5).

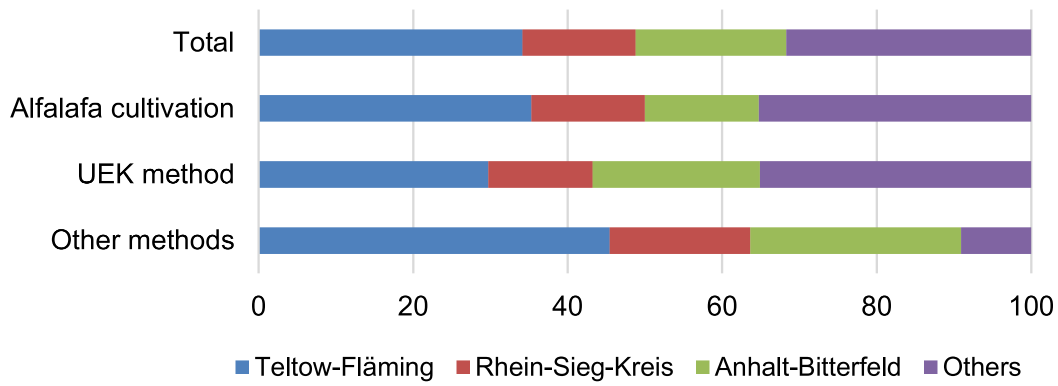

Figure 5. First group: Stakeholder‘s feature: Which region do you work in? (Region_Work).

The survey identified three distinct respondent groups based on their attitudes toward subsoil management practices. Group 1 emphasized improving subsoil conditions to reduce yield fluctuations. Respondents in this group expressed strong support for the UEK method, particularly for low-yield or degraded soils, and reported minimal concerns regarding its practical implementation. They also recognized the effectiveness of biological approaches, such as alfalfa cultivation, in enhancing subsoil quality. The percentage contributions were comparable within this group, with both the alfalfa cultivation and UEK methods accounting for approximately 34–35%.

Group 2 similarly prioritized yield stabilization through subsoil improvement. Respondents in this group were receptive to innovative techniques like IEC but emphasized the importance of scientific validation before adoption. Stakeholders generally favored practices with a positive cost–benefit balance, including organic methods such as alfalfa cultivation. The distribution of responses in this group mirrored that of Group 1, with no notable variation in percentage shares.

Group 3 proposed integrating subsoil management into agricultural practices only under specific conditions. These respondents preferred biological methods, particularly alfalfa cultivation, over mechanical approaches such as UEK, citing the long-term benefits of organic techniques for soil health and sustainability. While the overall contribution rates in this group were similar to those in Groups 1 and 2, the share of both alfalfa and UEK methods was approximately 6% lower (Fig. 6).

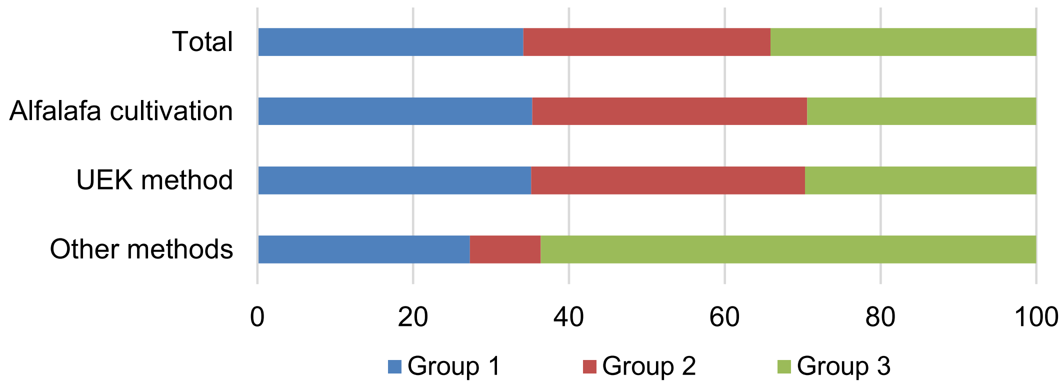

Figure 6. First group: Stakeholder‘s feature: Which groups would you assign yourself to? (Assigned_Groups).

The analysis of respondents’ perspectives on policy measures supporting subsoil management identified seven key instruments: (1) financing information campaigns for stakeholders and agricultural advisors, (2) financing information campaigns for the general public, (3) promoting the exchange of experiences between stakeholders and agricultural advisors, (4) promoting consulting services, (5) encouraging the exchange of knowledge among stakeholders (e.g., field schools, field days), (6) establishing region-specific test areas under real conditions, and (7) providing additional, targeted, and long-term research funding.

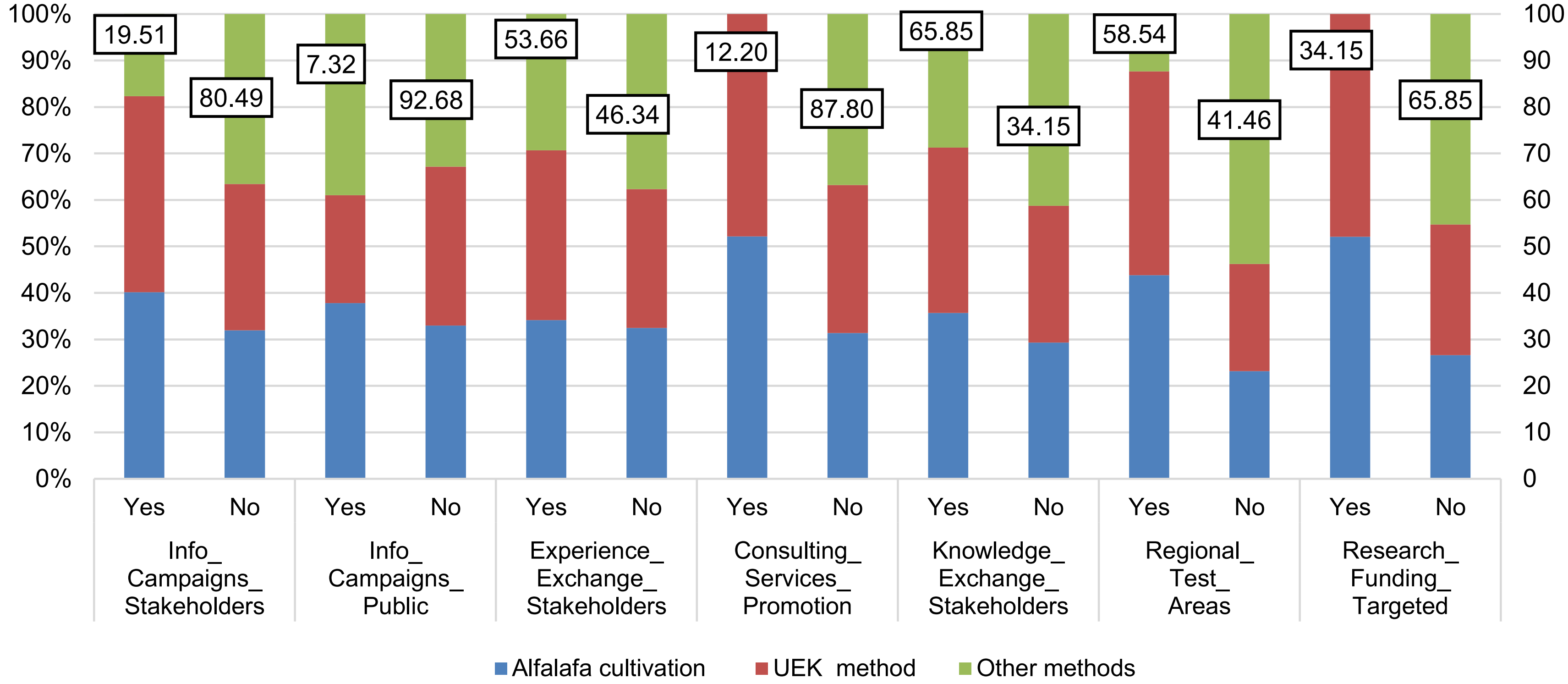

Figure 7. First group: Stakeholder's feature: How can policy-makers facilitate the practical application of knowledge in subsoil management? (Politics_Knowledge_Application).

The findings revealed that knowledge exchange among stakeholders - for instance, through field schools and field days - was perceived as the most effective policy measure, supported by approximately 66% of all respondents. This perception was consistent among both users of the alfalfa cultivation and UEK methods, with around 68% in each group endorsing this option. The establishment of region-specific test areas ranked second, receiving 58% overall support and roughly 65% from both method groups. The promotion of experience exchange between stakeholders and agricultural advisors was identified as the third most effective measure, cited by 53% of respondents overall, including 57% of UEK users and 53% of alfalfa users.

In contrast, measures such as financing information campaigns for the general public (93%), promoting consulting services (88%), and financing information campaigns for stakeholders and agricultural advisors (80%) were regarded as less effective for facilitating the practical application of knowledge in subsoil management (Fig. 7).

The analysis revealed that more than 65% of respondents – across both the alfalfa cultivation and UEK methods – perceived humus-building bonuses as an effective incentive for encouraging the adoption of mechanical and biological subsoil management practices. This finding highlights a strong consensus among stakeholders regarding the role of financial and policy-based incentives in promoting sustainable subsoil management approaches (Fig. 8).

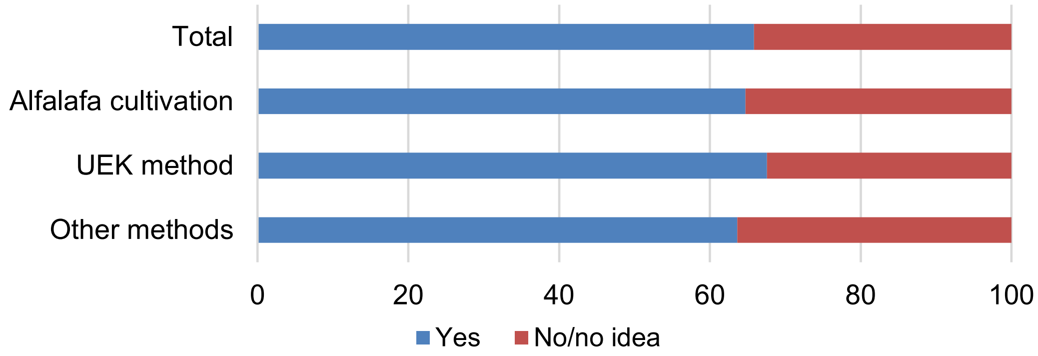

Figure 8. First group: Stakeholder‘s feature: Do humus-building bonuses provide incentives for adopting mechanical or biological subsoil management practices? (Humus_Bonus_Incentive).

The assessment of respondents’ interest in implementing humus-building bonuses within their regions focused on three main target groups: local politicians, civil society representatives, and stakeholders. The analysis showed that stakeholders demonstrated the strongest interest, with 44% reporting high interest and 22% indicating very high interest in introducing humus-building bonuses. In contrast, approximately 32% of civil society respondents expressed a neutral position or no opinion, while around 37% of local politicians reported very low interest in implementation.

Across the two subsoil management methods, the pattern remained consistent with the overall results. Among stakeholders, the highest level of engagement was observed – 41% showing high interest and 23% very high interest for the alfalfa cultivation method, and 51.35% high interest and 19% very high interest for the UEK method (Fig. 9).

The study evaluated seven key factors influencing the implementation of subsoil management methods, specifically the alfalfa cultivation and UEK methods. These factors included the low yield level of the area, insufficient water storage capacity of the soil, existing soil compaction in the subsoil, financial resources of the enterprise, business orientation (e.g., arable farming, horticulture, fodder farming, livestock farming, mixed operations), form of farming (organic or conventional), and ownership relationships (such as the duration of lease agreements and land ownership).

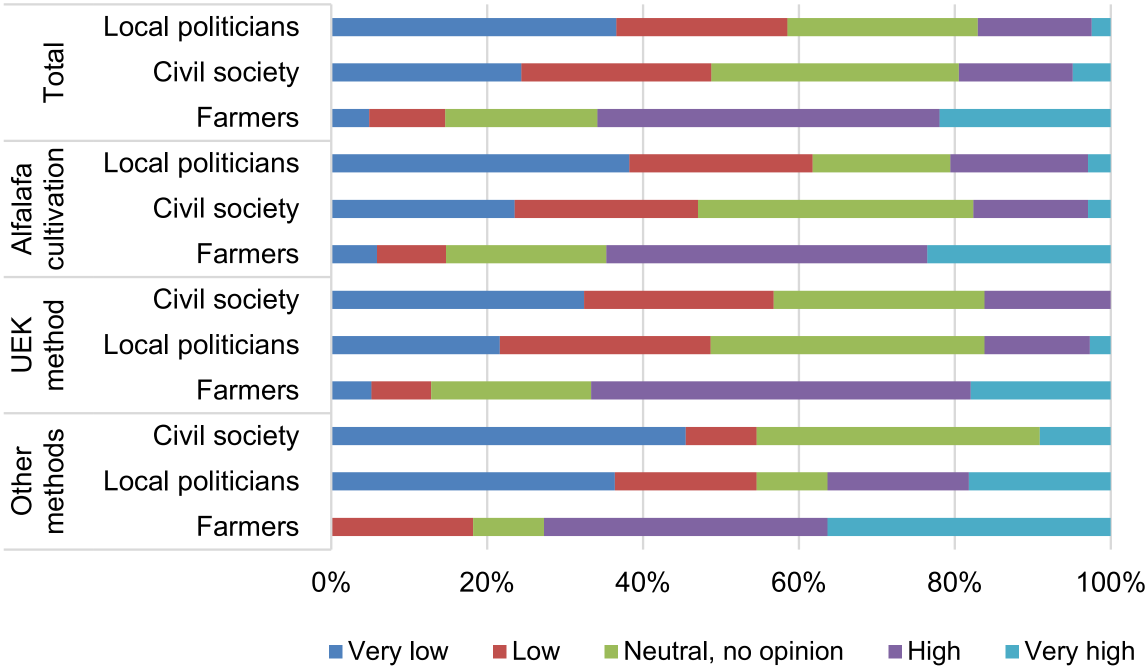

Figure 9. First group: Stakeholder's feature: How would you assess stakeholder s' interest in implementing humus-building bonuses in agriculture within your region? (Stakeholder_Interest_Humus_Bonus).

The analysis revealed that respondents were most neutral about the effects of low yield level (46%), insufficient water storage capacity (39%), and ownership relationships (37%) on subsoil management implementation. Nonetheless, over half of respondents indicated that low yield level and insufficient water storage capacity exert a high or very high influence on adoption decisions. Existing soil compaction (24% high, 37% very high) and business orientation (27% high, 32% very high) also emerged as significant determinants. In contrast, financial resources were generally perceived as having limited relevance for implementation outcomes.

When disaggregated by management method, the results showed a more differentiated pattern. For the alfalfa cultivation method, respondents identified existing soil compaction and business orientation as the most influential factors, while financial resources were rated as having a low or very low impact. Conversely, among respondents using the UEK method, financial resources and ownership relationships were recognized as having a substantial influence on implementation decisions (Fig. 10).

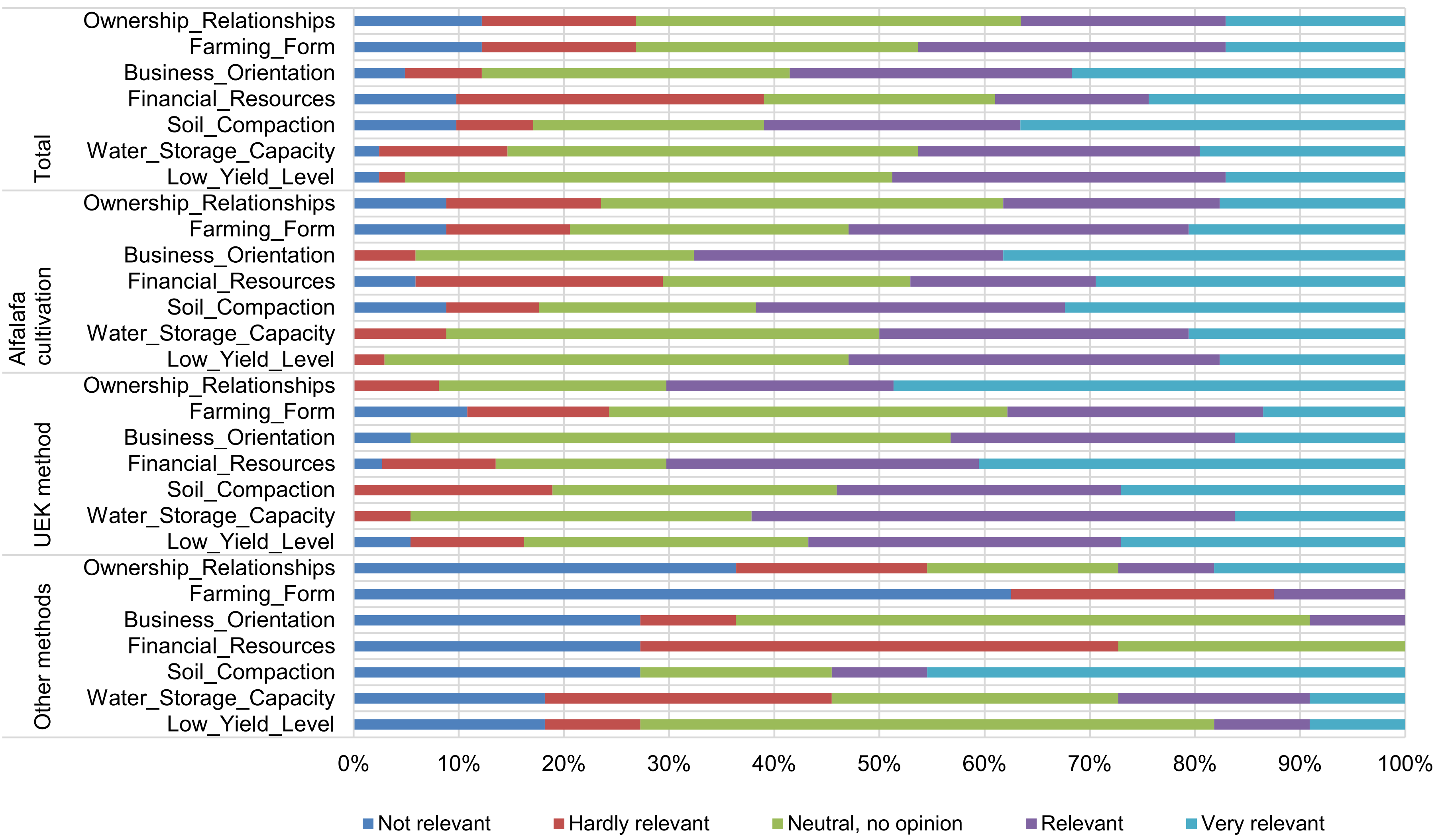

Figure 10. Second group: What factors influence the implementation of subsoil management; Alfalfa cultivation method, UEK method and other.

The analysis of respondents' readiness to grow alfalfa revealed generally low levels of willingness across all groups. More than half of the respondents – both overall and within the two subsoil management methods (alfalfa cultivation and UEK) – reported very low or low readiness to engage in alfalfa cultivation. This finding suggests that, despite the recognized agronomic benefits of alfalfa for subsoil improvement, significant reservations remain among stakeholders regarding its practical adoption (Fig. 11).

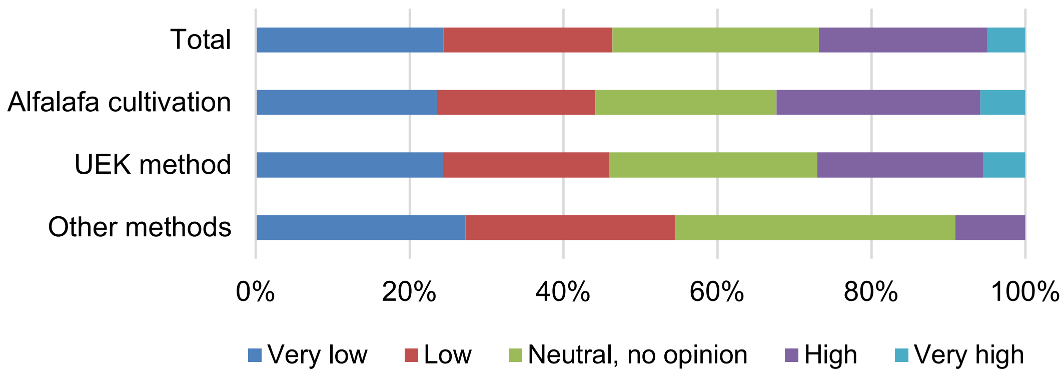

Figure 11. Third group: Alfalfa cultivation method features: Readiness to grow Alfalfa (Alfalfa_Readiness).

The evaluation of policy measures to promote alfalfa cultivation considered a range of potential strategies, including: (1) increasing support for alfalfa cultivation through the Common Agricultural Policy (CAP), (2) integrating alfalfa into contractual nature conservation schemes, (3) promoting local marketing initiatives for alfalfa-based feed, (4) encouraging feeding strategies that use alfalfa as a substitute for soy in ruminant, pig, poultry, and horse diets, (5) supporting fertilizer production derived from alfalfa, (6) funding experimental facilities for protein extraction from alfalfa, and (7) promoting alfalfa as a biogas substrate through financial premiums. Respondents evaluated each option using a binary (yes/no) scale, with both current users of alfalfa cultivation methods and users of alternative subsoil management approaches participating in the assessment.

The results indicated that enhanced CAP support for alfalfa cultivation was the most widely favored policy option, endorsed by 51% of respondents as an effective strategy. The promotion of local marketing initiatives followed, receiving 41% support. Moderate approval levels – around 36% – were recorded for measures such as developing feeding strategies, funding experimental protein production facilities, and promoting alfalfa-based biogas substrates through premiums. In contrast, 76% of respondents considered fertilizer production based on alfalfa an ineffective approach, yielding the highest share of 'no' responses among all options.

Importantly, the response patterns were consistent across both respondent groups – those applying alfalfa cultivation and those using other methods – indicating a shared perception of which strategies are most and least effective in promoting alfalfa cultivation (Fig. 12).

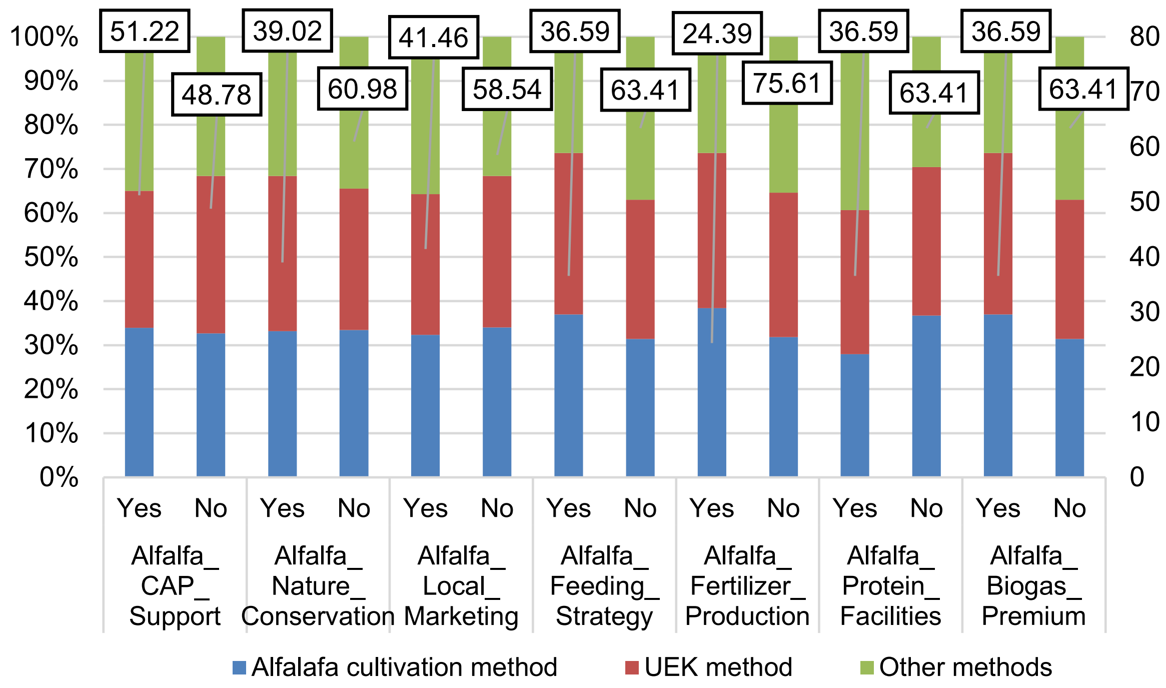

Figure 12. Third group: Alfalfa cultivation method features: How should politics promote the cultivation of alfalfa?

The analysis of respondents' openness to adopting technical innovations, such as the UEK method, revealed notable differences among stakeholder groups. The findings indicated that most respondents expressed neutral or uncertain attitudes toward the adoption of such innovations, with this uncertainty more prevalent among those practicing alfalfa cultivation. In contrast, respondents already implementing the UEK method demonstrated a higher level of willingness to embrace technical advancements. This pattern is both logical and expected, as the UEK approach inherently requires a greater degree of technical adaptation and familiarity with mechanized subsoil management practices (Fig. 13).

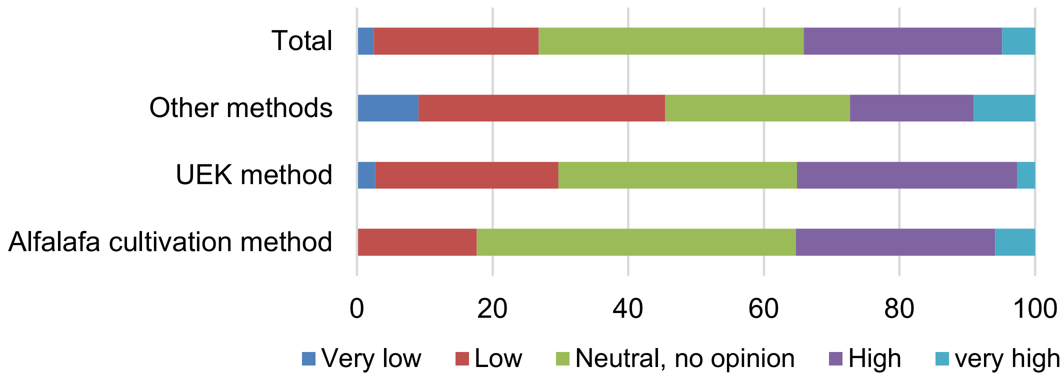

Figure 13. Fourth group: UEK method features: Stakeholder s' openness in implementing technical innovations such as UEK (Stakeholder_Openness_UEK).

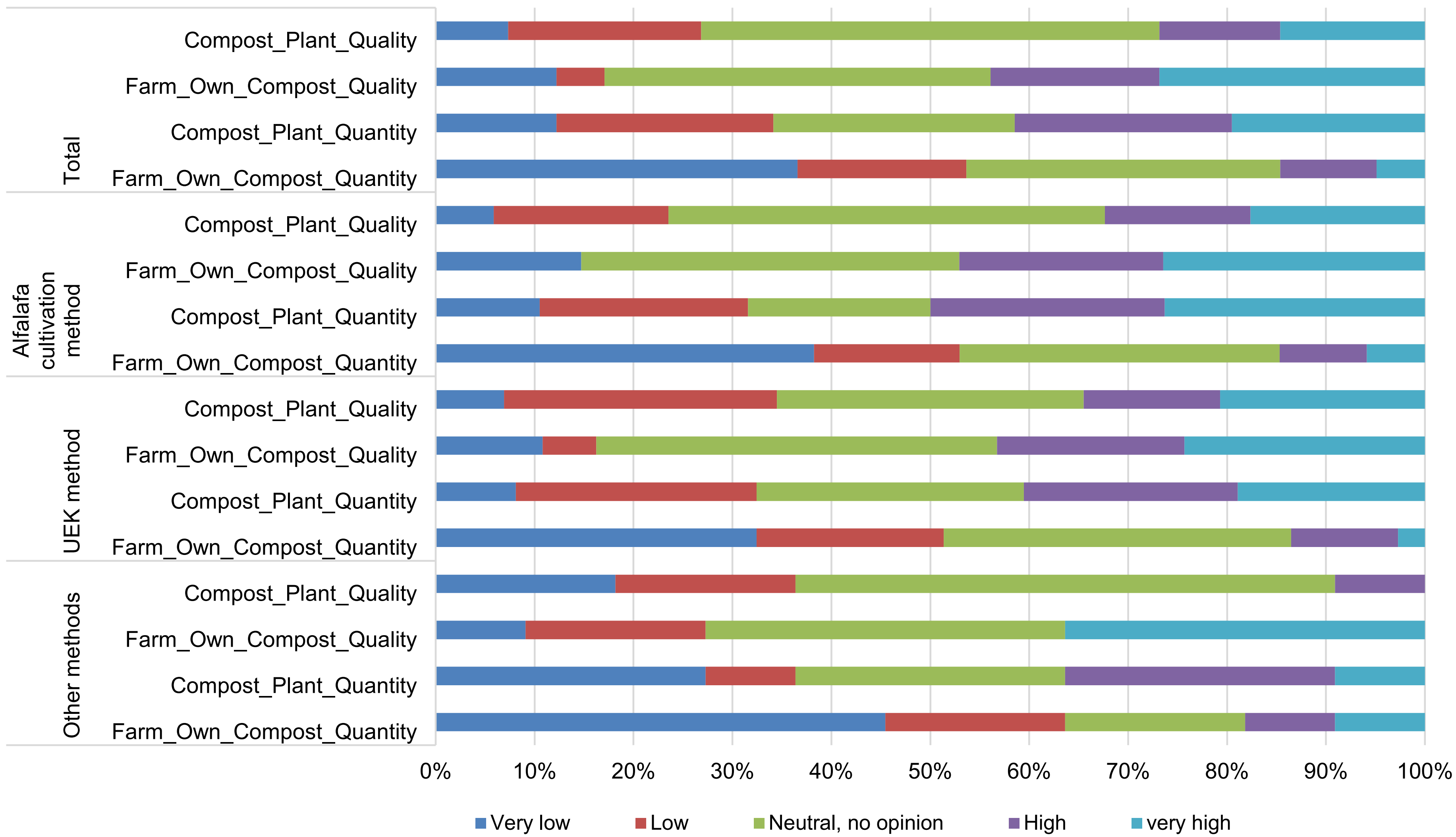

Figure 14. Fourth group: UEK method features: How do you assess the availability and quality of compost for the implementation of UEK in your district?

The evaluation of compost availability and quality for implementing the UEK method considered four main aspects: (1) the available quantity of farm-own compost, (2) the available quantity of compost purchased from compost plants, (3) the quality of farm-own compost with respect to pollutant content, and (4) the quality of purchased compost based on pollutant levels. Respondents rated these factors on a five-point scale ranging from very low to very high, with an additional no opinion option.

The results indicated that more than 40% of respondents perceived both the availability of purchased compost and the quality of farm-own compost as having a high to very high impact on the implementation of the UEK method. When analysed separately for each management approach, these two aspects consistently received the highest importance ratings. In contrast, the available quantity of farm-own compost recorded the largest share of very low and low assessments, both overall and within the alfalfa cultivation and UEK groups. These findings suggest that respondents generally regard farm-own compost availability as less influential for the successful application of the UEK method compared to externally sourced compost and quality-related factors (Fig. 14).

Data analysis techniques and model specification

The multinomial logit (MNL) model is a statistical technique used to model choice behavior among multiple discrete alternatives (Train, 2002). The MNL model is an extension of the binary logit model to accommodate multiple categorical outcomes (Cameron & Trivedi, 2016). This model is particularly useful in understanding the factors that influence decision-making processes and widely used in the field of econometrics and social sciences for analysing choice data where the dependent variable is categorical and comprises more than two categories (Hensher et al., 2015). The MNL model assumes that individuals select the option that maximizes their utility, which is influenced by the attributes of the alternatives and the characteristics of the individuals (Maddala & Lahiri, 2009). In this study, the MNL model is employed to understand the factors influencing how stakeholders differ in their perceptions on preferences and barriers in the subsoil management practices. The multinomial logit model is formulated under the assumption that the choices are mutually exclusive and exhaustive (Li, 2011). Let y_i be the categorical dependent variable representing the choice made by individual i from J alternatives (Eq. 1). The probability that individual i choose alternative j (where j=1, 2, …, J) is given by:

$$P(y_i = j) = \frac{e^{X_i \beta_j}}{\sum_{k=1}^{J} e^{X_i \beta_k}} \quad (1)$$

Here X_i is a vector of independent variables for individual i and β_j is vector of coefficient associated with alternative j.

The assumptions for the MNL model include the following: Independence of Irrelevant Alternatives (IIA), which states that the relative odds of choosing between any two alternatives are unaffected by the presence of other alternatives; Mutually Exclusive and Exhaustive Choices, meaning each individual chooses exactly one alternative from the set (Train, 2002); and No Perfect Multicollinearity, which requires that the independent variables must not be perfectly correlated (Wooldridge, 2016).

The parameters β_j are estimated using the maximum likelihood estimation (MLE) method. The likelihood function for the multinomial logit model is given by (Greene, 2018) (Eq. 1):

$$L(\beta) = \prod_{i=1}^{N} \prod_{j=1}^{J} P(y_i = j)^{y_{ij}} \quad (2)$$

In Eq. 2, y_{ij} is an indicator variable that equals 1 if individual i choose alternative j and 0 otherwise. The log likelihood function is:

$$\ln L(\beta) = \sum_{i=1}^{N} \sum_{j=1}^{J} y_{ij} \ln P(y_i = j) \quad (3)$$

The coefficient β_j are estimated by maximizing the log-likelihood function (Eq. 2).

Marginal effects in the multinomial logit model indicate how a change in an independent variable affects the probability of choosing a particular alternative relative to a baseline alternative (Greene, 2018). In Eq. 4, the marginal effect of variable X_k on probability of choosing alternative j is given by:

$$\mathrm{ME}_j(X_k) = \frac{e^{X_i \beta_j} \beta_{jk}}{\sum_{k=1}^{J} e^{X_i \beta_k}} \quad (4)$$

β_{jk} is the coefficient of X_k associate with alternative j in Eq. 4 (Heckman & Leamer, 2007). Marginal effects can be computed for each independent variable to understand their impact on choice probabilities across all alternatives. They provide insights into the direction and magnitude of the effect of explanatory variables on the likelihood of choosing different alternatives (Hensher et al., 2015).

The estimated coefficients β_j in Eq. 4, represent the log odds of choosing alternative j relative to the baseline alternative. In simpler terms, βj tells us how the odds of picking alternative $j$change when a predictor variable increases by one unit. A positive βj means the odds of choosing alternative $j$go up, while a negative βj means the odds go down. The log odds help us understand these changes in a way that keeps the probabilities between 0 and 1. For interpretation purposes, the coefficients can be exponentiated to obtain odds ratios (Winkelmann, 2008). Marginal effects can also be computed to understand the impact of a unit change in an independent variable on the probability of choosing a particular alternative (Li et al., 2005).

Goodness-of-fit and model validation for the MNL model are assessed using several measures. The Likelihood Ratio Test compares the fitted model with a null model (a model with only intercepts) to evaluate improvement in fit. The Pseudo-R-squared provides an indication of the model's explanatory power. Additionally, a Confusion Matrix and Predictive Accuracy are used to evaluate the model's predictive performance (Friedman et al., 2019).

The MNL model is employed using data gathered from an online survey to investigate influential factors affecting the adoption of various subsoil methods in specific regions. The dependent variable categorically represents stakeholders' preferences and perceived barriers toward methods such as alfalfa cultivation, UEK, and others. Independent variables, detailed in Table 1, are included to ascertain substantial predictors of stakeholders' perceptions and preferences regarding subsoil management methods, quantifying their respective impacts (Greene, 2018).

To ensure the reliability and stability of our estimates, we applied a penalized multinomial logit (MNL) model. This method is particularly useful when working with a relatively small sample size, as it applies a penalty to the model's coefficients, preventing overfitting and improving estimation accuracy. By incorporating this penalty, the model adjusts for potential issues such as collinearity or the influence of outliers, which could distort results in smaller datasets. Penalized MNL models are widely recognized for their ability to enhance the robustness of choice models, ensuring more reliable and consistent predictions, even in the presence of limited observations. This approach is well-suited for our study, where the goal is to identify key factors influencing the adoption of subsoil management practices while mitigating potential biases associated with small sample sizes. The multinomial logit model provides a robust framework for analyzing choice data with multiple categories. Its flexibility in handling categorical dependent variables and multiple predictors makes it an ideal choice for this study. The results obtained from the MNL model offer valuable insights into the determinants of factors and help in understanding the decision-making process of implementing subsoil management practices (De Jong et al., 2018; Rainey & MacCaskey, 2021).

Although binary logistic regressions could be used to model each subsoil management method separately, we opted for the Multinomial Logit Model (MNL) due to the nature of our dependent variable, which includes three distinct and mutually exclusive categories: Alfalfa cultivation, the UEK method, and other methods. The MNL is particularly suited for modeling situations where there are multiple choice outcomes, as it allows for the simultaneous estimation of the relative probabilities of each choice being adopted, based on the influencing factors. Using separate binary logistic regressions would not account for the interdependencies between the choices and would limit our ability to compare the likelihood of adopting each method in a single framework. Therefore, the MNL provides a more comprehensive and appropriate approach for analyzing the factors influencing the adoption of different subsoil management methods.

In consideration of econometric neoclassical assumptions and degrees of freedom, it is not feasible to incorporate all factors (variables) into the model. To discern the primary influential variables that could impact the adaptation barriers in implementing diverse subsoil management practices, a multicollinearity test was conducted following (Midi et al., 2010), utilizing the Variance Inflation Factor (VIF) as outlined in Table 2.

This test was undertaken because, despite explicit separation of subsoil management practices in the model, there exists implicit and indirect interdependence among them. This phenomenon, often referred to as variables with high correlation values, can undermine the meaningfulness and significance of estimated parameters. Such high correlation may hinder variables from demonstrating their individual impacts. The VIF is employed at two levels: VIF = 1 indicates no multicollinearity, signifying that the variable lacks correlation with other predictors; VIF between 1 and 5 suggests acceptable multicollinearity, indicating high correlation with other predictors, potentially leading to unreliable estimates. To guarantee the model's robustness, factors with varying VIF values were systematically added and removed in the logit model. Variables exhibiting high multicollinearity VIF values were excluded, enhancing the reliability of the model by avoiding variables with intertwined correlations. This process ensured the stability and significance of coefficient values and strengthened the reliability of the model (Bianco & Martinez, 2009). As a result of these tests, the most distinguishing variable between subsoil management were determined by grey color in Table 2 as follows: ‘Insufficient water storage capacity of the soil,’ ‘Orientation of the business,’ and ‘Ownership relationships’.

RESULTS

To identify the key factors influencing the implementation of different subsoil management methods, the analysis was organized into four distinct groups: Stakeholder Characteristics, Factors Influencing SubSoil Management Implementation, Features of the Alfalfa Cultivation Method, and Features of the UEK Cultivation Method. These groups were designed to identify the primary determinants of stakeholders' preferences for various subsoil management techniques.

For more precise modeling and clearer interpretation, the independent variables, which were assessed on various levels, were aggregated into three main categories. The first group combines responses rated as 'Not relevant' and 'Hardly relevant,' the second group includes 'Neutral' and 'No opinion,' and the third group consists of 'Relevant' and 'Very relevant.' A similar aggregation was applied to the variable categories: 'Very low' and 'Low' were grouped together, 'Neutral' and 'No opinion' formed a second group, and 'High' and 'Very high' were combined into the third group.

After addressing multicollinearity and completing the variable selection process, the coefficients were estimated using a multinomial logit model. This model incorporates dummy variables for each category within the independent variables and provides outputs for each variable category and region. The multicollinearity tests identified three key distinguishing variables: 'Insufficient water storage capacity of the soil,' 'Orientation of the business,' and 'Ownership relationships.' The results are presented based on these selected variables, which are expected to notably impact the perception and adoption of different subsoil management methods. The results include: (1) the coefficients and their significance levels, and (2) the Marginal Effects of each variable. These outputs are detailed below, offering insights into how these factors influence the adoption of various subsoil management techniques.

Synthesis of differences in perceptions towards subsoil management practices at regional level

To estimate a multinomial logit model (Eqs 2 and 3) aimed at assessing the critical factors influencing the implementation of various subsoil management techniques, we conducted an analysis using both dependent and independent variables. The dependent variable consists of three distinct subsoil categories: Alfalfa Method, UEK Method, and Others. Within the framework of the multinomial logit model, the 'Others' category serves as the reference group, against which the interpretations of the Alfalfa and UEK methods are compared.

Independent variables were selected following a thorough evaluation of their statistical characteristics and distribution percentages across the three subsoil management categories. To mitigate multicollinearity, a diagnostic procedure was performed to finalize the choice of independent variables. Consequently, variables such as 'Insufficient water storage capacity of the soil,' 'Orientation of the business,' and 'Ownership relationships' were identified as pertinent factors influencing the subsoil management methods under study.

In this analysis, the 'Other method' is designated as the base outcome for the dependent variable (Subsoil methods), while 'not relevant/hardly relevant' is the reference category for the independent variable. Additionally, Anhalt-Bitterfeld is chosen as the base region[4]. The estimated coefficients and their statistical significance are presented in Table 2.

In the multinomial logit model estimation conducted using Stata, the statistical analyses were performed with Stata 18, developed and distributed by StataCorp LLC, College Station, Texas, USA. This software provides a reliable environment for estimating discrete choice models such as the multinomial logit (MNL), ensuring accurate computation of coefficients, standard errors, and *p*-values while allowing for robust diagnostic testing and model validation.

The first output is related to the iteration log. This log tracks the likelihoods at each iteration of multinomial logistic regression. It's an iterative process aiming to maximize likelihood. Iteration begins with a null model, then predictors are added. Convergence, signaled by minimal differences between iterations, halts the process, displaying results.

In the multinomial logit model estimation using Stata, the iteration log records the likelihood values at each step. This iterative process aims to maximize the likelihood function, starting with a null model and adding predictors until convergence is achieved.

Table 2. variance inflation factor (VIF) results for identifying key factors with differential preferences among subsoil management methods

N	Variable name	VIF	1/VIF
1	Alfalfa_Local_Marketing	9.66	0.10
2	Alfalfa_Protein_Facilities	7.36	0.14
3	Farm_Own_Compost_Quality	6.56	0.15
4	Humus_Bonus_Incentive	6.56	0.15
5	Politician_Interest_Humus_Bonus	6.24	0.16
6	Alfalfa_Fertilizer_Production	6.16	0.16
7	Stakeholder_Openness_UEK	6.11	0.16
8	Info_Campaigns_Public	5.9	0.17
9	Knowledge_Exchange_Stakeholders	5.51	0.18
10	Business_Type	5.67	0.18
11	Civil_Society_Interest_Humus_Bonus	5.36	0.19
12	Low_Yield_Level	5.28	0.19
13	Alfalfa_Readiness	4.58	0.22
14	Farm_Own_Compost_Quantity	4.44	0.23
15	Alfalfa_Nature_Conservation	4.41	0.23
16	Alfalfa_CAP_Support	4.34	0.23
17	Actor_Group	4.08	0.25
18	Water_Storage_Capacity	4.03	0.25
19	Assigned_Groups	3.63	0.28
20	Consulting_Services_Promotion	3.61	0.28
21	Regional_Test_Areas	3.57	0.28
22	Alfalfa_Biogas_Premium	3.49	0.29
23	Experience_Exchange_Stakeholders	3.41	0.29
24	Info_Campaigns_Stakeholders	3.21	0.31
25	Research_Funding_Targeted	3.07	0.33
26	Alfalfa_Feeding_Strategy	2.71	0.37
27	Soil_Compaction	2.6	0.38
28	Financial_Resources	2.51	0.40
29	Stakeholder_Interest_Humus_Bonus	2.47	0.40
30	Farming_Form	2.43	0.41
31	Compost_Plant_Quantity	2.41	0.42
32	Ownership_Relationships	2.31	0.43
33	Business_Orientation	2.17	0.46
34	Compost_Plant_Quality	2.12	0.47

VIF = 1: No multicollinearity. The variable has no correlation with other predictors. VIF between 1 and 5: multicollinearity acceptable. The variable is highly correlated with other predictors, and its estimates may be unreliable. Source: Result of model.

[4] Any region other than Anhalt-Bitterfeld could also be chosen as the baseline region in the multinomial logit model estimation. The choice of baseline region does not affect the relative comparisons between alternatives, but it will change the interpretation of the coefficients, as they are expressed relative to the chosen baseline.

Convergence, indicated by minimal changes between iterations, was reached after 6 iterations. This shows the model's parameters stabilized, suggesting a successful estimation where further iterations would not significantly alter the coefficients. This outcome is typical in multinomial logit models, reflecting the process of finding optimal parameter values that best fit the observed data.

The multinomial logit model was estimated, and the model's overall significance was confirmed by a likelihood ratio chi-squared test (LR chi2(18) = 51.97, $p < 0.001$). This indicates that at least one predictor in the model has a statistically significant effect on the outcome. The model demonstrated a moderate level of explanatory power, explaining approximately 31.89% of the variance in the outcome variable, as indicated by the pseudo-R-squared value. Additionally, the model exhibited a good fit to the data with a log likelihood of -55.490. These results collectively suggest that the multinomial logit model effectively predicts or explains the categorical outcome variable, with the included predictors contributing significantly to the model's performance and explanatory capacity (Table 3).

The results of the multinomial logit model indicate that the relevance of insufficient water storage capacity of the soil notably influences the choice of method. When 'insufficient water storage capacity of the soil is neutral compared to not relevant/hardly relevant, the log odds[5]of choosing the Alfalfa method over the 'Other method' increase by 3.53 (*p*-value = 0.08), and for the 'UEK method' over the 'Other method', the increase is 3.91 (*p*-value = 0.05). Similarly, when 'insufficient water storage capacity of the soil 'is relevant compared to not relevant/hardly relevant, the log odds of choosing the 'Alfalfa method' over the 'Other method' increase by 3.69 (*p*-value = 0.04), and for the 'UEK method', the increase is 3.88 (*p*-value = 0.03). These results are statistically significant at the 10% level, indicating a strong influence of insufficient water storage capacity of the soil (insufficient water storage capacity of the soil) relevance on method choice. However, the coefficients for the regional variables related to 'insufficient water storage capacity of the soil' are not statistically significant (*p*-values > 0.10). This indicates that regional differences in insufficient water storage capacity of the soil do not significantly influence the choice of method in this sample. While the positive coefficients suggest that the likelihood of choosing 'Alfalfa or UEK methods' over the 'Other method' may increase in regions like 'Rhein- Sieg- Kreis' and 'other regions' compared to 'Anhalt-Bitterfeld', the lack of statistical significance means we cannot confidently assert these differences. These findings highlight the importance of insufficient water storage capacity of the soil relevance in influencing method choice and suggest that factors like regional differences may require further investigation with larger samples or additional variables to better understand their potential impacts (Table 3).

The analysis suggests that the relevance of the 'Orientation of the business' significantly impacts the choice of both the Alfalfa and UEK methods over the other method. Specifically, when business orientation is considered relevant, the odds of choosing the Alfalfa method are significantly higher (6.38 times the odds, *p*-value = 0.01), and the odds of choosing the UEK method are also significantly higher

[5] Odds refer to the ratio of the probability of an event occurring (e.g., choosing a specific method) to the probability of it not occurring (e.g., choosing the 'Other method').

(5.99 times the odds, p-value = 0.01). Even when business orientation is neutral, the odds of choosing the UEK method over the other method are significantly increased (3.79 times the odds, p-value = 0.02). These findings underscore the importance of business orientation in method selection, particularly when it is perceived as relevant. The statistically significant results for the relevant orientation levels highlight its crucial role in influencing decisions between the methods, suggesting that businesses that consider their orientation as relevant are more likely to choose the Alfalfa or UEK methods over the other method (Table 3).

The analysis shows that the relevance of 'Ownership relationships' has a notable impact on the choice of methods, particularly for the UEK method when they are 'relevant/ very relevant'. For the UEK method, when ownership relationships are 'relevant/ very relevant', the odds of choosing the 'UEK method' over the 'Other method' increase substantially (5.43 times the odds, p-value = 0.005), indicating a strong and significant influence. Although the coefficient for 'relevant/ very relevant' ownership relationships for the 'Alfalfa method' is just above the conventional threshold for significance (p-value = 0.06), it still indicates a notable trend that 'relevant/ very relevant' ownership relationships may influence method choice. Similarly, the coefficient for 'neutral/no opinion' ownership relationships for the 'UEK method', with a p-value of 0.09, suggests a marginally significant effect. These findings highlight the importance of ownership relationships in method selection, particularly when they are perceived as 'relevant/ very relevant'. The statistically significant results for 'neutral/no opinion' and 'relevant/ very relevant' ownership levels underscore their role in influencing decisions between methods, suggesting that ownership relationships are a critical factor in determining the choice of Alfalfa or 'UEK methods' over the 'Other method'.

The variable 'Insufficient Water Storage Capacity of the Soil' shows that both 'neutral/no opinion' and 'relevant/very relevant' levels notably increase the likelihood of choosing the Alfalfa and UEK methods over other methods, with a slightly stronger significance observed for the UEK method. Regional differences do not significantly alter this effect. Similarly, 'Business Orientation' indicates that a 'relevant/very relevant' business orientation strongly and significantly raises the likelihood of selecting both the Alfalfa and UEK methods. A 'neutral/no opinion' orientation also proves significant for the UEK method. Regarding 'Ownership Relationships', 'relevant/very relevant' ownership relationships significantly influence the choice of the UEK method. 'Neutral/no opinion' ownership relationships show marginal significance for both methods. Overall, while the factors of insufficient water storage capacity and business orientation significantly impact the choice of subsoil management methods, regional differences do not notably affect these outcomes. Ownership relationships are also crucial, especially for the UEK method when deemed 'relevant/very relevant.' This comparative analysis highlights the importance of these factors in the selection of subsoil management methods across different regions (Table 3).

Table 3. Multinominal logit model estimation

SubSoil Management Method			Coefficient	Standard error	z	P>|z|	[95%'Conf.'Interval]	
Alfalfa cultivation method	Water_Storage_Capacity	Neutral/ no opinion	3.53	2.07	1.71	0.09	-0.53	7.59
		Relevant/very relevant	3.70	1.86	1.99	0.05	0.06	7.34
	Business_Orientation	Neutral/ no opinion	2.29	1.76	1.30	0.19	-1.16	5.75
		Relevant/very relevant	6.39	2.47	2.59	0.01	1.55	11.23
	Ownership_Relationships	Neutral/ no opinion	2.60	1.37	1.90	0.06	-0.08	5.27
		Relevant/very relevant	3.49	1.90	1.84	0.07	-0.22	7.21
	Region_Work	Teltow-Fläming	1.19	1.30	0.92	0.36	-1.36	3.75
		Rhein-Sieg-Kreis	2.24	1.80	1.25	0.21	-1.29	5.77
		Other	3.49	2.40	1.45	0.15	-1.22	8.20
	Constant		-8.31	3.58	-2.32	0.02	-15.32	-1.30
UEK method	Water_Storage_Capacity	Neutral/ no opinion	3.92	2.07	1.89	0.06	-0.14	7.98
		Relevant/very relevant	3.88	1.86	2.09	0.04	0.25	7.52
	Business_Orientation	Neutral/ no opinion	3.79	1.71	2.22	0.03	0.44	7.15
		Relevant/very relevant	6.00	2.48	2.42	0.02	1.13	10.86
	Ownership_Relationships	Neutral/ no opinion	2.35	1.41	1.66	0.10	-0.42	5.12
		Relevant/very relevant	5.44	1.93	2.82	0.01	1.65	9.22
	Region_Work	Teltow-Fläming	1.13	1.30	0.88	0.38	-1.41	3.67
		Rhein-Sieg-Kreis	2.15	1.83	1.18	0.24	-1.43	5.73
		Other	4.08	2.41	1.69	0.09	-0.64	8.80
	Constant		-9.99	3.65	-2.74	0.01	-17.15	-2.84
Other method	Constant (base come)							
Iteration 0: log likelihood=	-81.47	Iteration 4: log likelihood=	-55.49		Number of observations=			82
Iteration 1: log likelihood=	-60.12	Iteration 5: log likelihood=	-55.49		LR chi2(18)=			51.97
Iteration 2: log likelihood=	-56.23	Iteration 6: log likelihood=	-55.49		Prob>chi2=			0
Iteration 3: log likelihood=	-55.53	Pseudo R2=	0.32		Log likelihood=			-55.49

Source: result of model.

Marginal effects of key factors influencing stakeholders' preferences and perceptions for implementing various subsoil management methods

When examining the marginal effects of the independent variables on the choice of three different categories of the dependent variable (subsoil methods) while also considering the three different levels of the dependent variable(not relevant/ hardly relevant, neutral/no opinion, relevant/very relevant) and four regions simultaneously in a multinomial logit model (Eqs 3 and 4), the interpretation focuses on how changes in the independent variables ('insufficient water storage capacity of the soil ', Orientation of the business,' and 'Ownership relationships') impact the probability of choosing each category of the dependent variable over the base outcome (often set as one of the categories). The outcomes of marginal effects pertaining to both subsoil management methods and regions are detailed in Tables 4. This helps us understand how variations in independent variables affect the likelihood of choosing one subsoil method over others by examining the marginal effects across the three dependent variable categories, revealing the factors driving method selection.

The marginal effects analysis provides insight into how a one-unit increase in perceived 'insufficient water storage capacity of the soil' influences the selection of subsoil management methods. Across all three methods – Alfalfa, UEK, and Others – a higher perceived relevance of water storage capacity corresponds to increased probabilities of method selection. Specifically, for the Alfalfa method, each one-unit increase in perceived relevance leads to a 0.31 percentage point increase ($p = 0.02$) for not relevant/hardly relevant, 0.40 percentage point increase ($p = 0.00$) for neutral/no opinion, and 0.44 percentage point increase ($p = 0.00$) for relevant/very relevant levels. Similarly, for the UEK method, a one-unit increase results in a 0.28 percentage point increase ($p = 0.05$) for not relevant/hardly relevant, 0.49 percentage point increase ($p = 0.00$) for neutral/no opinion, and 0.46 percentage point increase ($p = 0.00$) for relevant/very relevant levels. The Others method also responds to perceived relevance levels, albeit with weaker effects, indicating a 0.41 percentage point increase ($p = 0.00$) for not relevant/hardly relevant, 0.11 percentage point increase ($p = 0.00$) for neutral/no opinion, and 0.10 percentage point increase ($p = 0.00$) for relevant/very relevant levels (Table 4).

To compare the marginal effects of three primary factors across two subsoil management practices, we analyzed the results presented in Table 4. The marginal effects of 'insufficient water storage capacity of the soil' for both the 'relevant' and 'very relevant' statuses in alfalfa cultivation and the UEK method are similar, with values of 0.44 and 0.46, respectively. In contrast, the marginal effects for the other two factors show notable differences between the two methods. For the 'orientation of the business' factor, the marginal effect in the alfalfa cultivation method is 0.61, while in the UEK method, it is approximately 0.35, which is roughly half of the alfalfa value. Similarly, for the 'ownership relationships' factor, the marginal effect in the UEK method is 0.67 for both the 'relevant' and 'very relevant' statuses, whereas in the alfalfa cultivation method, this value is less than half, at 0.27. Overall, it appears that 'orientation of the business' is more influential in the alfalfa cultivation method compared to the UEK method, whereas 'ownership relationships' has a greater marginal effect in the UEK method compared to alfalfa cultivation.

Table 4. Marginal effects of key factors influencing stakeholders' preferences and perceptions for implementing various subsoil management methods

Factor	Subsoil management method	Status	Margin	Standard error	z	P>|z|	[95%'Conf.'Interval]	
Water_Storage_Capacity	Alfalfa cultivation method	Not relevant/hardly relevant	0.31	0.14	2.21	0.03	0.04	0.59
		Neutral/ no opinion	0.40	0.09	4.58	0.00	0.23	0.58
		Relevant/ very relevant	0.44	0.07	6.37	0.00	0.31	0.58
	UEK method	Not relevant/hardly relevant	0.28	0.14	1.94	0.05	0.00	0.56
		Neutral/ no opinion	0.49	0.09	5.51	0.00	0.32	0.66
		Relevant/ very relevant	0.46	0.07	6.62	0.00	0.32	0.59
	Other method	Not relevant/hardly relevant	0.41	0.12	3.29	0.00	0.17	0.65
		Neutral/ no opinion	0.11	0.04	2.35	0.02	0.02	0.19
		Relevant/ very relevant	0.10	0.04	2.61	0.01	0.03	0.18
Business_ Orientation	Alfalfa cultivation method	Not relevant/hardly relevant	0.25	0.15	1.60	0.11	-0.06	0.55
		Neutral/ no opinion	0.21	0.06	3.27	0.00	0.08	0.34
		Relevant/ very relevant	0.61	0.07	8.77	0.00	0.48	0.75
	UEK method	Not relevant/hardly relevant	0.27	0.12	2.14	0.03	0.02	0.51
		Neutral/ no opinion	0.62	0.07	8.84	0.00	0.48	0.76
		Relevant/ very relevant	0.35	0.07	5.18	0.00	0.22	0.48
	Other method	Not relevant/hardly relevant	0.49	0.14	3.48	0.00	0.21	0.76
		Neutral/ no opinion	0.17	0.05	3.72	0.00	0.08	0.26
		Relevant/ very relevant	0.04	0.02	1.68	0.09	-0.01	0.08
Ownership_ Relationships	Alfalfa cultivation method	Not relevant/hardly relevant	0.44	0.09	4.73	0.00	0.26	0.63
		Neutral/ no opinion	0.61	0.09	6.74	0.00	0.43	0.79
		Relevant/ very relevant	0.27	0.06	4.21	0.00	0.14	0.39
	UEK method	Not relevant/hardly relevant	0.19	0.09	2.10	0.04	0.01	0.36
		Neutral/ no opinion	0.24	0.08	2.96	0.00	0.08	0.40
		Relevant/ very relevant	0.67	0.07	10.07	0.00	0.54	0.80
	Other method	Not relevant/hardly relevant	0.37	0.09	4.33	0.00	0.20	0.54
		Neutral/ no opinion	0.15	0.06	2.55	0.01	0.03	0.27
		Relevant/ very relevant	0.06	0.02	2.64	0.01	0.02	0.11

Source: Result of model.

DISCUSSION

Our analysis has shown that the variables 'Insufficient water storage capacity of the soil', 'Orientation of the business', and 'Ownership relations' play a key role when it comes to the preferences and perceptions related to the implementation of subsoil management methods in the four case study regions. To some extent, these findings can be explained by the results of previous sociological research, which has been carried out in the frame of the Soil[3] project.

In times of climate change, nutrient capacity of the soil has become a focus point of stakeholders and policy-makers. Climate scientists predict and increasing sequence of extreme weather events in Germany, such as droughts or heavy rainfalls, with potentially detrimental effects for stakeholder s but, in the case of flooding events, also for the surrounding communities (World Weather Attribution, 2024). The acceptance analysis among agricultural stakeholders in Germany carried out by (Hinzmann et al., 2021) showed that a majority of the interviewed stakeholders was well aware of the challenges that the agricultural sector in Germany will have to face when those predictions become reality. At the same time, the acceptance analysis revealed a high awareness among agricultural stakeholders with regard to the role that subsoil and related management strategies can play in mitigating the effects of droughts and, to some extent, also flooding events. Overall, the importance of water storage capacity of the soils has been highly ranked across the three groups of stakeholders identified in the context of the acceptance analysis. Pedological research carried out in the frame of the Soil[3] project supports the assumption that subsoil, when managed appropriately, have positive effects on the hydrologic balance of the managed area, with water (and nutrients) being increasingly absorbed by the crops, suggesting that crop yields can be stabilized in times of drought (Bauke et al., 2024). Similar evidence has been reported in recent studies demonstrating that tillage systems significantly affect soil moisture distribution and retention. Conservation-oriented approaches, such as subsoiling with ridgers or chisel-rotary combinations, enhance soil water storage in both surface and deeper layers, thereby improving crop resilience and yields during dry periods (Abo-habaga et al., 2022). These findings underline the crucial link between soil structure management and hydrological balance, reinforcing the role of subsoil-related practices in mitigating drought effects.

Given that the marginal effect values of the statuses 'relevant' and 'very relevant' are similar for the alfalfa cultivation method and for the UEK method (see Table 4), one can hold that stakeholders in the four case study regions perceive the potentials, which the methods hold for increasing the water storage capacity of the soil, are relatively high for both methods, implying also that the implementation potential is equally high for both methods in view of this variable. For other methods, our results suggest that this variable is not relevant or hardly relevant.

The orientation of the business is a highly relevant determinant when it comes to the application of subsoil management techniques. Farms that focus predominantly on open livestock farming and have mainly grassland under management, are not usually suitable candidates for the application of either the alfalfa cultivation method or the UEK method, as the conversion of grassland into cropland is restricted in Germany. Among the farm types that can be considered for application of both methods, however, one can find a broad range of business orientations, including arable farming, horticulture, fodder farming, livestock farming, and mixed business (i.e. crop and livestock farming). Mixed farming is particularly suitable for alfalfa cultivation, as alfalfa can be used as cattle fodder (Schneider et al., 2024). Overall, the existence of utilization opportunities for alfalfa has emerged as a significant acceptance factor for its cultivation (Hinzmann et al., 2021), which may either be realized in the form of an on-farm circular economy approach (utilizing alfalfa as fodder and, subsequently, the resulting manure as natural fertilizer), or by creating new, regional alfalfa-based value chains. As implied by the different marginal effect values of the statuses (relevant / very relevant' in the case of the alfalfa cultivation method versus 'neutral / no opinion in the case of the UEK method', see Table 4), it becomes apparent that the above-mentioned considerations play an important role when it comes to deciding between application of the two methods. The orientation of the business and existing utilization potentials are key factors when it comes to alfalfa cultivation. The application of the UEK method, on the other hand, is not dependent on related considerations and can thus be applied in a broader set of business orientations. For other methods, our results suggest that this variable is not relevant or hardly relevant.

Finally, our results suggest that ownership relationships play an important role when it comes to the implementation of subsoil management strategies. As implied by the marginal effect value of the status 'relevant/ very relevant' in the case of the UEK method, one can hold that land ownership can be considered a decisive factor on the side of the stakeholder s. This means that it makes a difference if a stakeholder owns the land which is considered for subsoil management, or if the land is leased. Although lease contracts usually run over a longer period of time (6–12 years in Germany), which could lead to the conclusion that this is not a relevant factor, stakeholder s and other agricultural stakeholders who participated in our survey seem to consider this to be a relevant aspect. One reason for this could be the perceived invasive nature of the UEK method (altering subsoil conditions for a longer period of time), the costs related to the application of the UEK method (approx. 750€ per hectare) as well as possible investment in new technology, or the perceived uncertainty with regard to the expected yield effect. Recent research addressing the optimization of tillage machinery operation also points to the potential for improving the cost-effectiveness and energy efficiency of such interventions. For instance, studies using response surface methodology (RSM) to model tractive performance of agricultural tractors during semi-deep tillage have identified optimal combinations of speed, depth, and loading that minimize fuel use and wheel slip while maintaining soil loosening effectiveness (Askari et al., 2021). Such advances highlight opportunities to reduce operational barriers associated with subsoil management techniques like the UEK method.

These are obviously relevant considerations when access to the land is limited until a certain point of time, and renewal of the lease contract is uncertain. While alfalfa cultivation also requires land access for a longer period of time due to its perennial cultivation, the perception among agricultural stakeholders in the four case study regions seems to be that land ownership is not a decisive factor. For other methods, our results suggest that this variable is not relevant or hardly relevant.

As regards the statistical analysis of the collected data, the multinomial logit (MNL) model serves as a widely adopted method for analysing categorical outcome data, particularly in predicting probabilities associated with various choices within discrete choice contexts. Its primary strengths include straightforward interpretation and a relatively simple estimation process, making it an effective tool for examining individual choice behaviour across multiple alternatives. Additionally, the MNL model demonstrates computational efficiency, which is advantageous for handling datasets, and it offers valuable insights into how predictor variables influence outcome probabilities (Jong et al., 2019). However, a limitation of the MNL model is its assumption of independence of irrelevant alternatives (IIA). This assumption posits that the relative odds of choosing between any two alternatives remain unaffected by the presence of other options (Tutz, 2021). Such a premise may not reflect real-world scenarios where choices can be similar or substitutable. Furthermore, the model's linearity in the logit of probabilities limits its flexibility, which can reduce predictive accuracy in more complex choice situations (Grange et al., 2024).

To enhance the robustness of our findings, increasing the number of surveyed stakeholder s would provide a more comprehensive assessment. The study's narrow focus on only three regions in Germany may restrict the generalizability of its findings to broader international contexts. The unique cultural, economic, and policy landscapes of Germany could limit the applicability of these results to other agricultural settings. Moreover, the lack of longitudinal data constrains our ability to observe changes in stakeholders' perceptions and practices over time, thereby limiting the establishment of causal relationships. This restriction hinders our capacity to capture long-term trends and responses to policy shifts, complicating efforts to draw robust conclusions about the sustained impact of such changes on stakeholders' decision-making processes. Another limitation is that we only focus on the data collected from the survey, and there is not any analysis of geophysical conditions and relevant socio-economic criteria within the selected German regions. Additionally, the study does not address the implications of any mismatch between geophysical conditions and socio-economic factors, which could notably impact the effectiveness of subsoil management efforts. Addressing these aspects can remarkably contribute to advancing subsoil management practices and promoting agricultural sustainability.

In summary, this study provides valuable insights into the key factors influencing the acceptance and implementation of subsoil management methods in Germany, particularly the roles of Water Storage Capacity, Orientation of the Business, and Ownership Relations. Stakeholders recognize the value of these methods in improving soil health and mitigating climate-related water scarcity, particularly in drought-prone regions. Specifically, we highlight the significant importance of water storage capacity in improving crop yields during drought conditions, the relevance of farm business orientation for adopting certain management techniques, and the critical influence of land ownership relationships on the implementation of subsoil management strategies. Our findings indicate that these factors are crucial when stakeholders decide on adopting techniques like alfalfa cultivation and the UEK method. However, barriers to implementation include soil conditions, the business orientation of farms, and land ownership. While alfalfa cultivation is preferred by mixed farming operations due to its dual utility, its adoption is limited by restrictions on converting grassland to cropland and lack of market opportunities. The more flexible UEK method can be applied across a broader range of farming systems, yet it still requires technical knowledge and infrastructure. Landowners are more likely to invest in these methods, while tenants face challenges due to uncertain land tenure and lack of long-term control over land. This study adds to the growing body of knowledge by providing empirical evidence supporting the adoption of these methods in the face of climate change challenges, offering new insights into stakeholder perceptions, and drawing on sociological and pedological research from the Soil³ project. Addressing these barriers will be crucial for enhancing the uptake of subsoil management strategies.

While this study provides substantial insights into stakeholder preferences, it has limitations. First, the focus is on only four case study regions in Germany, meaning the findings may not be fully representative of the broader agricultural landscape. The perceptions and practices of stakeholders in other regions or countries may differ, limiting the generalizability of the results. Second, our study does not explore in depth the economic or financial barriers to implementing subsoil management techniques, which could provide additional context for understanding stakeholders' decisions. Finally, while we have considered a variety of stakeholders, the study could benefit from a more diverse sample, including a broader representation of farm types, scales, and management practices to strengthen the validity of the conclusions.

CONCLUSIONS

The analysis of subsoil management methods using a multinomial logit model has revealed critical factors influencing stakeholders' decisions to adopt specific methods, such as alfalfa cultivation and the UEK method, compared to other alternatives. The study identified 'insufficient water storage capacity of the soil,' 'orientation of the business,' and 'ownership relationships' as notable determinants of method choice. Our findings indicate that the perceived relevance of 'insufficient water storage capacity of the soil' substantially increases the likelihood of choosing both alfalfa and UEK methods, with a slightly stronger effect observed for the UEK method. This underscores the importance of water management in influencing subsoil management decisions. Similarly, 'business orientation' emerges as a strong factor, particularly for the alfalfa method, where a relevant business orientation notably raises the probability of its adoption. In contrast, 'ownership relationships' play a more decisive role in the adoption of the UEK method, suggesting that land tenure and ownership considerations are pivotal in this context. The analysis of marginal effects further highlights the nuanced differences between the two subsoil management methods. While the orientation of the business is more influential for alfalfa cultivation, ownership relationships have a greater impact on the choice of the UEK method. These insights suggest that tailored interventions focusing on business incentives may promote alfalfa cultivation, while addressing ownership and land tenure issues could enhance the adoption of the UEK method. In conclusion, the study provides valuable evidence that can inform policy and decision-making aimed at increasing the uptake of sustainable subsoil management practices (Gerdes et al., 2024). By addressing the specific barriers identified in this research, stakeholders can more effectively promote practices that enhance soil health and agricultural productivity.

The research results are relevant for policymakers in the agricultural domain and beyond. As summarized by Gerdes et al. (2024), key policy recommendations for the implementation of subsoil management in Germany include the expansion of support for alfalfa cultivation due to its multifunctional benefits, the development of value chains for innovative alfalfa products, the enhancement of collaboration for better knowledge transfer between researchers and agricultural practitioners, the clarification of legal frameworks for subsoil intervention, and increased research funding to further explore subsoil management techniques across diverse conditions (Gerdes et al., 2024).

Future research should focus on increasing sample sizes to enhance statistical power and reliability. Additionally, expanding the diversity of regions and nations included in the analysis will facilitate a more comprehensive understanding of subsoil management practices across various contexts. Building on the results of this study, future investigations can explore how specific findings can be applied to improve subsoil management strategies. Incorporating geophysical conditions and relevant socio-economic criteria into these studies will yield valuable insights into the factors influencing the effectiveness of subsoil management approaches. By pursuing these avenues, subsequent research can significantly advance our understanding of sustainable agricultural practices and their broader implications for policy development and implementation.

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