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Grouping Agri-Environmental Practices in Germany Along Behavioural Drivers for Adoption

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Abstract: Widespread adoption of sustainable practices is crucial for a transformation of agriculture towards sustainability. Effective policy interventions to increase their adoption require an understanding of the behavioural drivers of adoption. Based on interviews with twelve experts on German agriculture, this study assesses the importance of a comprehensive set of behavioural factors for the adoption of 18 agri-environmental practices. The rated level of importance of the behavioural factors varies significantly across the practices. While enhancing farmers' capability in terms of knowledge is confirmed to be a key factor for adoption of most practices, opportunity-related factors such as financial resources, and motivation-related factors such as future-orientation or habits are more specific to certain sub-groups of practices. Cluster analysis reveals three robust groups of practices that share similar behavioural drivers. For instance, a cluster consisting of agroforestry, hedges, and permanent grassland coincided as overall demanding for farmers and difficult to reverse, requiring future-orientation, a favourable legal context without short-term leases, and financial resources. For another cluster – legumes, reduced mowing, reduced tillage, rotational fallow and reduced soil pressure – adoption of the practices may actually save workforce and time for farmers, but - in addition to knowledge needs - depend on proper integration within farmers' habits and routines. The findings of our study, both at the level of single practices and on cluster-level, can inform the design of targeted policy interventions such as trainings and financial support schemes.

Keywords: Agricultural Policy, Sustainable Agriculture, Farmer Behaviour, Agri-Environmental Practices, Theoretical Domains Framework

1 Introduction

The agricultural policy of the European Union (EU) faces the challenge of balancing production related objectives with objectives related to environmental sustainability (Pe'er et al., 2019). The sustainability-related objectives linked to the European Green Deal, such as climate neutrality, restoring a healthy balance in ecosystems, and reducing pollution[1], are still not well reflected in the post-2020 Common Agricultural Policy (CAP) framework (Pe'er et al., 2020). Improving the design of agri-environmental policies can benefit from insights on the behavioural drivers affecting the implementation of agri-environmental management practices by farmers (Dessart et al., 2019; Pannell and Claassen, 2020; Swart et al., 2023). This reflects the growing interest in using behavioural research to enhance the effectiveness of policy instruments (Van Valkengoed et al., 2022).

The rich and growing literature on farmers' environmentally relevant behaviour (e.g. Bartkowski and Bartke, 2018; Delaroche, 2020; Dessart et al., 2019; Schulze et al., 2024; Swart et al., 2023) demonstrates the breadth and complexity of the behavioural drivers, including economic, social, psychological and cultural factors. Their relative importance appears to be strongly context-specific – e.g., different behavioural factors explain the adoption of climate change adaptation measures (a private good) versus climate change mitigation (a public good) (Zhang et al., 2020). For the purpose of policy design, it would be helpful to understand and account for this heterogeneity and context-specificity. Research has often addressed this challenge by developing typologies or archetypes (Huber et al., 2024; Oberlack et al., 2023). In the agriculture context, research on farmer behaviour has focused on typologies of farms and farmers (Bartkowski et al., 2022; Huber et al., 2024), based on their various socio-demographic, psychological and economic characteristics. In the study presented in this paper, we aim to identify types of agri-environmental practices for which adoption may be characterised by similar behavioural factors. For instance, some practices may require specific knowledge that is currently unavailable to farmers. These could be targeted by training programs. The adoption of other practices may require particularly large financial investments and adoption would therefore benefit from financial support. Better understanding common drivers across sets of agri-environmental practices can therefore not only contribute to systematising the empirical evidence, but it can also help policy aimed at supporting sustainable agriculture to design more effective and coherent policy mixes.

In order to consider the full breadth of behaviourally relevant factors (Brown et al., 2021), our study relies on an encompassing behavioural framework – adapted from the Theoretical Domains Framework (TDF) (Michie et al., 2014, Atkins et al., 2017) to investigate the importance of 17 behavioural factors for the adoption of 18 agri-environmental practices. By importance we mean the extent to which this factor is a barrier or can be an enabler for the farmers towards implementation of the respective practice. The analysis is based on twelve interviews with experts from research, advisory services and public administration, who were asked to rate the importance of each factor for a sub-set of the practices and to justify their ratings. The rationale for selecting experts rather than farmers themselves is that experts have a broader view across different farms and farming contexts. Experts can give responses that are generalized enough to allow for reliable results for a wide set of practices despite a limited sample size. The interviews hence provide semi-quantitative and qualitative information about the behavioural drivers affecting the adoption of the selected practices, and they allow for an exploratory cluster analysis to identify types of behaviourally similar practices.

[1] See e.g. URL: https://www.consilium.europa.eu/en/policies/european-green-deal/#goals (accessed 22 May 2025).

2 Concepts and Methods

2.1 Theoretical Domains Framework (TDF)

The TDF helps to systematically explore both the barriers and the enabling factors affecting the adoption of agri-environmental practices. It integrates 84 theoretical constructs from 33 behavioural theories and proposes fourteen 'theoretical domains' as determinants of behaviour (Cane et al., 2012; Michie et al., 2014). Michie et al. (2014) relate the TDF domains to three overarching behavioural components – Capability, Opportunity and Motivation – that together can enable or hinder a Behaviour (COM-B).[2] Capability is defined as the individual's psychological and physical capacity to engage in a behaviour, including the necessary knowledge and skills; opportunity relates to the factors of the individual's social and physical environment that can make the behaviour possible or prompt it; motivation relates to automatic and reflective brain processes that initiate and direct behaviour, including goals and conscious analytical decision-making as well as habitual and emotional responses.

We regard as a main advantage of the COM-B and TDF frameworks their implementation orientation with a clear focus on reducing complexity to facilitate practical use (see Michie et al. 2014). Moreover, the frameworks include both psychological as well as external and contextual factors that can enable behaviour change, which makes them broader than established psychological frameworks applied to the agriculture context (e.g., Dessart et al., 2019). The TDF and COM-B frameworks have been extensively used in the healthcare context (Spillane et al., 2021), and increasingly for sustainability research (Axon et al., 2018; Gainforth et al., 2016; Hedin et al., 2019; Marselle et al., 2021; Tensi et al., 2022; Van Valkengoed et al., 2022, Rode et al 2024). To our knowledge, Baaken et al. (2023) and Baaken, Vollan (2024) are the only studies applying the TDF to the agricultural context. Based on lessons learned from Baaken et al. (2023) and two pre-tests[3], we adapted the fourteen original TDF factors to the specific context of farmers' uptake of agri-agricultural practices. The resulting 17 factors were the basis for the interview questions (see Table 1).

[2] The COM-B components constitute the inner part of the Behaviour Change Wheel (BCW) framework (Michie et al., 2014, 2011), which links behavioural factors to intervention options and policies.

[3] The pretests were interviews with two acquaintances, one researching on sustainable agriculture and other doing extension services for farmers. They both could also have counted as experts, but were not included in the sample. The pre-testing also served to ensure that the questions and definitions were easy to understand.

Table 1. COM-B components and TDF factors with their specification for the context of sustainable farming practices

COM-B	Adjusted TDF factors	Explanation - Question: how important is it for the uptake of this agri-environmental practice …
Physical capability	Skills	To have – and believe in - the ability or proficiency to implement the practice
Psychological capability	Knowledge	To be aware of the existence of a practice and to have the procedural knowledge how to implement it
Physical opportunity	Financial resources	To have sufficient financial resources to implement the practice
	Material resources	To have the machinery etc. to implement the practice (linked to financial resources)
	Workforce and time resources	To have the time and labour to implement the practice (linked to financial resources)
	Legal context	To have favourable legal conditions to implement the practice (e.g. no opposing tenure- and distribution-agreements)
	Biophysical context	To have farm land that meets the environmental requirements of the practice (e.g. soil, slopes, precipitation, sun exposure, etc.)
Social opportunity	Farm / household context	To have a favourable farm-internal situation (e.g., no opposing expectations between generations)
	Peer group influences	To act in line with (perceived) professional norms and the social sphere in the region (neighbouring farms, farmer associations, village community, etc.)
	Socio-political influences	To act in line with the (perceived) political atmosphere and the expectations of wider society
Reflective motivation	Optimism / future orientation	To think positively and long-term about the role of the practice for the desired future of the farm
	Beliefs about environmental consequences	To believe in the positive consequences of the practice for the environment
	Social-professional role and identity	To see the practice as in line with the farmer's role and identity
	Non-economic goals	To believe that implementing the practice allows for meeting personal non-economic (e.g. pro-environmental) goals
	Economic goals	To believe that implementing the practice allows for meeting the personal economic goals
Automatic motivation	Emotions	To have positive feelings about implementing the practice
	Habits/routines	To have habits or routines that align with or include the practice

Source: own elaboration, based on Michie et al. (2014) and Baaken et al. (2023)

2.2 Agri-Environmental Practices

The selection of the agri-environmental practices was based on Baaken's (2022) review-of-reviews on the environmental impacts of management practices relevant for the German agricultural context. The selection was further refined and specified for the purpose of this study. The 18 selected practices encompass a range of well-established environmentally beneficial measures and practices, such as flower strips, hedges, cover crops and legume cultivation. Additionally, the selection includes more innovative and less established practices, such as slow-release fertilisers or biochar. Table 2 presents the definitions of the practices as given to interviewees.

Table 2. Agri-environmental practices used in our study

Agri-environmental practice	**Definition and main characteristics**
Reduced tillage	Encompasses a broad spectrum of plough-less soil management practices, ranging from using cultivators or harrows to no-till approaches with minimal soil disturbance. The benefits include the reduction of erosion risk, improved infiltration and water storage capacity, increased biological activity, improved nutrient retention and cost savings due to reduced time and effort. Disadvantages include increased weed and pest pressure, reduced flexibility of crop rotation and high know-how requirements.
Reduced soil pressure	Soil pressure from machinery can be reduced by multiple technologies, including tires with air pressure adjustment, crab steering systems, double tires, caterpillars etc. The main benefit is a reduction of soil compaction with similar benefits to reduced tillage. Disadvantages are mainly related to investments in machinery.
No mineral fertilisers	Implies a complete replacement of mineral nitrogen and phosphorus fertilisation by alternatives, including organic fertilisers, compost, legume cultivation. The main benefits are the reduction of nutrient leaching into adjacent ecosystems, surface waterbodies and groundwater. Disadvantages include reduced absorption by plants and less precise application of fertilizer.
Slow-release fertilizer	Enables a slow and continuous release of nitrogen material by using granulates with degradable polymer coating. This practice is currently rarely used in Germany. The benefits are largely the same as in the case of No mineral fertiliser. The disadvantages are mainly related to higher costs of fertiliser.
Biochar	The incorporation of pyrolysis-based biochar in the soil is a rarely used practice in Germany. Its benefits include positive effects on nutrient cycles and permanent storage of carbon in the soil. The main disadvantage is the high cost of biochar.
No pesticides	Implies a complete replacement of synthetic pesticides by alternatives, which may include cultivation-related measures (e.g. diverse crop rotation, intercropping), physical measures (e.g. ploughing or hoeing) or the establishment of structural elements (e.g. hedges) to support biological control. The main benefits are that non-target organisms are less affected and contamination of waterbodies and soils is avoided. Disadvantages include higher risk of yield losses.
Buffer strips	Grassed or otherwise greened strips along adjacent waterways that are not fertilised. Minimum widths and the type of vegetation vary. The main benefit is the protection of waterbodies from fertilisation and pesticides. The main disadvantage is the opportunity costs of unused land.
Cover crops	The cultivation of crops over winter between two main crops. This form of cultivation supports soil fertility and contributes to erosion protection. Various grass and clover species can be used, which economically can be used as high-quality animal feed or for biogas production.
Legumes	Legumes are plants that live in symbiosis with mycorrhizal fungi, which can fix nitrogen from the air and transform it into plant-absorbable nitrogen compounds. They can be used for human consumption (e.g. pulses) and as fodder. Main benefits include reduction of fertiliser needs and improvement of soil structure, but also reduction of pest and weed infestation. Disadvantages include low prices for legumes.
Intercropping	The simultaneous cultivation of several crops on the same plot, e.g. legume-cereal mixtures. The main benefits include improvements in soil structure and reduced risk of pest infestation. Disadvantages are mainly related to harvesting logistics.
Long rotation	The temporal sequence of crops on an agricultural area, which usually is also (partly) reflected in spatial patterns of crops grown at a given point in time. In the German context, a long crop rotation can be assumed to consist of at least five main crops. The main benefits associated with temporal diversity of crops are soil fertility and reduced risk of plant diseases. Furthermore, the associated spatial crop diversity can have positive effects on biodiversity. Disadvantages include higher requirements in terms of machinery and storage to accommodate the needs of different crops as well as logistics associated with the different vegetation periods.
Agroforestry	A system in which arable crops and woody plants (trees or shrubs) are grown on the same plot at the same time. Usually, they are grown in lines next to each other. Agroforestry is associated with many different benefits related to soil structure and quality, biodiversity and nutrient cycles. Disadvantages include high investment costs and the need for specialised machinery and harvesting/production streams for woody products.
Rotational fallow	Temporary set-aside of a plot as part of a crop rotation. Both seed mixtures and self-greening are possible. The benefits are improved soil structure and biodiversity. Disadvantages include high opportunity costs.

Hedges	(Mostly) non-productive linear structural elements consisting of woody plants (but usually not trees). They are usually located at the borders of plots. The main benefits include improved soil structure, carbon storage, biodiversity habitat and erosion protection. Disadvantages are mainly investment and opportunity costs as well as legal restrictions to removal of hedges.
Flower strips	Relatively small areas seeded with flowering plants at plot edges or within plots. The main benefit is the provision of habitat for biodiversity. Disadvantages include opportunity costs and challenges associated with selecting the right seed mixture.
Permanent grassland	Refers to grassland areas that haven't been used as arable land for at least five years. Their mainly a source of grass and herbaceous plants used as fodder (either directly via grazing or indirectly in mown grasslands). The main benefits of permanent grasslands are the high carbon storage rates and biodiversity habitat vis-à-vis arable land. Disadvantages include low profitability and legal restrictions to conversion back to arable land.
Reduced mowing	The extensification of the management of existing grasslands. It requires a reduction of maximum two cuts per year, often also associated with changes in timing and mowing technology. The main benefits are related to improvements in habitat quality and reduced disruption of lifecycles of species living in the grassland, but also to reduced workload. The main disadvantage is low grass yields.
Extensive grazing	These are systems whereby animals spend all, or a substantial part, of each day outdoors and obtain most of their nutrients from pasture. Livestock are hence raised on food that comes mainly from natural grasslands, shrublands, woodlands, wetlands, and deserts. It differs from intensive grazing, where the animal feed comes mainly from artificial, seeded pastures.

Source: own elaboration, definitions based on Baaken et al. (2022) and various sources

2.3 Expert Sample and Interview Procedure

A total of twelve experts were selected on the basis of the knowledge of their German agricultural system and farmer behaviour. All experts have a long working experience with German farmers' efforts and challenges to implement agri-environmental practices, either as empirical researchers or agricultural consultants. We therefore assume that they can evaluate the role of the different factors, at least for a some of the practices. The experts belonged to three groups: agricultural extension (5), research (4), and governmental agencies (3). They were based in five different German states and one of them was at the time holding a position in Switzerland.

The structured interviews were conducted online between June and August 2022. They were recorded following informed consent by interviewees and ensuring their anonymity. The same co-author conducted all interviews and prepared the dataset. Prior to the interview, the experts selected those practices from the list of 18 agri-environmental practices (see Table 2) for which they considered themselves most knowledgeable. As orientation, they were encouraged to select at least five practices, but they were also free to select fewer ones. The 17 adapted TDF factors were the basis for the questions on behavioural drivers relevant for the implementation of the practices. The experts received the list of factors together with the definitions, and the interviewer explained them in detail. For each of the selected practices, experts rated the TDF factors using a scale from zero (not at all important) to five (very important). More precisely, they were asked: *"How important is this aspect [behavioural driver] for the implementation of the practice?"*. For each rating score, they were also asked to provide verbal explanations to justify their score (akin to a 'think-aloud' approach). The explanations were recorded and transcribed for qualitative analysis. The interview guidelines are included in the supplementary material (SM 3).

2.4 Data Analysis

The rating scores were analysed with descriptive statistics (means and standard deviations across experts). In addition, the qualitative data were used to provide more context to the rating scores and to understand the heterogeneity in ratings across interviewees. Furthermore, we used simple cluster analysis to identify groups of agri-environmental practices that require similar TDF factors for implementation. The cluster analysis should be considered an explorative exercise, given the small sample size. Accordingly, we restricted ourselves to identifying clusters; any further analysis and comparisons were done by means of the descriptive statistics and qualitative data. We used the k-means algorithm for clustering, which is a relatively simple algorithm that is not overly reliant on large sample sizes (Dalmaijer et al., 2022). Based on the individual rating scores, k-means clustering minimises the total sum of squared deviations of the scores of a practice from each cluster's centroid (thus minimising the heterogeneity within each cluster for a given number of clusters, k). Because of the small sample size, we checked the robustness by varying the number of clusters and also applying the k-medoids algorithm (which considers medians rather than means for the cluster centroids). Furthermore, we ran the analyses both for all practices and for only those practices that were evaluated at least three times. The identified clusters were largely coherent across the different variants (see Supplementary Material). In the results section, we report the results of k-means clustering with $k = 4$ and excluding practices with fewer than three evaluations.

The cluster analysis was conducted in the statistical software R, version 4.3.0 (R Core Team, 2023), using the packages *factoextra* (Kassambara, Mundt, 2020) and *cluster* (Maechler et al., 2023). Visualisations were created using the packages *ggplot2* (Wickham, 2016) and *ggpubr* (Kassambara, 2023).[4]

3 Results

3.1 Descriptive Analysis

The expert respondents selected and evaluated between two and eight practices each, with an average of 4.7 practices per expert. Slow-release fertilisation and intercropping were not selected at all and therefore could not be analysed. The supplementary material (SM 1) presents the complete set of ratings and verbal justifications. Table 3 presents the mean ratings of each TDF factor for the remaining 16 practices as well as the standard deviation. Three of these 16 practices were evaluated less than three times: no pesticides (evaluated twice), long crop rotation (once) and biochar (once). Although we present the (average) ratings for these three practices in the table, we consider the data too scarce for further analysis. Established sustainable practices such as flower strips, hedges or buffer strips were selected most often. Table 3 also indicates which TDF factors were deemed most important for each practice, by highlighting in color those TDF factors with a mean rating greater or equal to the overall mean for the practice.

[4] The code and quantitative data are available at https://github.com/BartoszBartk/practice_typology. The qualitative data are not shared in order to ensure that respondent identities are not revealed.

Table 3. Overall mean ratings across TDF factors for each agri-environmental practice (last row) and mean ratings and standard deviations for all TDF factors. In color those TDF factors with a mean rating greater or equal to the overall mean rating of the practice

	Flower strips	**Hedges**	**Buffer strips**	**Cover crops**	**Extensive grazing**	**Reduced soil pressure**	**Legumes**	**No mineral fertiliser**	**Reduced tillage**	**Permanent grassland**	**Agroforestry**	**Reduced mowing**	**Rotational fallow**	***No pesticides***	***Biochar***	***Long rotation***	**Average (57)**
Frequency	**8**	**6**	**5**	**4**	**4**	**4**	**4**	**3**	**3**	**3**	**3**	**3**	**3**	*2*	*1*	*1*	
Skills	2.0 (0.9)	3.0 (1.7)	1.6 (0.5)	3.7 (0.6)	3.3 (1.3)	2.7 (1.5)	3.3 (1.7)	1.7 (1.5)	3.5 (1.5)	3.0 (0.0)	2.7 (1.5)	2.3 (2.1)	2.0 (1.7)	3.0	5.0	5.0	**2.99**
Knowledge	3.4 (1.3)	3.5 (1.4)	2.8 (1.1)	4.3 (1.0)	3.5 (1.3)	2.8 (1.0)	4.0 (1.2)	4.0 (1.0)	3.5 (0.6)	2.0 (0.6)	4.3 (0.6)	2.7 (0.6)	3.0 (0.0)	4.0	5.0	5.0	**3.61**
Financial resources	4.5 (0.5)	4.8 (0.4)	1.6 (1.5)	2.8 (0.5)	3.8 (1.5)	3.8 (1.9)	2.5 (1.7)	3.3 (2.9)	1.0 (1.4)	3.5 (1.7)	4.0 (1.7)	2.7 (2.1)	3.0 (1.7)	5.0	3.0	3.0	**3.27**
Material resources	1.4 (1.1)	2.5 (1.6)	1.0 (1.2)	1.5 (1.3)	1.8 (2.2)	5.0 (0.0)	2.3 (0.6)	1.7 (2.9)	2.0 (1.4)	1.5 (1.0)	2.7 (0.6)	0.7 (0.6)	1.7 (2.1)	2.5	5.0	4.0	**2.33**
Workforce and time resources	2.3 (1.2)	3.0 (1.8)	1.8 (0.8)	3.3 (0.5)	1.8 (1.7)	1.0 (0.8)	0.3 (0.6)	1.0 (1.7)	0.5 (0.6)	2.0 (1.2)	3.3 (2.1)	0.3 (0.6)	0.3 (0.6)	2.5	4.0	0.0	**1.71**
Legal context	2.6 (1.3)	4.8 (0.4)	2.8 (1.3)	1.3 (1.0)	3.5 (1.0)	1.3 (1.5)	1.3 (1.5)	3.3 (1.2)	0.5 (0.6)	5.0 (0.6)	5.0 (0.0)	1.7 (2.1)	2.7 (1.5)	4.5	2.0	3.0	**2.83**
Biophysical context	2.4 (2.1)	1.7 (1.8)	4.6 (0.9)	2.5 (1.7)	3.5 (2.4)	2.0 (1.4)	2.3 (1.7)	2.7 (2.5)	3.0 (2.1)	2.0 (2.3)	1.3 (0.6)	1.0 (1.0)	2.3 (2.1)	0.0	1.0	5.0	**2.33**
Farm/household context	2.3 (1.8)	3.5 (1.4)	2.6 (1.8)	1.8 (0.5)	2.0 (2.0)	0.3 (0.5)	1.3 (1.3)	3.0 (2.0)	2.5 (2.1)	2.5 (1.7)	4.0 (0.0)	1.0 (1.0)	2.7. (2.1)	3.0	2.0	4.0	**2.41**
Peer group influences	2.8 (1.9)	3.1 (0.7)	3.3 (0.8)	3.0 (0.8)	3.1 (0.9)	1.8 (1.5)	2.5 (1.3)	2.8 (0.8)	2.5 (2.1)	2.5 (0.6)	2.7 (1.5)	2.3 (0.6)	3.0 (1.0)	3.5	3.0	4.0	**2.87**
Socio-political influences	3.6 (1.4)	2.6 (1.7)	3.9 (1.2)	3.3 (1.0)	3.1 (1.4)	1.5 (0.6)	2.0 (0.8)	2.8 (1.6)	2.0 (1.2)	2.0 (2.1)	3.0 (2.6)	1.0 (0.0)	2.0 (1.0)	3.0	1.0	3.0	**2.49**
Optimism/future orientation	2.5 (1.3)	3.8 (0.4)	3.2 (0.8)	3.3 (1.0)	4.5 (0.6)	2.8 (1.0)	3.0 (0.8)	3.7 (0.6)	2.5 (1.0)	5.0 (0.6)	5.0 (0.0)	3.7 (1.5)	3.3 (1.2)	4.5	4.0	4.0	**3.68**
Beliefs about envir. consequences	3.3 (1.2)	4.0 (1.1)	4.4 (0.9)	3.8 (1.0)	4.0 (1.4)	4.3 (0.5)	2.8 (0.5)	3.3 (1.5)	2.0 (2.0)	3.0 (0.6)	3.3 (1.2)	2.7 (1.2)	3.0 (1.0)	3.5	3.0	4.0	**3.40**
Social-professional role and identity	3.2 (0.8)	3.8 (1.0)	3.5 (1.5)	4.3 (1.0)	3.1 (0.9)	4.0 (0.0)	2.5 (1.7)	2.2 (1.3)	3.0 (1.4)	3.5 (1.0)	4.3 (0.6)	2.0 (0.0)	3.0 (1.7)	3.5	4.0	5.0	**3.43**
Non-economic goals	3.8 (1.4)	3.6 (1.6)	2.7 (1.1)	3.5 (0.6)	2.9 (1.4)	3.5 (1.0)	3.5 (1.3)	2.2 (1.0)	1.5 (1.5)	3.5 (1.5)	4.0 (1.0)	2.3 (1.5)	3.0 (2.0)	3.0	3.0	4.0	**3.13**
Economic goals	2.3 (2.0)	3.3 (1.6)	2.5 (2.0)	4.3 (1.0)	3.9 (0.9)	4.5 (1.0)	4.0 (0.8)	3.5 (1.5)	2.5 (1.5)	3.5 (1.7)	3.3 (0.6)	3.3 (2.1)	3.0 (2.0)	5.0	5.0	4.0	**3.62**
Emotions	3.6 (1.2)	3.9 (1.1)	2.1 (1.7)	3.5 (1.0)	3.9 (1.4)	3.5 (0.6)	3.5 (1.3)	3.2 (1.0)	3.0 (2.0)	3.5 (1.7)	4.0 (1.0)	1.7 (0.6)	2.3 (0.6)	3.5	4.0	4.0	**3.33**
Habits/routines	3.5 (1.6)	3.5 (1.4)	3.8 (1.1)	4.0 (0.8)	4.5 (1.0)	2.8 (2.6)	3.5 (0.6)	5.0 (0.0)	4.0 (0.0)	3.5 (1.7)	3.3 (1.5)	3.7 (1.2)	2.0 (2.6)	5.0	5.0	4.0	**3.82**
Average	**2.9**	**3.4**	**2.8**	**3.2**	**3.3**	**2.8**	**2.6**	**2.9**	**2.3**	**3.0**	**3.5**	**2.1**	**2.5**	**3.5**	**3.5**	**3.8**	**3.0**

Source: own elaboration

Figure 1 shows the mean ratings and standard deviations (as whiskers) across all practices for each TDF factor, coloured according to the three COM-B components. This reflects the overall importance of the TDF factors for the adoption of agri-environmental practices. The TDF factors related to *Motivation* exhibit the highest mean values with relatively low standard deviations, with *Habits/routines* having the highest mean rating. Meanwhile, the lowest means and the highest standard deviations were found in the *Opportunity* component. Here, the factor *Workforce and time resources* has the lowest mean rating. The high standard deviations often reflect systematic differences across practices, e.g. we observe high ratings of *Legal context* for hedges, agroforestry, and permanent grassland, but a low rating for no tillage (see next section).

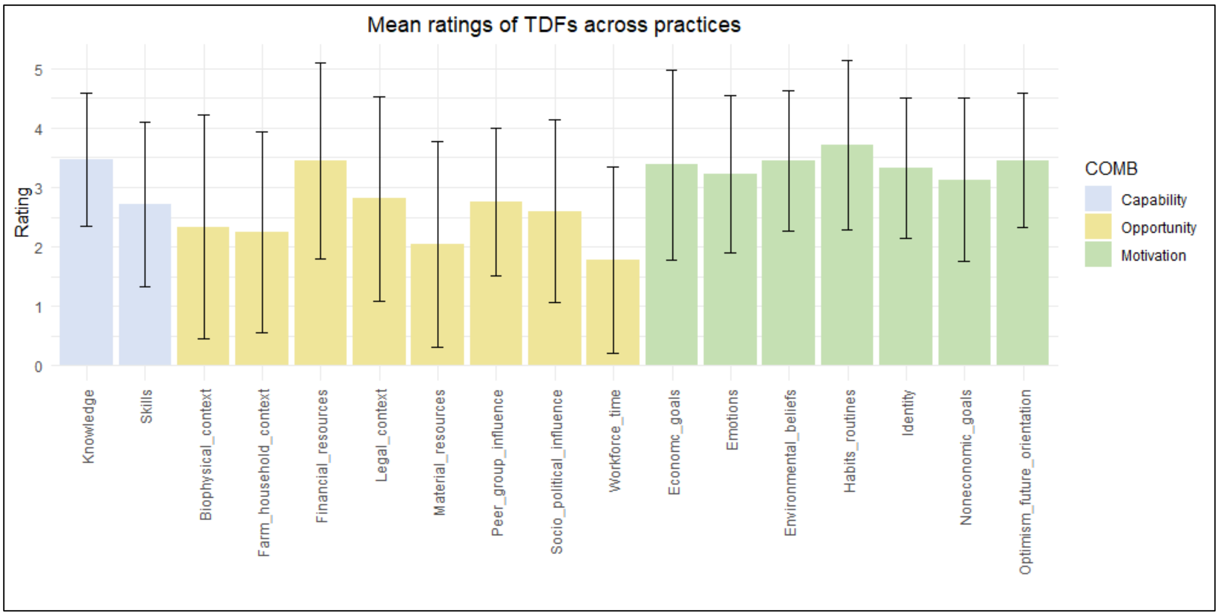

Figure 1. Mean ratings and standard deviations (as whiskers) across all practices for each TDF, colored according to the three COM-B elements

Source: own elaboration

3.2 Cluster Analysis

The cluster analysis with four clusters shows three multi-practice clusters and one that consists of a single practice (buffer strips) (Figure 2). These clusters are largely robust across different clustering variants (see Supplementary Material SM 2).

- Cluster 1: agroforestry, hedges, permanent grassland
- Cluster 2: cover crops, flower strips, extensive grazing, no mineral fertiliser
- Cluster 3: legumes, reduced mowing, reduced soil pressure, reduced tillage, rotational fallow
- Cluster 4: buffer strips

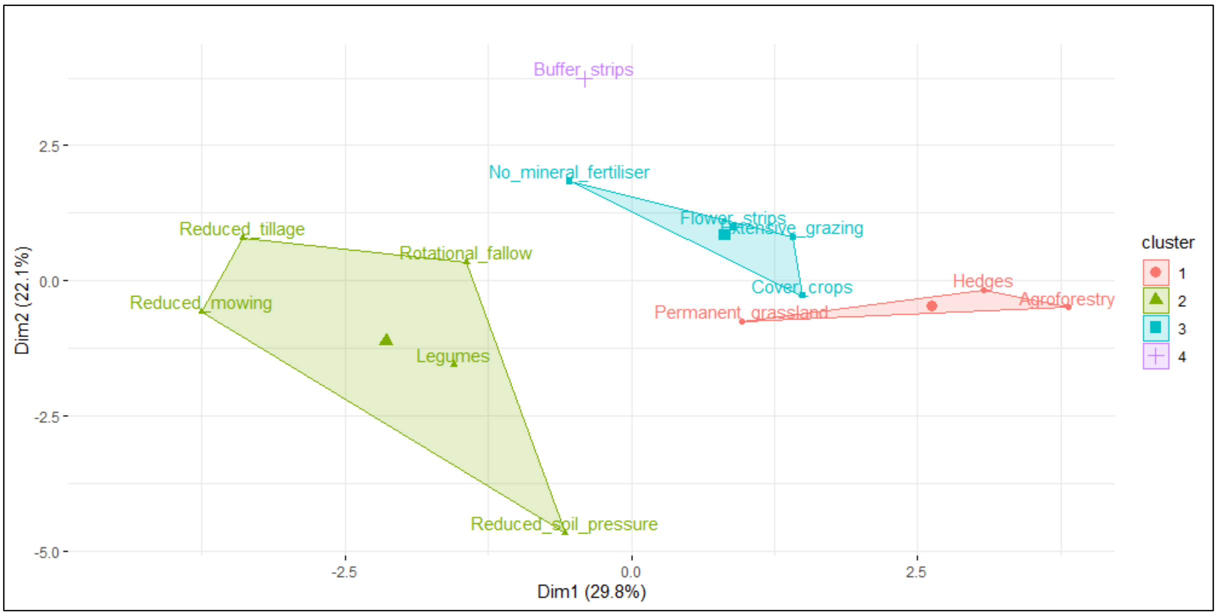

Figure 2. Results of the k-means clustering of agri-environmental practices based on the importance of TDF factors for their adoption

Source: own elaboration

The ratings within each cluster show similarities particularly regarding certain TDF factors. These cluster-forming similarities can refer either to TDF factors that were rated to be of high importance for all practices within the cluster, or to those TDF factors rated as rather unimportant. For clusters 1, 2, and 3, Table 4 presents the cluster-forming similarities in more detail, also providing experts’ verbal justifications for their ratings. We do not report here Cluster 4, which consists only of buffer strips, but illustrate the TDF factors for that practice within the discussion section.

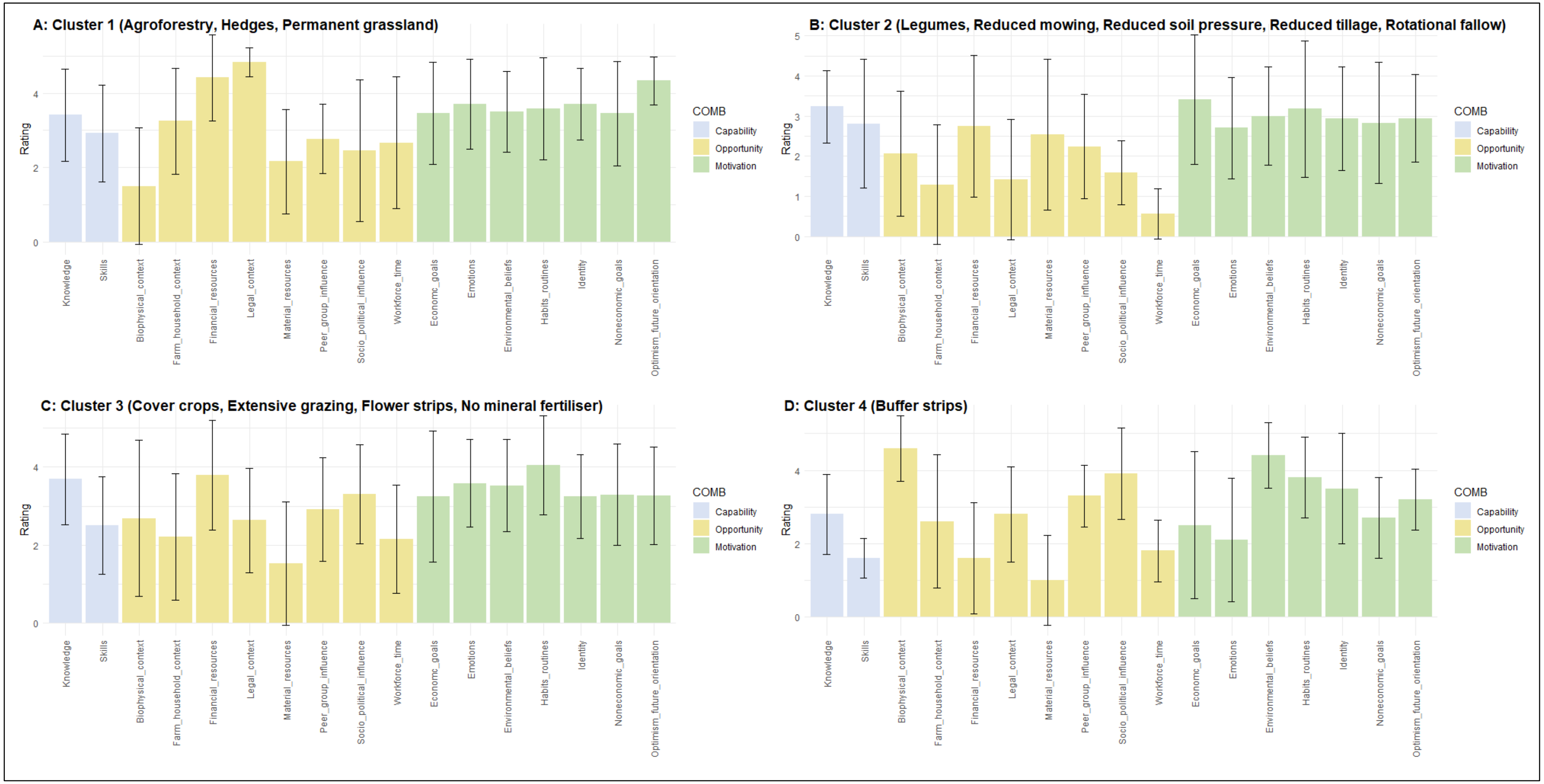

Figure 3. Mean ratings and standard deviations of TDF factors within the four clusters

Source: own elaboration

Table 4. Cluster-forming TDF factors for the four clusters. For each practice within a cluster, the table reports the mean rating of the TDF factors and the reasons for ratings given by the experts in the interviews

Cluster 1	**Agroforestry**		**Hedges**		**Permanent grassland**	
Cluster forming factors (important)						
Optimism/ future orientation	5.0	• loss of use for many years, but farmer has the hope and vision • economic and ecological effects only visible in the future	3.8	• investment in the future for 25 years • nature protection and erosion control • durable structure	5.0	• the farmer commits him/herself and either needs animals or the fodder is sold • outcome is important
Legal context	5.0	• lease agreements: trees cannot simply be planted on leased land • composition of species	4.8	• hardly possible on leased land because it is a permanent investment • decrease in value of the land	5.0	• prohibition of conversion after 5 years; land loses economic value
Financial resources	4.0	• extremely high initial investment	4.8	• expensive	3.5	• *no explanations*
Cluster forming factors (rather unimportant)						
Biophysical context	1.3	• can be implemented everywhere	1.7	• for the hedge rather unimportant, but in the planning important	2.0	• depends on the planned usage e.g. grazing livestock need shade

Cluster 2	Legumes		Reduced tillage		Reduced mowing		Rotational fallow		Reduced soil pressure	
Cluster forming factors (important)										
Habits/ routines	3.5	• marketing of the crop and different processing times lead to a change of routines	4.0	• for a long-term abandonment of tillage, alternative pesticides products are needed	3.7	• timing of mowing particularly important, routine tasks are subordinated by mowing dates • marketing opportunities for mown crop	2.0	• high standard deviation, opinions differ (not at all important for one expert (0) and particularly important (5) for another expert)	2.8	• initial investment, but then in principle no new routines • no problem, the conditions are met
Knowledge	4.0	• seeding • sowing depth • threshing times	3.7	• knowledge of machines, soils and mulch layer • very specialised and involves a lot of practice (skills and knowledge play together)	2.7	• suitable mowing times • sensible use of the mown material • easy to implement with little knowledge, if farmer knows of practice	3.0	• knowledge about land selection based on weed pressure • what type of fallow (e.g. black fallow, self-vegetation) • no specific knowledge necessary for planting	2.8	• not so complicated, only adapted machinery • quite important in order not to destroy the tires • farms in Saxony have 30 years of experience, rather technology is lacking behind
Cluster forming factors (rather unimportant)										
Workforce/ time	0.3	• the farmer needs less	0.7	• farmer saves workforce	0.3	• less workforce and time overall	0.3	• less time required, unless the land is taken up again, then it costs more time	1.0	• no additional requirements, just need to change tires

Cluster 3	**Flower strips**		**Buffer strips**		**Extensive grazing**		**No mineral fertiliser**		**Cover crops**	
Cluster forming factors (important)										
Knowledge	3.4	• for a successful flowering effect (perennial), knowledge about the site, sowing depth, seeds, time of sowing and maintenance measures is required	2.8	• buffer strip width • definition of water bodies • technical understanding • the European Water Framework Directive	3.5	• livestock farming is a complex system • farmer needs sensitivity for the cattle, experiences in herd management, calculation of feed requirements	4.0	• knowledge about composition of soils • knowledge about consequences required (if... then analyses)	4.3	• knowledge about crop rotation principles, timing, location and mixture required
Habits/ routines	3.5	• it needs time to deal with it beforehand and it needs maintenance • farm procedures need to be adapted (advice important)	3.8	• this area must remain free from cultivation	4.5	• it should be adapted in such a way that it has the least possible effort and other side effects are achieved through it	5.0	• conversion of usual working procedures	4.0	• must fit into crop sequence • adapted seeds • reconsideration again and again
Beliefs about environ. consequences	3.3	• accepted practice, which is why the positive effects are believed in • pollinator performance is perceived by farmers	4.4	• if the difference or impact is visible, farmers are more likely to adopt it and possibly also implement it voluntarily	4.0	• believing in environmental consequences is exactly why farmers implement extensive grazing	3.3	• *No (suitable) explanation by experts*	3.8	• *No (suitable) explanation by experts*
Cluster forming factors (rather unimportant)										
Material resources	1.4	• seed drill required • standard technology • outsourcing to contractors possible	1.0	• can be implemented with existing technology • keeping a distance when fertilizing requires technical effort	1.8	• pasture fences • significantly less effort than with intensive farming	1.7	• if alternative fertiliser is used, special equipment is needed	1.5	• standard agricultural devices

Source: own elaboration

Cluster 1: agroforestry, hedges, permanent grassland

All practices in this cluster seem particularly demanding, as rating scores are high across a majority of the TDF factors (mean scores across all TDF factors are 3.5 for agroforestry, 3.4 for hedges, and 3.0 for permanent grassland). The cluster-forming factors with high importance are the *future and vision of the farm,* the *legal context*, and *financial resources*. According to the experts interviewed, the behavioural drivers also influence each other. For example, "agroforestry requires high initial investments" (Interview: I06), which sets high expectations for the future of the farm. The *legal context* plays a decisive role for all three practices, which respondents explained with the importance of land tenure. On leased land, "trees cannot simply be planted" (I12) and irreversible changes (such as planting hedges or conversion to permanent grassland) are hardly possible. In addition, the factor *biophysical context* was assessed by the experts as rather unimportant, implying that these practices are not particularly sensitive to the local environmental conditions.

Cluster 2: legumes, reduced mowing, reduced tillage, rotational fallow, reduced soil pressure

Overall, the practices in Cluster 2 were rated as least demanding, with mean scores across TDF factors of 2.6 (legumes), 2.1 (reduced mowing), 2.0 (reduced tillage) and 2.5 (rotational fallow), and 2.8 (reduced soil pressure). The most noticeable agreement in (low) rating scale scores is in the TDF factor *workforce and time*. The experts argue that this factor is hardly relevant for these practices – in fact, they may actually save workforce and time (I12, I05, I08, I03). *Habits and routines* in the operational process show similar evaluation patterns, but are justified differently. For instance, mowing dates are crucial in extensive management of agricultural land and marketing strategies for legumes run counter to habitual routines of other crops (I05, I08). For rotational fallow, *habits and routines* were rated as rather unimportant (score of 2.0). *Knowledge* is rated comparably high for these practices, where of course the specific knowledge gaps vary across practices.

Cluster 3: flower strips, extensive grazing, cover crops, no mineral fertilisation

Three practices in this cluster (flower strips, extensive grazing and cover crops) are already well established, whereas no mineral fertilisation is currently found mainly in organic farms. Cover crops and extensive grazing were classified as demanding with aggregate mean values of 3.2 and 3.3 across TDF factors. Flower strips, no mineral fertilisation, and buffer strips exhibited lower mean values of 2.8 to 2.9. *Knowledge* is a rather important factor in this cluster. For instance, ecologically effective establishment of flower strips requires knowledge regarding the appropriate location, seed selection, and timing of sowing (I01, I04, I05). According to the interviewees, similar requirements apply to the practice of cover cropping, which also necessitates knowledge of crop rotation principles (I01, I03). *Beliefs about the positive environmental impacts* of these practices are also regarded as important. According to one expert, this is even the main reason for taking up extensive grazing (I04). *Material resources* are relatively less important for this cluster since the practices can be implemented with existing technologies.

4 Discussion

4.1 How Relevant are Different Behavioural Drivers for the Implementation of the Agri-Environmental Practices?

This study systematically compares the importance of a comprehensive set of 17 behavioural drivers (based on the Theoretical Domains Framework) for 18 agri-environmental practices. In addition to demonstrating the relative importance of individual behavioural drivers for each practice, it provides indications about which clusters of practices are similar in that respect. Our basic results are in line with Baaken's et al. (2023) conclusion that the behavioural drivers included in the adapted TDF framework are all relevant for the uptake of agri-environmental practices, but that their importance varies significantly across the practices. These differences are relevant for policy formulation and design, as they indicate which instruments may be particularly suitable for increasing the adoption of a given agri-environmental practice. For instance, researchers or decision-makers interested in the uptake of a particular practice may find it valuable to look at the ratings in the respective column of Table 3 in combination with the qualitative justification provided by the experts who were interviewed (see supplementary material SM 1). Table 5 exemplarily illustrates such a synthesis for the uptake of agroforestry.

The TDF factors as behavioural drivers can be structured within the three broader behavioural domains of capability, opportunity, and motivation (COM-B) (Michie et al., 2014). A closer look at the aggregate ratings reveals that the experts rated the TDF factors related to motivation as particularly important, with higher average ratings compared to the TDF factors in the domains of capability and opportunity. Especially the factors *habits and routines* and *optimism/ future orientation* are regarded as highly relevant in the motivation domain. From the other two domains, in particular *financial resources* and *knowledge* stick out. The latter may not come as a surprise. Although a recent study (Swart et al., 2023) found that general economic outcomes play a relatively minor role, many other studies highlight financial requirements as a key barrier to the adoption of agri-environmental practices (Dessart et al., 2019).

Our results also highlight links and possible interactions between different behavioural components, as described in Michie et al. (2014, p. 60). *Economic goals*' (a motivational factor within the COM-B model) is obviously related to *financial resources* (a TDF factor belonging to the COM-B component 'physical opportunity') in the sense that the achievement of economic goals can be enhanced by the availability of additional financial resources, e.g. in the form of subsidies, tax exemptions, or other forms of material support (e.g., Bartkowski, Bartke, 2018; Brown et al., 2021; Stupak et al., 2019; Zinngrebe et al., 2017). At the same time, the availability of financial resources may free up space for other motivations beyond economic outcomes. Similarly, motivation can be related to influences captured within the 'social opportunity' component of the COM-B model. For instance, Mills et al. (2020) state that motivations in the agricultural context can come from financial rewards through direct payments, but also from reactions of the peer-group and the socio-political context.

Provision of more knowledge was rated as highly relevant for several practices in Clusters 2 and 3, particularly for flower strips, which, according to the experts, only yield effective results with adequate management (maintenance, seed mix, location) and corresponding knowledge. Along the same lines, farmers may require support to find viable markets and marketing skills for their produce, so that the shift from their routines to new practices becomes economically viable (e.g. for legumes, agroforestry) (Gütschow et al., 2021; Mawois et al., 2019). In such cases, targeted advisory services may be an effective policy instrument fostering adoption (see also Bartkowski et al., 2023). Our study also highlights the relevance of beliefs in the positive environmental impacts of practices. This is particularly evident in the case of extensive grazing and the creation of buffer strips along water bodies. Lastra-Bravo et al. (2015) argue in their study that intergenerational knowledge exchange is particularly important in encouraging future generations of farmers to adopt these practices by conviction. In the context of extensive grazing, it is apparent that a positive attitude and conviction are crucial, as the economic benefits are perceived as relatively low by the experts. Promoting programs for young farmers may facilitate the process of instilling these convictions and ensure the long-term sustainability of the measures.

Table 5. Agroforestry synthesis (n = 3 expert respondents)

Definition: The German association for agroforestry defines agroforestry as follows: "The term agroforestry is used to describe land use systems in which woody plants (trees or shrubs) are combined with arable crops and/or livestock farming on one area in such a way that ecological and economic benefits arise between the various components (Nair, 1993). Typical for all types of agroforestry are deliberately utilized interactions between woody and arable crops" (DeFAF, 2022).

TDF ratings		Explanations
Skills	2.7 (1.5)	• need for skills to cut and manage trees • no particular skills needed
Knowledge	4.3 (0.6)	• there are specific providers of trainings on species composition and management • specific knowledge required to improve biodiversity • knowledge on the results and economic viability is missing so far • knowledge is vague, since effects may only be observable in 30-40 years
Financial resources	4.0 (1.7)	• extremely high initial investments • it has to grow without much costs, but loss of income over many years
Material resources	2.7 (0.6)	• you need pecial equipment to harvest the trees • planting the seedlings can be done with a machine or per hand; can also be sub-contracted
Workforce and time resources	3.3 (2.1)	• in the beginning requires high efforts • definitely additional time and workforce required to set it up
Legal context	5.0 (0.0)	• the lease contracts need to allow for it: can it be used or not? can foreign species be planted? can it be reversed later on or not? • as soon as the farmers know they can abandon it again, things change • crucial whether or not the land is own property, you cannot just plant trees if it is leased
Biophysical context	1.3 (0.6)	• you can implement it everywhere, possibly precipitation could be an issue
Farm/household context	4.0 (0.0)	• a big transformation • previous generations have worked hard and this can be seen as a step backwards
Peer group influences	2.7 (1.5)	• it is widely talked about • external judgements (Außenwirkung) play a role
Socio-political influences	3.0 (2.6)	• only few implement it because the political sentiment is not yet in that direction • nothing yet • is seen very positively, as „solution to all problems"
Optimism/future orientation	5.0 (0.0)	• important to have a vision for the future • very important to think about the future, requires complete change
Beliefs about envir. consequences	3.3 (1.2)	• is not necessarily seen as an agri-environmental measure, particularly the biodiversity effects can be very diverse depending on type of management • not necessarily the environmental benefits central, also has an economic value via timber production etc. • farms can decide to do it due to fear of climate change (provision of shade)
Social-professional role and identity	4.3 (0.6)	• to do it on the entire area you need to be completely convinced of it,,that is different if it is only about doing it on a smaller part
Non-economic goals	4.0 (1.0)	• the landscape aesthetics, e.g. of meadow orquards ("Streuobstwiesen") • those who implement it partly have strong convictions with environmental objectives and intrinsic motivation to do agro-ecology, particularly when it is not about timber production but about mixed use
Economic goals	3.3 (0.6)	• estimating the economic viability is currently very difficult for the producers • no one can predict if the timber, berries, nuts, or whatever they are planning will be economically viable in the future • what about costs of salaries
Emotions	4.0 (1.0)	• with innovative measures it is easier to generate positive emotions and those are then important
Habits/routines	3.3 (1.5)	• not possible to rely on old habits and routines, requires complete transition and the willingness to try something new
Average	**3.4**	

Source: own elaboration

4.2 What Characterises Clusters of Practices and How Can this Inform Targeted Policy Design for Sustainable Agriculture?

Our study reveals considerable heterogeneity among agri-environmental practices in terms of which behavioural drivers are relevant for their adoption (see Table 3 and Figure 3). A study on the action space of farmers (a concept related to the COM-B dimension opportunity) (Gütschow et al., 2021) revealed similar heterogeneity. One of the objectives of the present study was to explicitly consider and structure this heterogeneity by clustering the practices according to the significance of behavioural drivers. The results of this exercise were surprisingly robust and intuitively plausible. This was especially true for Cluster 1 (agroforestry, permanent grassland, hedges), which consists of practices with long-term impacts that are difficult to reverse and, in the case of agroforestry and hedges, involve high investment costs. For this cluster, thinking about the future of the farm and creating a vision as part of the reflective motivation were seen to be most important for implementing the practices, together with the legal context and financial resources (i.e., the physical opportunity). Targeted policy interventions could, for example, include innovative funding options that reflect the varying time horizons involved (e.g. investment support for agroforestry or longer-term compensation for hedge maintenance). The planning horizon could thus be extended and the hurdle of larger initial investments and conversions avoided. Relatedly, the analysis of Cluster 1 highlights the importance of ownership-related factors (see also Bartkowski et al., 2023; Wittstock et al., 2022). According to the experts, there are significant uncertainties among farmers regarding the lease agreements and their extension, which hinders the adoption of agri-environmental practices. Here, legal provisions related to these specific practices – such as strict hedge removal bans and bans on the conversion of permanent grassland – may be counter-productive by protecting the status quo and creating strong incentives against introduction of new hedges and permanent grassland in the first place. In fact, this seems to have been partly recognised by German legislators who relaxed the regulations regarding the conversion of recently established permanent grassland back to arable land (see Reiter et al., 2024). Incentive measures or awareness raising and information campaigns could directly target the landlords in order to increase their willingness to initiate long-term lease agreements with corresponding ecological criteria (Wittstock et al., 2022).

Clusters 2 (legumes, reduced mowing, reduced tillage, rotational fallow, reduced soil pressure) and Cluster 3 (flower strips, extensive grazing, cover crops, no mineral fertilization) have similarities with respect to the importance of knowledge and habits/routines. The major differentiator is that Cluster 2 practices require very little (or even no) additional workforce/time, whereas implementing Cluster 3 practices requires few material resources, but may well imply additional working time. Moreover, beliefs in pro-environmental consequences can have a high motivating effect for Cluster 2 practices, but not for those in Cluster 3.

The results of our study could, albeit with caution, provide insights regarding new agri-environmental practices: if a (new) practice fits reasonably well into a certain cluster, suitable supportive policy instruments could be identified faster. This may also apply to the use of empirical behavioural data for the parameterisation in modelling studies. This might meet an important challenge in modelling (Elsawah et al., 2020; Schlüter et al., 2017). For instance, if the impact of a policy on a new practice shall be tested by a model but empirical behavioural data are not yet available, empirical insights from practices falling in the same cluster may be used as first proxy for the parameterisation of the behavioural model component. Clearly this has to be done with caution and the impact should be tested by a sensitivity analysis.

4.3 Discussion of Methods

With this paper we made first steps towards a grouping of agricultural practices based on similar behavioural drivers. The cluster analysis pointed towards three groups of practices. The clusters identified turned out to be fairly robust (see SM2). One practice (buffer strips) formed a cluster of its own. This may be due to the small sample size or may reveal a “true outlier” that is substantially different from all other practices in terms of its behavioural determinants (e.g. reflecting that buffer strips are legally required, so farmers do not have much choice in adopting them). The construction of a robust typology of agri-environmental practices, which could be used to inform policy processes, would require developing our approach further. First, more data points would be needed to make the quantitative analysis – especially clustering – more reliable. In addition, follow-up studies could interview farmers instead of experts, or combine interviews with both groups using appropriate methodologies (e.g., Braito et al., 2020, Leonhardt et al., 2022). We opted for expert opinions in order to obtain generalised responses that allowed for reliable results from a limited sample size. As farmers will necessarily base their assessments primarily on their experiences within their personal farm context, their assessments may reveal substantial differences to those of experts (see Brown et al., 2021; Rommel et al., 2023; Gütschow et al., 2021). Some experts in our study had difficulties in rating the behavioural factors (especially social opportunities), because of the differences in farmers' personalities and personal circumstances. We aimed to assess farmers' needs for the uptake of the respective practices generally and across different systems and regions. Characteristics of both farmers and the farming context are of course likely to influence the relevance of the practices studied and possibly also the importance of behavioural drivers for their implementation. A similar study focusing on a specific context, e.g. large arable farms in a specific region, might enlighten the relevance of these considerations. Alternatively, this heterogeneity can be addressed by surveying or interviewing farmers while using farm typologies to reduce and structure the heterogeneity (Bartkowski et al., 2022; Huber et al., 2024).

The Theoretical Domains Framework served as the theoretical foundation of our study, adapted to the agricultural context. Whereas overall the adapted TDF factors seem to have worked well, an adaptation of the TDF framework to the agricultural context may still benefit from further adjustments. For instance, the differentiation between *knowledge* and *skills* proved challenging in the agricultural context, as skill acquisition often requires corresponding knowledge. Several experts pointed out that the physical capabilities, such as operating machinery, are fundamental prerequisites in the farming profession.

5 Conclusion

Based on expert interviews and the Theoretical Domains Framework (TDF) for categorizing drivers of behaviour change, this study explored the relevance of different behavioural factors for the implementation of agri-environmental practices. Cluster analysis was used to specify groups of practices characterised by similar barriers or needs from the perspective of farmer behaviour. The analysis revealed three robust clusters. One of these clusters, consisting of agroforestry, permanent grassland, and hedges, stands out as a prominent example: implementation of the practices in this cluster is overall very demanding for farmers and difficult to reverse, and it requires in particular a strong future-orientation, a favourable legal context without short-term leases, and financial resources. Since the agri-environmental practices within any particular cluster group can require similar interventions for supporting farmers with their adoption, the results may help prioritise support mechanisms in policy design for sustainable agriculture. Additional research could replicate our approach based on farmer interviews and an increased sample size.

Statement on Competing Interests

The authors hereby declare that they have no competing interests.

Authors' Contributions According to the Credit Guideline

- Julian Rode: Conceptualization, Methodology, Writing - Original Draft
- Bartosz Bartkowski: Conceptualization, Methodology, Formal analysis, Writing - Review & Editing
- Nina Büttner: Formal analysis, Investigation, Data Curation
- Birgit Müller: Conceptualization, Methodology, Writing - Review & Editing

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