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Interdisciplinary study into the association between farmer-scientist collaboration, farmers' proenvironmental behaviors, and barn owl conservation in Switzerland

MILLIET Estelle

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Faculté de biologie
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par

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Master of Science in Behaviour, Ecology and Evolution
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Jury

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Prof. Francesca Amati

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Summary

The environment is facing unprecedented degradation due to human activities, notably agricultural intensification, urban expansion and transportation. Therefore, urgent and comprehensive conservation solutions are necessary. Agriculture, due to its substantial influence on biodiversity, must be at the center of these solutions, and recognizing the key role of farmers in implementing sustainable practices is essential for leveraging agriculture's potential to conserve biodiversity.

In this thesis, we explored the factors motivating Swiss farmers to engage in pro-environmental agricultural practices, with a focus on their collaboration with scientists from the University of Lausanne. This collaboration is centered around a project for the conservation of the barn owl (*Tyto alba*), which began in the 1990s with the installation of artificial nest boxes in western Switzerland. This study aimed to assess whether this collaboration was associated with farmers' attitudes and behaviors towards science and the environment. Additionally, we estimated the influence of agricultural practices on the barn owl breeding success and nest occupancy.

In the first chapter, we presented a systematic literature review in order to evaluate the current understanding of the effect of collaboration on farmers' pro-environmental behaviors. In the second chapter, we analyzed the factors predicting farmers' self-reported attitudes towards science and pro-environmental attitudes and behaviors, focusing on differences between farmers who collaborate with the research group and those who do not. The results showed that collaborators had more positive attitudes towards science than non-collaborators, but there were no differences in their pro-environmental attitudes or behaviors. The third chapter explored how attitudes towards science and the environment relate to actual on-farm measures of pro-environmental behaviors. Pro-environmental attitudes were found to predict sustainable practices, emphasizing the importance of considering psychosocial variables when studying farmers' pro-environmental behaviors. In the fourth chapter, we evaluated the effect of land use changes since the 1990s on barn owl breeding success and nest occupancy. Additionally, the short-term effects of biodiversity promotion areas, urban areas and nest box density on barn owl breeding success and nest occupancy were investigated in the last chapter. These two chapters highlight the resilience of barn owl and the critical importance of maintaining agricultural landscape heterogeneity for biodiversity conservation.

In conclusion, this thesis emphasizes the importance of social factors in conservation research, advocating for the recognition of farmers as essential allies in biodiversity conservation. The study contributes valuable insights into the dynamics of farmer-scientist collaborations and emphasizes the need for inclusive, interdisciplinary approaches to address the pressing challenges of environmental degradation and biodiversity loss by bridging the gap between ecology and social psychology.

Résumé

L'environnement est confronté à une dégradation sans précédent due aux activités humaines. Il est donc nécessaire et urgent de trouver des solutions globales en matière de conservation. L'agriculture, en raison de son influence marquée sur la biodiversité, doit être au centre de ces solutions. Reconnaître le rôle clé des agriculteurs dans la mise en œuvre de pratiques durables est essentiel pour tirer parti du potentiel de l'agriculture en matière de conservation de la biodiversité.

Cette thèse explore les facteurs qui motivent les agriculteurs suisses à s'engager dans des pratiques agricoles pro-environnementales, en mettant l'accent sur leur collaboration avec des scientifiques de l'Université de Lausanne. Cette collaboration est centrée sur un projet de conservation de l'Effraie des clochers (*Tyto alba*), qui a débuté dans les années 1990 avec l'installation de nichoirs artificiels en Suisse romande. Cette thèse vise à évaluer le lien entre cette collaboration et les comportements pro-environnementaux des agriculteurs et leurs attitudes à l'égard de l'environnement et de la science.

Dans le premier chapitre, nous avons effectué une revue systématique de la littérature afin d'évaluer la compréhension actuelle de l'effet de la collaboration sur les comportements pro-environnementaux des agriculteurs. Dans le deuxième chapitre, nous avons étudié les facteurs prédisant les attitudes à l'égard de la science, ainsi que les attitudes et comportements pro-environnementaux auto-déclarés des agriculteurs, en se concentrant sur les différences entre les agriculteurs qui collaborent avec le groupe de recherche et ceux qui ne collaborent pas. Les résultats montrent que les agriculteurs qui collaborent ont des attitudes plus positives à l'égard de la science que les non-collaborateurs, mais qu'il n'y a pas de différences dans leurs attitudes ou comportements pro-environnementaux. Dans le troisième chapitre, nous avons exploré la manière dont les attitudes à l'égard de la science et de l'environnement sont liées aux mesures réelles des comportements pro-environnementaux dans les exploitations agricoles. Il s'avère que les attitudes pro-environnementales prédisent les pratiques durables, soulignant l'importance de considérer les variables psychosociales lors de l'étude des comportements pro-environnementaux des agriculteurs. Finalement, les deux derniers chapitres ont évalué le lien entre l'intensification de l'agriculture et l'expansion des zones urbaines depuis les années 1990, ainsi que les zones de promotion de la biodiversité, et le succès de reproduction de l'Effraie des clochers. Ces deux chapitres mettent en évidence la résilience de l'Effraie des clochers et l'importance cruciale du maintien de l'hétérogénéité des paysages agricoles pour la conservation de la biodiversité.

En conclusion, cette thèse souligne l'importance des facteurs sociaux dans la recherche sur la conservation, en plaidant pour la reconnaissance des agriculteurs en tant qu'alliés essentiels dans la conservation de la biodiversité. L'étude apporte des informations précieuses sur la dynamique des collaborations entre agriculteurs et scientifiques et souligne la nécessité d'approches inclusives et interdisciplinaires pour relever les défis pressants de la dégradation de l'environnement et de la perte de biodiversité en comblant le fossé entre l'écologie et la psychologie sociale.

General introduction

We are at the dawn of the sixth mass extinction – an event attributed to the actions of a single species (Barnosky et al. 2011; Cowie et al. 2022). Human activities have escalated to an aberrant scale, leading to the irreversible degradation of our environment (IPCC 2023). Agricultural intensification, deforestation, urban expansion, or transport contribute to the exploitation of natural resources and the decline of biodiversity worldwide (Maxwell et al. 2016). This crisis, unprecedented in modern times, poses profound challenges to our ecosystems, economies, and ways of life. It is not just an environmental issue, but a complex societal problem that requires urgent and comprehensive solutions. However, the solutions to this crisis are as complex as its causes, requiring significant changes in behavior, policy, and collaboration across all levels of society. To date, emphasis has been primarily placed on the ecological and biological aspects of conservation, often overlooking the critical role of the social aspects (Bennett et al. 2017a). Yet, conservation is fundamentally about people and the choices they make, and the success of conservation initiatives is intimately tied to the ability to influence human behavior (Mascia et al. 2003; Ehrlich and Kennedy 2005; Schultz 2011). Thus, a greater emphasis on human psychology is essential for the future of conservation efforts (Kareiva and Marvier 2012).

The field of conservation psychology emerges as a key discipline in this context, focusing on "*understanding why people act in environmentally sustainable or unsustainable ways, and to use this understanding to promote more environmentally sustainable behavior*" (Clayton and Brook 2005). This perspective challenges the traditional biology-centric model, which risks misdiagnosing problems and proposing ineffective solutions. Instead, recognizing the central role of human attitudes and behaviors in shaping our environment encourages the adoption of multidisciplinary strategies (Kareiva and Marvier 2012). Such strategies necessitate navigating across disciplinary boundaries and incorporating social sciences to inform the development of conservation plans that are culturally, politically, and socioeconomically viable in addition to ecologically (Chan et al. 2007; Bennett et al. 2017b).

Knowing that agriculture is one of the main pressures on biodiversity (Maxwell et al. 2016; IPCC 2023), farmers play a crucial role as practitioners being key actors in biodiversity conservation due to the high potential for conservation measures to be implemented in agricultural fields (Perfecto and Vandermeer 2010; Tscharntke et al. 2005; Tscharntke et al. 2012). Agricultural land, when managed extensively, provides several ecosystem services, such as increased soil fertility, water regulation, or increased carbon sequestration (Swinton et al. 2007; Wittwer et al. 2021). The adoption of sustainable agricultural practices by farmers can therefore make a significant contribution to conserving biodiversity while maintaining agricultural productivity. Farmers have extensive knowledge of local conditions and can adapt conservation measures to local ecosystems. In addition to the financial incentives provided by subsidies to implement such measures, many farmers have an intrinsic motivation based on their reliance on natural resources and climatic conditions for agricultural production, making them uniquely placed to appreciate the benefits of biodiversity conservation and willing to invest in long-term sustainable practices (Riley 2011; de Snoo et al. 2013). Therefore, they should be recognized as critical partners in biodiversity conservation and involved in developing and implementing conservation policies and strategies (de Snoo et al. 2013). However, not all farmers are equally engaged in pro-environmental behaviors. Some show reticence or face barriers to fully adopting sustainable practices. Additionally, those who are committed often find their efforts silenced (Lucas 2021), with society tending to over-accuse them of being the most and only culprits. This overlooks the reality that many farmers are actively engaged in, or open to, sustainable practices. Recognizing and understanding the factors that motivate farmers to adopt sustainable practices is essential to addressing this misrepresentation.

The role of agriculture in conservation has been increasingly recognized in policy-making, leading to the implementation of a variety of measures aimed at promoting sustainable agricultural practices worldwide. Several countries have adopted policies to promote wildlife-friendly agriculture and have launched specific programs to enhance farmland biodiversity on agricultural lands (OECD 2023). In Europe, the Common Agricultural Policy (CAP), introduced in 1962, created the Agri-Environment Schemes in the 1980s (European Union [EU] Regulation 797/85). These schemes have been instrumental in promoting landscape protection, farmland biodiversity, and natural resources conservation by financially supporting farmers who engage in pro-environmental practices (Polman and Slangen 2007; Batáry et al. 2015). To get financial support, farmers are required to allocate at least 5% of their land to ecological focus areas (Regulation 1307/2013), with plans to increase this requirement to 10% in the period 2023-

2027 (European Commission, 2024). In Switzerland, in order to get direct payments, farmers have been required since 1993 to allocate at least 7% of their agricultural land as Biodiversity Promotion Areas (BPAs) (OFAG, 2024). These areas are an integral part of the Swiss Agricultural Policy, which provides subsidies to farmers to enhance the ecological quality of their land (OFAG-OPD, 2024). The effectiveness of BPAs in conserving biodiversity is now being rigorously evaluated, with higher subsidies being offered for areas of higher quality that support higher ecological values and ecosystem functions (Aviron et al. 2009; OFAG-OPD, 2024). Plans to expand effective BPAs by 2025 include increasing the allocation of arable land to at least 3.5%, prioritizing habitats such as wildflower strips for their significant ecological benefits. These areas strengthen ecosystem services, support small mammal populations leading to enhanced raptors and other predators' food sources, increase pollination, and boost farmland bird populations (Aschwanden et al. 2005; Arlettaz, Krähenbühl, et al. 2010; Sutter et al. 2018; Zingg et al. 2019).

Engaging in collaborative projects with governmental agencies, NGOs, or research institutions has been shown to positively influence farmers' commitment to nature conservation (Lobley et al. 2013). Such collaborations serve as a mechanism for generating new knowledge through social learning between professionals from various fields. Collaboration plays an important role in bridging different knowledge systems, combining insights from different fields to improve understanding and implementing sustainable practices (Tengö et al. 2014; Bodin 2017). These collaborative efforts not only facilitate the production of new knowledge (Fazey et al. 2013) but also improve farmers' environmental awareness, which in turn could positively influence their pro-environmental behaviors, as demonstrated among the Swiss population and students from the United States respectively (Frick et al. 2004; Meinhold and Malkus 2005). Through collaboration, farmers can receive accurate information or field-applicable advice on sustainable on-farm practices, as they have been developed jointly. This could in turn increase their willingness to implement measures that promote biodiversity (Gabel et al. 2018).

One particular type of collaboration is between farmers and scientists, which emerges as a central tool for promoting pro-environmental behaviors in agricultural practices (Amel et al. 2017; Bennett et al. 2017b; Farwig et al. 2017). This partnership goes beyond traditional scientific collaboration, which has historically been limited to academic or professional circles and is often isolated from the broader community (Farwig et al. 2017). To effectively address the multifaceted challenges of conservation and sustainability, it is essential to expand these collaborations to include a diverse array of stakeholders – ranging from the general public and practitioners in various fields to those directly impacted by research results, such as farmers – as evidenced by Arlettaz, Schaub, et al. (2010) and proposed by many others (Braunisch et al. 2012; Laurance et al. 2012; Young et al. 2014; Farwig et al. 2017). These broader collaborations not only help demystify scientific concepts (Young et al. 2014; Roche et al. 2022) but also enrich scientists' understanding of practical, real-world contexts and applications (Balmford et al. 2012). Indeed, scientific research alone is not sufficient to address complex conservation challenges (Billaud et al. 2020), and practical implementation must take into account a range of scientific evidence when implementing conservation measures to ensure their effectiveness (Bennett et al. 2017b; Landis 2017). Scientists, with their expertise in environmental monitoring and assessment techniques, provide a theoretical basis for conservation efforts and can analyze the environmental impact of agricultural practices on the environment. Meanwhile, farmers contribute by providing access to their land for study and by sharing their observations and experiences, which may not be apparent from scientific data alone, and carry out the practical implementation on the ground, ensuring that conservation initiatives are feasible and sustainable. This exchange of knowledge and data is essential for providing concrete, actionable feedback to farmers (Tengö et al. 2014; Bennett et al. 2017a). This feedback loop, facilitated by farmer-scientist collaboration, ensures that agricultural practices evolve in harmony with ecological conservation efforts, which requires effective communication and collaboration between these two sectors. To improve farmers' influence on the environment, it is of main importance that the field of ecology evolves and becomes more interdisciplinary and accessible to practitioners (Robinson 2006), thus increasing farmers' interest in pro-environmental behaviors (de Snoo et al. 2013). By integrating ecological knowledge with insights from social psychology, it is possible to explore and understand the motivations of farmers towards pro-environmental practices (Clayton and Brook 2005). Agricultural practices should contribute to the fight against climate change and biodiversity loss, and no longer be a pressure factor, but rather a lever for the ecological transition.

In this thesis, we focus on a specific collaborative project that has been carried out in Switzerland. In the mid-1980s, Prof. Alexandre Roulin from the University of Lausanne initiated a project to install nest boxes for the barn owl (*Tyto alba*) on agricultural barns, thereby starting a long-term collaboration between scientists and farmers. This cosmopolitan raptor species is highly dependent on agriculture and mostly hunts small mammals in agricultural areas (Frey et al. 2011; Roulin 2020). It is therefore a valuable ally for farmers, who can reduce their use of rodenticides in the presence of barn owl, as a pair of barn owls consumes around 800 prey items during the short 62-day chick-rearing period per breeding attempt alone (George and Johnson 2021; Schalcher et al. 2023). Originally, barn owls nested in cavities in old trees or in structures such as bell towers and barns. However, modern trends of renovation and reconstruction have significantly reduced the availability of natural nesting sites for these birds (Roulin 2020). The intensification of agriculture and the loss of natural nesting sites thus contributed to the decline of their population in Europe and in Switzerland in the 1990s (de Bruijn 1994; Newton 2004; Altwegg et al. 2006; Roulin 2020). The most effective solution identified thus far is the installation of artificial nest boxes in their natural habitat, mainly agricultural areas. Alexandre Roulin's first nest box had been installed in Payerne, Switzerland, in 1980. By 1985, three nest boxes had been installed in the same region, and over the years, an average of about ten nest boxes were added each year. Currently, nearly 400 nest boxes are visited annually by Alexandre Roulin's research group at the University of Lausanne in collaboration with the Swiss Ornithological Institute, actively monitoring barn owl populations in western Switzerland (Fig.1). This project has not only contributed to the conservation of this specific barn owl population, but has also created a unique relationship between scientists and farmers as well as a large and valuable dataset that has contributed to the in-depth study of barn owls, from their habitat preferences (e.g. Séchaud et al. 2021; Bühler et al. 2023; Schalcher et al. 2023) to their genetics (e.g. Uva et al. 2018; Cumer et al. 2022) and behaviors (e.g. Roulin and Ducrest 2011; San-Jose et al. 2019; Becciu et al. 2023; Schalcher et al., 2023) to name just a few.

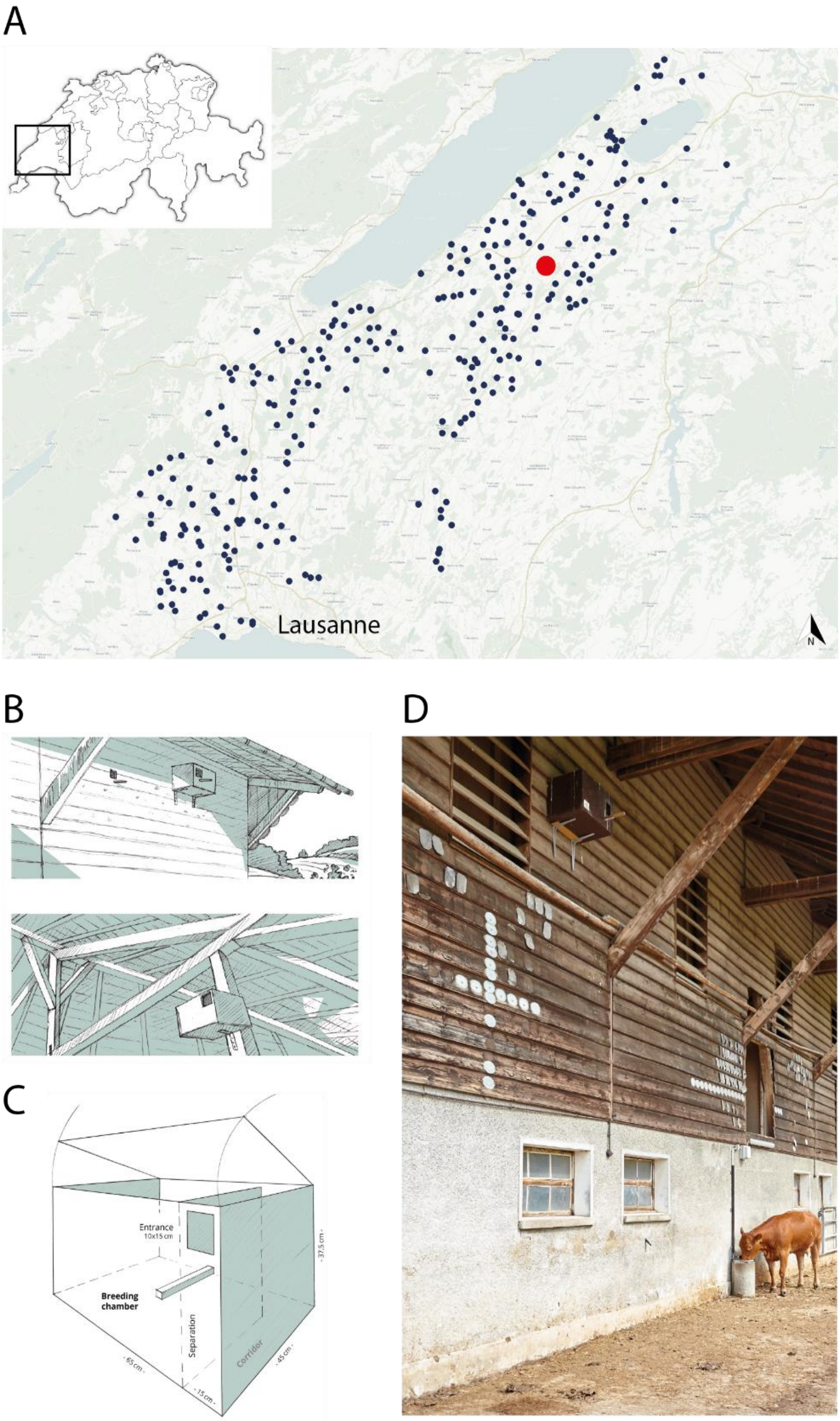

Figure 1 : Illustration of the collaboration project: *(A) All nest boxes installed by Alexandre Roulin's research group in an area of 1000 km² in Western Switzerland, with Payerne, where the first nest boxes were installed, indicated in red; (B) Representation of barn owl nest boxes installed on barns, with nest boxes being usually placed either inside or outside barn walls; (C) Scheme of a nest box, with internal dimensions ©Laurent Willenegger for the artwork from Roulin (2020); (D) Picture of a nest box being placed outside of a barn ©Jeremy Bierer*

Despite more than 30 years of collaboration between farmers and scientists, the farmers' experience of this collaboration has not been explored yet. So far, the interaction between farmers and scientists has been focused on the biological aspects of the projects disregarding the social aspects and focusing on the barn owl as the main research subject. However, the mere fact that scientists are studying a bird on farmers' property should influence how farmers view research, the scientific world, but also on their engagement towards biodiversity conservation. This is the focus of the present thesis, which aims to bridge biology and social psychology. The aim of this project is to consider the social aspect of this farmer-scientist collaboration, and to assess how such interdisciplinary collaboration influences farmers, both in their perceptions of the scientific world and in their sustainable farming practices. Furthermore, we aim to estimate the impact of agricultural practices and land use changes on barn owl breeding success and nest box occupancy, to provide concrete information and feedback to farmers interested in the conservation of this species.

In the first chapter, we conducted a systematic literature review focusing on collaboration between farmers and other people regarding sustainable farm management and practices. Specifically, we analyzed 44 published scientific papers on collaboration between farmers and any other people, to understand the state of knowledge in this specific area and to identify the existing research gaps. With this review, we aimed at contributing to the understanding of farmers' pro-environmental behaviors by highlighting the critical role of collaboration. We found an overall positive effect of collaboration on farmers' pro-environmental behaviors, which encourages future collaboration with them.

Then, in the second chapter, we focused on the specific collaboration between Swiss farmers and the scientists from Alexandre Roulin's research group. We estimated whether this collaboration is associated with farmers' self-reported pro-environmental behaviors, by comparing farmers who collaborate with the scientists through the installation of a nest box with farmers who do not. We extracted data on their attitudes towards science and towards the environment, to assess whether the collaboration could also influence such measures. Through questionnaires sent to farmers each year in 2020, 2021, and 2022, we had access to their concrete attitudes towards the scientific world, as well as their engagement towards ecology and the environment, in relation to their collaboration with scientists. Our results show that Swiss farmers' are already well engaged towards pro-environmental practices, with no differences between collaborators and non-collaborators. However, collaborators showed higher trust towards science than non-collaborators over the years, showing the importance of concrete collaboration with scientists in improving attitudes towards science.

In chapter three, our objective was to explore the predictive power of attitudes towards science and the environment on structural measures of pro-environmental behaviors. We analyzed various on-farm measures, including the proportion of high-quality biodiversity promotion areas and their richness, to estimate farmers' actual commitment to pro-environmental practices. Our results highlight the key role attitudes towards the environment play in predicting such behaviors among Swiss farmers, emphasizing the importance to consider and integrate psychosocial variables in the study of pro-environmental behaviors.

In the last two chapters, we aimed to return to the starting point of this collaboration, which is the conservation of the barn owl, and to provide concrete recommendations to farmers interested in joining the project. In Chapter 4, our goal was to assess the adaptability of barn owls to land use changes since the 1990s, focusing on both the intensification of agricultural practices and the expansion of urban areas. Although our results emphasized the remarkable resilience of barn owls, the critical role of landscape heterogeneity emerged as an important factor influencing barn owls breeding performance and nest box occupancy. Finally, in Chapter 5, we further analyzed barn owl breeding success and nest box selection according to specific factors that farmers can consider when installing a new nest box. We specifically focused on biodiversity promotion areas, urban areas, and surrounding nest box density. Our results highlight the importance of biodiversity promotion areas such as extensive pastures and hedgerows for barn owl breeding success and nest box occupancy, as well as specific nest box characteristics. Overall, this chapter bring key information to provide targeted recommendations for farmers on optimal nest box installation practices.

Overall, this thesis marks a major shift in our research group's approach, bridging the gap between social sciences and ecology. For the first time since 1990, we have moved beyond the traditional view of farmers as mere facilitators of nest box installation for barn owl studies. Instead, we now recognize and value their role as partners in scientific research and biodiversity conservation. This paradigm shift not only enhances our understanding of agricultural practices, but also serves as a trigger for raising environmental awareness and promoting sustainable practices among farmers.

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Chapter 1

The effect of collaboration on farmers' pro-environmental behaviors – a systematic review

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The effect of collaboration on farmers' pro-environmental behaviors – A systematic review

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ABSTRACT

Given the impact of agriculture on the environment, pro-environmental farming practices are growing in importance. Collaboration has an essential role to play in addressing environmental problems and promoting pro-environmental behaviors. As ecosystems are interdependent and diverse, their management is shared among numerous groups of people who are bound to collaborate to achieve common objectives. Through their farming practices and behaviors, farmers have a key role to play in protecting the environment, and by collaborating with each other or with other experts in ecology, objectives at a larger environmental scale could be achieved. However, a systematic review of the effect of collaboration on farmers' pro-environmental behaviors has not been conducted yet. We identified and reviewed 44 articles published in peer-reviewed scientific journals. We classified the articles into 4 categories reflecting reasons for collaboration: program participation, technical training, collaboration among farmers, and peer influence. Moreover, to consider the hierarchical structure in which collaboration unfolds, we differentiated between symmetrical and asymmetrical collaboration, allowing us to estimate whether one type of collaboration is more efficient than another. Overall, collaboration has a positive effect on farmers' pro-environmental behaviors in all four categories, and both in symmetrical and asymmetrical collaborations. The review provides insights for future research directions. In particular, future collaborations with farmers may focus on groups of farmers instead of individuals, as well as on proactively involving them in the decision-making process.

1. Background

The agricultural system of present societies has an undeniable impact on the environment (Foley et al., 2005; Green et al., 2005; McLaughlin & Mineau, 1995; Norris, 2008; Sharpley et al., 2001). With human population constantly increasing, the pressure on farmers to provide more food is rising, prompting them to manage their land in a more intensive way to increase their yields (Baulcombe et al., 2009; McIntyre, 2009; Pelletier & Tyedmers, 2010). However, this has been at the expense of biodiversity, which is inextricably linked to farming as it performs a variety of ecosystem services indispensable for agricultural production (Altieri, 1999; Zhang et al., 2007). Farmers, with their unique position at the intersection of food production and environmental impact, are thereby facing a dilemma, torn between pressure to increase their production and at the same time lower their negative impact on the environment and biodiversity. They thus have a key role to play in preserving the environment on which they rely (Mendelsohn, 2009; Lehmann & Finger, 2013), by adapting their farming practices and behaviors (McLaughlin & Mineau, 1995; Šálek et al., 2018). In line with this, it is of utmost importance to understand which factors can impact their pro-environmental behaviors, defined as any behaviors benefitting the environment or the decision to stop behaviors that harm it (Lange & Dewitte, 2019).

1.1. *The policy-making approach*

In policy-making, an increasing focus is put on farmers' pro-environmental behaviors. For example, in Europe, the Common Agricultural Policy (CAP) was first introduced in 1962 and created the Agri-Environment Schemes in the 1980s (European Union [EU] Regulation 797/85). These schemes aim to protect and enhance landscapes, improve farmland biodiversity, and protect natural resources (Polman &

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Slangen, 2007, p. 31), by financially helping farmers committed to pro-environmental practices, such as organic farming, integrated production, or reduction of fertilizer and pesticide use (Batáry et al., 2015). In the USA, the Government already focused on soil protection in the 1930s, and in 1985 created the Conservation Research Program which aims at increasing the control of soil erosion by proposing direct payments to farmers agreeing to remove environmentally sensitive land from agricultural production and to plant species that will improve environmental health and quality for example (Hellerstein, 2017). However, the availability of such programs is not sufficient to decrease biodiversity loss (Ait Sidhoum et al., 2022; Batáry et al., 2015). There is thus a need to understand what are the factors motivating farmers to behave in a pro-environmental way.

1.2. Predictors of farmers' pro-environmental behaviors

The scientific literature focused on farmers' willingness to take part in conservation programs, considering this willingness as a pro-environmental behavior. For instance, Burton (2014) summarized farmers' demographic characteristics and showed that younger, more experienced, more educated or female farmers engage more easily with environmental programs. Lastra-Bravo et al. (2015) analyzed the factors influencing farmers' decision to join agri-environmental schemes (AES) and disentangled the impact of economic factors and other demographic factors. They found that farmers who highly depend on farm income or involve a high proportion of family labor are less likely to join an AES, whereas larger farms, the absence of a successor on a farm, or previous experience with AES positively affect farmers' willingness to join. Knowler and Bradshaw (2007) focused on the adoption of conservation agriculture worldwide and concluded that there is a lack of universal variables explaining it, emphasizing the need to focus on local conditions to promote adoption. Bartkowski and Bartke (2018) pointed out that financial incentives and constraints have a strong impact on farmers' decision-making, but also other factors such as farmers' pro-environmental attitudes or past experience. Unlike the previous reviews that focused on farmers' participation in conservation programs, our study specifically examines their actual pro-environmental behaviors. This means that we focus on tangible actions taken by farmers to protect the environment, such as sustainable farming practices and resource conservation, rather than merely their enrollment in formal conservation initiatives. Moreover, they focused on individual characteristics, when it has long been recognized that individual conservation efforts need to be articulated with the participation of the wider community (Haenn et al., 2014). In particular, as stated by Bartkowski and Bartke (2018), there is a need to shift the focus to collective understudied factors, such as advisory services and collaborative projects, which have a high potential role in facilitating sustainable practices.

1.3. The collaboration approach

When aiming to decrease human impact on the environment, research shows that it is essential to focus on collaboration among people. Ecosystems are interdependent and various, and their management is spread among numerous people, from land managers to governments, who are bound to collaborate to achieve a common management goal (Bodin, 2017). There are already several collaborative projects especially between various scientists in ecology to find the best solutions for the environment (Cheruvelil et al., 2014). However, despite farmers being the main actors in ecosystem management, there is a clear lack of synthesis on the impact of collaboration between farmers and other people.

Collaboration, which is defined in the present article as any interaction between farmers and other people regarding sustainable farm management and practices, plays a major role in the agricultural world and is an essential tool to increase the production of new knowledge through social learning. It is also important to better connect insights from various knowledge systems, as emphasized by Bodin (2017) and Tengö et al. (2014). Indeed, collaborative projects with governmental agencies, NGOs, or research institutes positively impact farmers' engagement in nature conservation. For example, farmers participating in advisory programs, which are designed to help farmers understand why and how to implement the best ecological on-farm practices, are more confident and positive toward agri-environmental management (Lobley et al., 2013). Such programs can also increase farmers' knowledge about the environment, which has a positive impact on their pro-environmental behaviors (Frick et al., 2004; Meinhold & Malkus, 2005), or give them precise information, which increases their willingness to implement measures promoting biodiversity (Gabel et al., 2018). There is thus a need to focus on collaborative approaches, to estimate in what contexts they are most effective, as highlighted by Bodin (2017). The latter performed an interdisciplinary research on collaborative networks and highlighted the need to understand the effectiveness of collaboration in addressing environmental issues. This involves discerning the types of collaboration, identifying the key actors involved, and understanding their connections within the ecosystem's structures. Collaboration is thus essential for addressing environmental problems, but our understanding of how collaborative network structures contribute to expected outcomes is still not clear enough.

1.4. The present research

Considering the above, we conducted a systematic review of collaboration's effect on farmers' pro-environmental behaviors. The review includes articles published in peer-reviewed scientific journals and aims to answer how collaboration influences farmers' pro-environmental behaviors and whether one type of collaboration is more effective than another.

Let us start by situating the present review in the theoretical framework that guided our analysis. Social Interdependence Theory is a conceptual framework that defines how people interact depending on the social structure in which they are embedded (Johnson & Johnson, 2005). This theory draws from the early work by Deutsch (1949), who was the first to differentiate cooperation from competition focusing on the social structure that organizes interaction between two or more actors, that is, social interdependence. Cooperation occurs when the actors' goals are positively interdependent, and the success of one party requires or implies the success of the other (like within a rowing team). This involves negotiation to achieve a common goal and alignment of different opinions and interests through compromise-making (see also Butera & Buchs, 2019). Competition occurs when the actors' goals are negatively interdependent, and the success of one party requires or implies the failure of the other (like in a swimming race). Cooperation is what interests us here, as we wish to study collaborative actions involving farmers. It should be noted that the terms cooperation and collaboration are sometimes differentiated (e.g., Davidson, 1994; Dillenbourg, 1999) and sometimes merged (e.g., Topping, 1992), but most of the time they are used interchangeably. We will use the term collaboration from now on.

Although collaboration always implies positive interdependence (common goals), the hierarchical structure within the group can be either more horizontal or more vertical, and therefore give way to either, symmetrical or asymmetrical collaborations, respectively. Symmetrical collaboration is described as an interdependent relationship without hierarchy between two or several actors (Duveen & Psaltis, 2008). Such relationships usually imply interaction between actors that hold complementary competencies, roles, or resources (Colomer et al., 2021). Asymmetrical collaboration implies a hierarchy between the different actors, in a classic teacher-learner vertical relationship (Duveen & Psaltis, 2008). Such relationships usually imply interaction between actors that hold different levels of competencies and roles, where higher competence is generally associated with superior status

(Butera & Darnon, 2017). These two types of collaboration have already been studied in other fields, such as firm management or leadership (Glasø et al., 2018; Johnsen & Ford, 2002), but there is a lack of synthesis concerning symmetrical and asymmetrical collaborations with farmers, how they can impact farmers' decision-process in their involvement for biodiversity conservation and whether one is more efficient than the other. The present study will thus focus specifically on symmetrical versus asymmetrical collaborations because these concepts allow us to take into account the hierarchical structure in which collaboration unfolds.

Our main objective is therefore to review and discuss the extent of literature on the role played by collaboration on farmers' pro-environmental behaviors in a very broad way. We wish to contribute to the literature by conducting a comprehensive review, considering all types of collaboration between farmers and other people impacting their decision-making regarding sustainable farming practices, as well as all types of on-farm pro-environmental behaviors. Such a review should result in an overview of what is currently studied in this largely neglected area and what is lacking. We hypothesize that collaboration will have a positive effect on farmers' pro-environmental behaviors, for reasons that pertain to the results obtained within the framework of Social Interdependence Theory (Johnson & Johnson, 2005). Indeed, several meta-analyses have documented the positive effects of working and studying collaboratively, in terms of quality of social relations, self-efficacy, interest in the subject, and learning (e.g., Hattie, 2008; Johnson & Johnson, 1989; Slavin, 1983). It is then possible that collaboration on sustainable farm management and practices may lead to high levels of comprehension and adoption of pro-environmental behaviors. This holds particularly true for symmetrical collaborations, which is the reason why we expect the proportion of studies reporting a positive effect to be larger in studies focusing on symmetrical collaboration compared to those centered on asymmetrical ones. In particular, as stated in the case of firm management by Johnsen and Ford (2002), asymmetrical relationships have a negative impact on the self-esteem and confidence of the parties in subordinate positions. This can then lead such parties to adopt prescribed behaviors for extrinsic reasons (Ryan & Deci, 2000), for example under the form of mere compliance, i.e. behavior change motivated by the superior status of the influence source, which is immediate or manifest, and does not translate in long-term or deep change (Pérez & Mugny, 1996). On the other hand, in symmetrical relationships, skills and knowledge will be developed proactively by all parties (Johnsen & Ford, 2002). In this case, there is a real exchange of knowledge because all actors are free to project their own ideas, analyze the opinions of others, and defend their own independent points of view (Butera et al., 2019). These increased exchanges will lead to the development of new ideas, leading to new shared knowledge (Duveen & Psaltis, 2008; Johnsen & Ford, 2002) and thus to interiorized and long-lasting behaviors.

2. Data and methods

As the general objective of this review is to get an overview of the current state of knowledge on the effect of collaboration on farmers' pro-environmental behaviors, only studies that clearly define this effect are considered.

For the purpose of this study, pro-environmental behaviors were defined following the definition proposed by Lange and Dewitte (2019) as any behaviors that benefit the environment, such as plant native species or wildflower strips, or the decision to stop behaviors that harm it, such as decrease pesticide or fertilizer use. We decided to focus only on on-farm behaviors that are consistent with the definition of "Conservation Agriculture" as described by the Food and Agriculture Organization of the United Nations, which is a farming system preventing arable land loss and regenerating degrading land, based on three interlinked principles, namely "minimum mechanical soil disturbance, permanent soil organic cover, species diversification" (FAO, 2022).

On the other hand, collaboration was defined as any interactions between a farmer and other people regarding sustainable farm management and practices, such as meetings, study groups, trainings, or workshops. To differentiate between symmetrical and asymmetrical collaboration, every article was classified according to the interactions between the different actors: (1) Symmetrical collaboration was attributed when a positively interdependent relationship without hierarchy between the farmers and the other people was described, such as farmers' actively participating in the elaboration of the management plan or discussing the best practices given their own experience. (2) Asymmetrical collaboration was attributed when a hierarchy between the other people and the farmers was described, in a classic teacher-learner vertical relationship, with farmers having the lower status position, such as with experts explaining the best practices to implement without discussing them with farmers.

2.1. Inclusion criteria

To be included in the review, the articles must follow two main criteria: (1) they estimate the effect of collaboration between farmers and any other group of people on pro-environmental behaviors; (2) they study and measure farmers' pro-environmental behaviors, either in an endogenous self-reported way or with exogenous on-farm measurements. To increase the number of studies, we decided to also consider intentions to behave in a pro-environmental way, as intentions are directly linked to behaviors according to the Theory of Planned Behaviors (Ajzen, 1991). However, while we acknowledge this link, it is imperative to bear in mind the potential intention-behavior gap when interpreting the results of studies measuring intentions instead of behaviors.

We included all kinds of collaboration, if there is a measure of its effect on the farmers' pro-environmental behaviors, and then classified them into either symmetrical or asymmetrical categories. No limit on publication date nor location has been applied, nor on study design, as long as there is a measure of the effect of collaboration. The literature search was restricted to English- and French-language peer-reviewed articles, according to the authors' language skills.

2.2. Search

A scoping search, i.e. a brief search of the existing literature on the different themes of the present review, has been performed in February 2022 to determine relevant keywords. The final research process took place in September 2023 and consisted of an extensive literature review conducted on Web of Science including all databases, using the following query:

AB = [(farmer* OR producer* OR "land manager*" OR "land owner*" OR "land employee*" OR "land tenant" OR agricultur* OR grower*) AND (behavio$r*) AND (ecolog* OR environment* OR conservation OR sustainab* OR biodiversity OR agri-environment OR eco-friendly) AND (collaboration* OR cooperat* OR coordinat* OR expert* OR specialist* OR scienti* OR partnership* OR group* OR ecologist*)]

A total of 3697 articles matching the combination search terms were identified. All screening process was performed on Rayyan, an online software for reviews (Ouzzani et al., 2016). After removing the duplicates (128) and screening for all titles and abstracts, 3481 articles were excluded, because they did not meet the inclusion criteria (3470) or because they were inaccessible, after requesting them to the authors (11). The remaining 88 articles were full-text screened: 56 articles were excluded because they did not meet the established criteria and finally, 32 articles were selected to be included in the review. As a final step, a forward search of citations as well as a backward search of references of the 32 selected papers were performed to find any other eligible papers, ending up with 12 additional research papers. In the end, 44 articles were included in the review. The flow chart summarizing the whole selection process is illustrated in Fig. 1. All exclusion reasons for the 3537 articles are available in supplementary material.

To extract information about the effect of collaboration on farmers' pro-environmental behaviors, various factors have been identified for each reviewed paper, such as collaboration type (then classified as symmetrical versus asymmetrical), pro-environmental behavior studied as described previously, and effect of the collaboration on the latter (positive, negative or null). Table 2 presents the exact breakdown of these factors as found in the current review.

3. Results

3.1. Bibliometric results

A total of 44 published studies were identified, from 35 different journals. Most of these journals are categorized into environmental sciences (18), agricultural and biological sciences (15), and social sciences (10). Most studies were published after 2008, and only 2 studies before 2000 (Fig. 2). Analysis of the location of the studies shows that 48% were conducted in developed countries (as classified according to

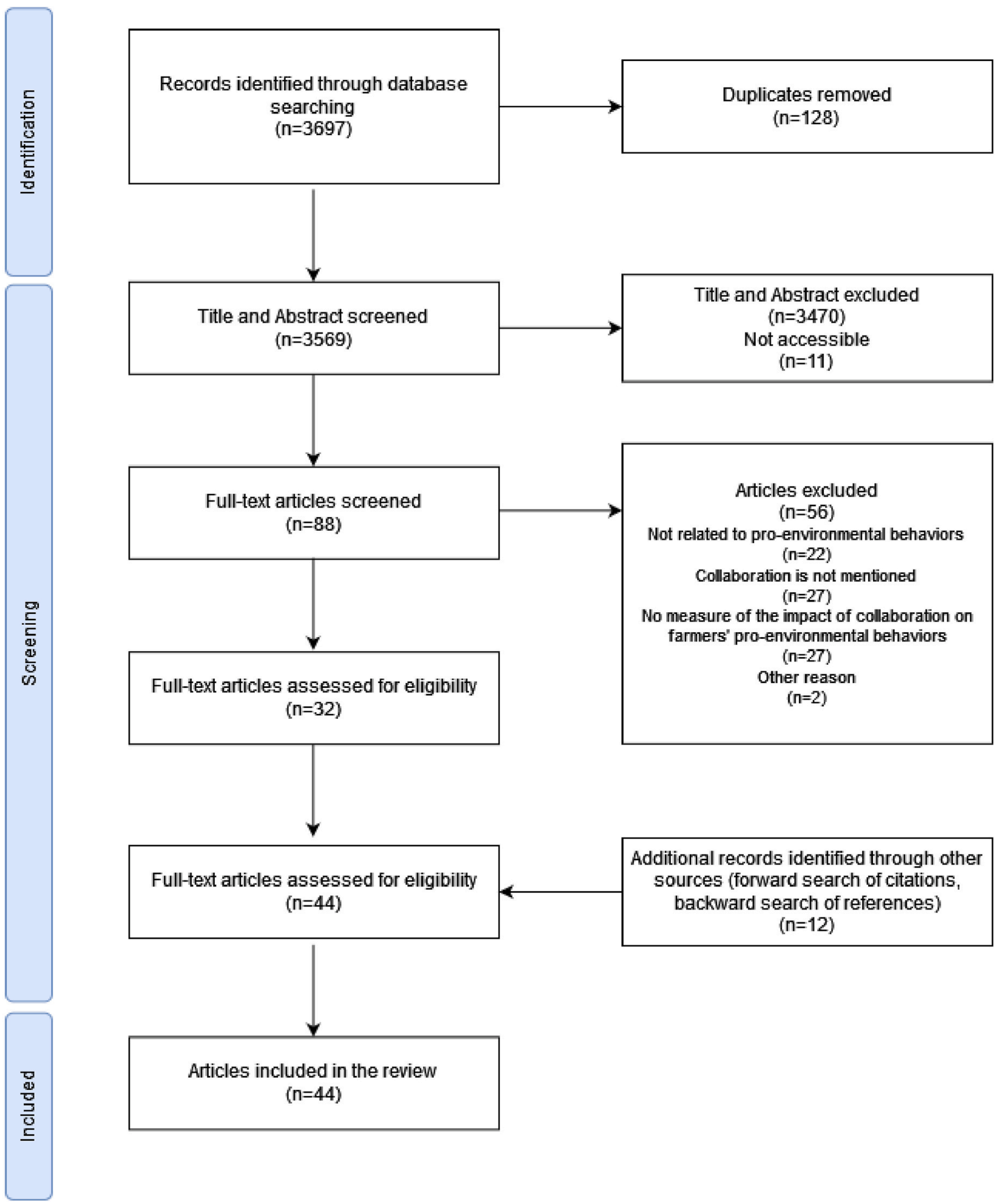

Fig. 1. PRISMA flow diagram for the review, with exclusion reasons. Some articles have several exclusion reasons, explaining why they do not sum up to 56. Adapted from: Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMK 2021; 372:n71. https://doi.org/10.1136/bmj.n71.

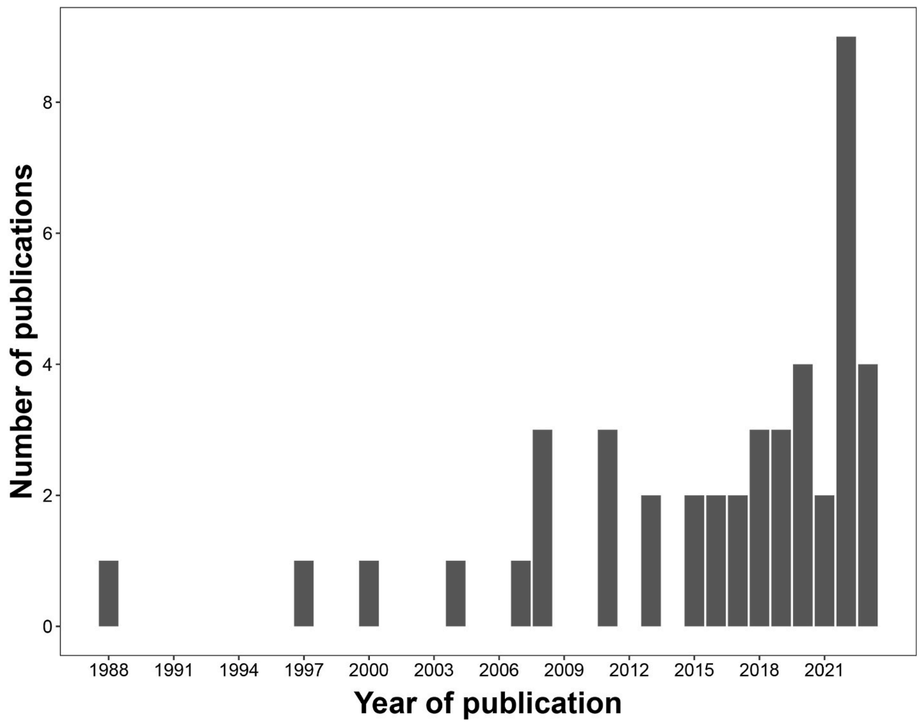

Fig. 2. Temporal distribution of the studies: Distribution of the reviewed studies according to their year of publication.

the Human Development Index (UNDP, 2019)). Differences in results between developed and developing countries are discussed in section 3.3.5 below.

3.2. Overall results

There is a very high variability among the different reviewed papers, and the various research trends, gaps, and shortcomings are summarized in Table 1. The number of participants ranges from 22 to over 4800, with a median of 355 and a mean of 674. The type of analysis conducted is also variable, some studies doing simple statistics such as percentage analysis, chi-square tests, or t-tests, and others deepening the analysis with logit regressions, generalized linear multilevel models, partial least squares modeling, or structural equation modeling.

There is also a high variability in methodologies, from experimental, to cross-sectional, longitudinal, or correlational. Not all of them allow causal claims. We thus considered a positive or negative impact when an independent variable, whatever its nature, predicted a dependent variable with clear causality drawn. Otherwise, we considered a positive or negative effect. Null effect or impact was considered when no statistical significance was reached.

Concerning pro-environmental behaviors, most studies used endogenous self-reported measurements. However, a number of different behaviors were measured, from very specific ones, such as pesticide use, organic fertilizer use, or intentions to incorporate trees in coffee plantations, to very broad measures, testing many different practices (up to 44 different sustainable practices tested in a single study, including management of disease, weed, pest, vine, water, and soil, and alternative energy use). Only two studies assessed pro-environmental behaviors with exogenous measures, one of them measuring livestock loads (number of livestock per hectare), and the other the amount of organic fertilizer used.

Concerning collaboration, it varied both in terms of duration and kind. For example, some papers focused on collaboration lasting for several years, or on collaboration for only a few meetings. Some papers studied collaboration among a large number of different people such as experts in ecology, governments or other farmers and others studied one-to-one collaborations. Moreover, only one paper among the 44 reviewed studied a field experiment involving a collaboration between farmers and scientists from a university.

The connection between collaboration and pro-environmental behaviors took two primary forms in the papers examined: direct and related (or indirect). In the first form, the collaboration directly influences a specific pro-environmental behavior, serving as an incentive for the adoption of that specific behavior. For example, a collaboration may actively promote a particular behavior (such as reducing pesticide use), which is then assessed in the study. In the second form, the link between collaboration and pro-environmental behaviors is indirect or related. Collaboration may foster a range of pro-environmental practices, or raise awareness about broader conservation issues that, while not directly tied to the specific pro-environmental behavior being assessed, contribute to an overall understanding of the importance of environmental conservation. Notably, within the scope of our review, no studies lacked any discernible connection between the collaboration type and the pro-environmental behavior studied. All connections are described in Table 2.

3.3. Results by collaboration groups

In light of the diverse reasons for collaboration found across the selected studies, we undertook a re-classification into four distinct groups to help synthesize the effects. These groups were defined inductively after reading the papers and discovering similarities between them. They correspond to (1) Program participation: when farmers are involved in a specific and well-defined program, with fixed duration; (2) Technical training: when farmers take part in specific training courses, conducted as one-time events; (3) Collaboration among farmers: when farmers work collectively, either through common management or discussions leading to decision-making about agricultural practices; and (4) Peer influence: how farmers are influenced by other farmers, without necessarily direct interaction. Moreover, each article was categorized into symmetrical versus asymmetrical collaboration to estimate whether one type influences farmers' pro-environmental behaviors more than the other. To ensure a

Table 1
Summary of Research Trends, Research Gaps, and Research Shortcomings in the 44 articles selected.

Category	Description
Research trends	Most studies primarily assessed farmers' pro-environmental behaviors as general land management and conservation practices. The second most common aspect of farmers' pro-environmental behaviors examined was pest management, followed by the use of agrochemicals. Among collaboration groups, participation in technical trainings garnered the most research attention, followed by program participation. A majority of the reviewed papers focused on a symmetrical collaboration measurement approach. In nearly all cases, collaboration was linked to pro-environmental practices promotion. In the majority of cases, collaboration was directly linked to the pro-environmental behavior measured. A well-balanced distribution of studies is evident regarding countries' development status, with research conducted in both developed and developing countries.
Research gaps	A limited number of studies focused on specific pro-environmental behaviors (e.g. invasive species management or livestock load). Little research has been conducted on measured and concrete data on actual on-farm pro-environmental behaviors. Notably, no study focused on anti-environmental collaboration, such as collaboration with pesticides or agrochemical producers.
Research shortcomings	Most studies primarily focused on self-reported measures to assess farmers' pro-environmental behaviors. Most of the studies are performing qualitative analyses. Many studies exhibited selection bias of the participants, as they compared farmers participating in a program or a training that was not randomly distributed. Demographic variables, such as age, gender, education level, and farm size, were frequently omitted from the analyses, potentially introducing bias. Some studies lacked control groups for meaningful comparisons or did not use pre-post analyses, thereby limiting the ability to draw causal conclusions. Some studies used intentions instead of actual pro-environmental behaviors.

comprehensive and unbiased classification, we proceeded to a systematic categorization with two authors and compared the independent classifications. When differences in categorization arose, only in two cases, the two authors reached a consensus through thorough discussions on the final classification for each paper.

These groups, types, their effect on farmers' pro-environmental behaviors, and the link between the behavior and the collaboration are listed in Table 2 and outlined in the following sections.

3.3.1. Program participation

Among the 44 reviewed articles, 16 studied the effect of program participation on farmers' pro-environmental behaviors. These programs are specific conservation programs proposed by NGOs (Josefsson et al., 2017; Shaw et al., 2011), governmental agencies (Boz, 2016; Byerly et al., 2021; Drescher et al., 2019; Goodale et al., 2015; Knook et al., 2020; McGinty et al., 2008; Petursdottir et al., 2017), research institutes (Adimassu et al., 2013; Buyinza et al., 2020; Forté-Gardner et al., 2004; Lentijo & Hostetler, 2013; Márquez-García et al. 2018, 2019), or groups of stakeholders (Campbell et al., 2011). Symmetrical collaborations included participatory programs, which aim at involving farmers in the decision-making, problem identification, and management process. Asymmetrical collaborations included programs giving information to farmers about conservation measures and pro-environmental practices through meetings, reports, or expert advice.

Within program participation, most of the studies focusing on *symmetrical collaboration* were found to have a positive effect on farmers' pro-environmental behaviors. Adimassu et al. (2013) and Campbell et al. (2011) both focused on watershed management and found that farmers behave more pro-environmentally when participating in collective management programs in Ethiopia and in the USA, respectively. The positive effect of participation is emphasized by Campbell et al. (2011), who compared participants in a collective management watershed with non-participants in the same watershed, and found that participating farmers adopt more best management practices, such as using cover crops, planting vegetated buffers or using reduced tillage farm practices, especially when participating to meetings. However, they also compared two different watersheds, one with collective management and one without, and did not find any difference between the two. Program participation was also found to positively influence farmers' motivation to adopt agroforestry practices in Uganda, through a project for increasing tree plantation: the T4FS project (Buyinza et al., 2020). Farmers might not be aware of programs' effect, as found by Knook et al. (2020), who focused on Participation Extension Program (PEP) in Scotland and found that PEP-participants have higher pro-environmental behavior scores than non-participants, even if they do not explicitly state that it is because of their participation. Some programs offer the opportunity for experimental projects. A notable example is the study by Forté-Gardner et al. (2004), which examined the impact of the Ralston Project in the USA, a field experiment involving both scientists and farmers and aiming at estimating the "economic, environmental and agronomic feasibility of reduced tillage and continuous spring cropping systems". They found that participation in this project positively impacts farmers' intentions to adopt new technologies, such as the use of no-till drill, crop stubble, or spring crop cycle. It is the only article focusing on a collaboration between farmers and scientists from a university. Pro-active management from farmers was found deeply important by Drescher et al. (2019), who compared two different conservation programs in Canada both providing tax relief to enrolled farmers: Conservation Lands Tax Incentive Program (CLTIP), which has no management plan and proposes only 1-year contracts to farmers, and Managed Forest Tax Incentive Program (MFTIP), which asks farmers for a clear management plan and proposes 10-years contracts. They found that MFTIP has a positive effect on farmers' invasive species management, as more MFTIP participants than expected removed invasive species and planted native ones, compared to CLTIP which has a null to negative effect on the adoption of those two practices. Some studies also found null effects of such programs. Márquez-García et al. (2018) compared two different education programs in Chile, one conventional with technical training and outdoor activities and one participatory, involving farmers in decision-making, but found no differences between the two on various pro-environmental actions. McGinty et al. (2008) found that participation in an agroforestry program did not influence farmers' intentions to adopt agroforestry practices in Brazil. However, farmers' intentions to implement sustainable practices are positively influenced when participating in a bird conservation program in Sweden (Josefsson et al., 2017). Finally, participation in a rangeland restoration program did not have an effect on rangeland management and restoration practices in Iceland, even if participants were more aware of the potential of such restoration, as shown by Petursdottir et al. (2017).

Reviewed studies also focused on *asymmetrical collaborations*, through programs offering information and advice by experts in ecology to interested farmers. Most of those programs are based on farmers' willingness to get involved, and their effects vary. For example, sustainability winegrowing programs are found to be effective in promoting pro-environmental behaviors, as shown by Márquez-García et al. (2019) in Chile and by Shaw et al. (2011) in California. Participation in a bird conservation project had a positive effect on farmers' knowledge about birds, but not on their conservation practices in Columbia (Lentijo & Hostetler, 2013). Boz (2016) also focused on participation in a specific program in Turkey, which provides precise on-farm advice and promotes sustainable practices, such as crop rotation, use of animal manure, or proper use of chemical fertilizers and pesticides, and found a positive

Table 2
Summary of findings of the different groups of collaboration on various pro-environmental behaviors and how they were measured. See the text for details. Effect symbols indicate a positive and significant effect (+), not significant (N), and negative and significant effect (−).

Group of collaboration	Type of collaboration	Country development status	Behavior	Measure of behavior	Connection between collaboration and behavior	Effect	Reference
Program Participation	Symmetrical	Developed	Invasive species management	Self-reported	Related	+	Drescher et al., 2019
			Land management and conservation practices		Direct		Forté-Gardner et al., 2004; Knook et al., 2020
						N	Petursdottir et al., 2017
					Related		Márquez-García et al., 2018
						N/+	Campbell et al., 2011
		Developing			Direct	+	Adimassu et al., 2013
				Intentions		+	Josefsson et al., 2017
			Adoption of agroforestry practices			+	Buyinza et al., 2020
						N	McGinty et al., 2008
	Asymmetrical	Developed	Land management and conservation practices	Self-reported	Direct	+	Márquez-García et al., 2019; Shaw et al., 2011
						N	Goodale et al., 2015
					Related	+	Boz, 2016; Byerly et al., 2021
		Developing			Direct	N	Lentijo and Hostetler, 2013
Technical Training	Symmetrical	Developed	Land management and conservation practices	Self-reported	Direct	+	Hillis et al., 2018
		Developing					Quang et al., 2019
	Asymmetrical	Developing	Agrochemical use	Self-reported	Direct	+	Cui & Liu, 2022; Liu, K. Shi et al., 2022
					Related		Matous & Todo, 2018; Yang et al., 2023
			Pest management		Direct	+	Liu, R. Shi et al., 2022; Flor & Singleton, 2011; Zhou et al., 2020
						N	Li & Jin, 2022
		Developed			Direct	+	Bager & Proost, 1997; Thomas et al., 1988
Technical Training	Asymmetrical	Developed	Pest management	Self-reported	Related	+	Ohmart, 2008
				Intentions	Direct		Jowett et al., 2022
			Land management and conservation practices	Self-reported	Related	+	Beedell & Rehman, 2000
					Undefined		Lubell & Fulton, 2007
		Developing			Direct		Ataei et al., 2022; Faridi et al., 2021; Gao et al., 2023; Xiuling et al., 2023
						N	Liu et al., 2023
Collaboration among farmers	Symmetrical	Developed	Livestock load	Measured	Related	+	Di Falco and Van Rensburg, 2008
			Pest management	Self-reported	Related	+	Bager & Proost, 1997; Ohmart, 2008
		Developing			Direct		Li & Jin, 2022
			Land management and conservation practices		Direct	+	Deng et al., 2022
					Related		Faridi et al., 2021; Liu et al., 2023
			Adoption of new technology	Intentions	Related	+	Sarkar et al., 2022
			Agrochemical use and pest management	Self-reported	Related	+	Yang et al., 2023
Peer influence	Symmetrical	Developed	Bioenergy crops adoption	Intentions	Direct	+	Huang et al., 2016
			Land management and conservation practices	Self-reported	Related	+	Byerly et al., 2021
		Developing			Direct		Gao et al., 2023; Liu et al., 2023; Ma et al., 2022
			Adoption of agroforestry practices	Intentions	Direct	+	Buyinza et al., 2020
			Pest management	Self-reported	Direct	+	Zhou et al., 2020
						N	Li & Jin, 2022
			Agrochemical use		Direct	+	Cui & Liu, 2022
					Related		Matous, 2015; Matous & Todo, 2018; Yang et al., 2023
	Asymmetrical			Measured	Direct		Vu et al., 2020

effect on only 6 out of 16 practices, the other 10 practices being equally used by program participants and non-participants. Byerly et al. (2021) studied farmers' participation in 5 major conservation programs that provide rental payment, financial resources, and assistance in the USA, and found that farmers adopt more biodiversity management practices, including cover crops, or hedgerows and native grasses planting when participating in those conservation programs. Goodale et al. (2015) studied a conservation program in Canada which provides visits, inventories, and personalized conservation reports to farmers and compared the use of various sustainable practices by program participants and non-participants. Interestingly, they found that only practices promoted by the program, namely riparian management and modified harvesting techniques, were more adopted by participants than non-participants but found no differences for the other 8 practices not promoted by the program.

The overall effect of program participation on farmers' pro-environmental behaviors is positive, even if a few studies found null effects. These differences seem to depend on various factors, such as farmers' proactive engagement, but also on the program itself, how advice is provided to farmers, and the region where the program is taking place. There is no clear difference between symmetrical and asymmetrical collaborations among program participation, both having in majority positive effects.

3.3.2. Technical training

Technical training is considered here as any collaboration between a farmer and an expert in ecology, in the context of a specific event, as opposed to program participation which involved a subscription to a program and thus a longer-term contract. We identified 21 studies investigating the effect of such technical training on farmers' pro-environmental behaviors. These trainings are provided to farmers by voluntary partnerships (Hillis et al., 2018; Ohmart, 2008), NGOs (Quang et al., 2019), Universities (Jowett et al., 2022; Matous & Todo, 2018; Quang et al., 2019; Thomas et al., 1988), agricultural cooperatives (Liu, R. Shi et al., 2022 ; Liu, K. Shi, et al., 2022;), Government (Bager & Proost, 1997; Cui & Liu, 2022; Faridi et al., 2021; Flor & Singleton, 2011; Li & Jin, 2022; Yang et al., 2023; Zhou et al., 2020), advisory groups (Ataei et al., 2022; Beedell & Rehman, 2000; Gao et al., 2023; Xiuling et al., 2023) or local agencies (Lubell & Fulton, 2007). As in the case of program participation, these technical trainings were classified into two different types: (i) symmetrical trainings, which takes into account farmers' expertise together with experts'; (ii) asymmetrical trainings, which gives direct information to farmers through workshops or personal advice.

Two articles highlight the effect of *symmetrical* training (Hillis et al., 2018; Quang et al., 2019), in two different ways. Hillis et al. (2018) focused on sustainability partnerships in California, which bring together people from many different fields such as growers, industry partners, or consumers, to propose different sustainable activities promotion such as field meetings, newsletters, or certification programs. They found that the probability of adoption of sustainable practices, such as disease, weed, or pest management, is positively associated with partnership participation, with a stronger effect for the least financially costly practices. Quang et al. (2019) estimated the effect of transformative learning in two different environments in Vietnam, both involving farmers to test new technologies and then demonstrate them with sample fields to other farmers. They found that this type of learning leads to changes in farmers' perceptions and agricultural practices.

Nineteen articles concentrate on *asymmetrical* trainings (Thomas et al., 1988; Bager & Proost, 1997; Beedell & Rehman, 2000; Lubell & Fulton, 2007; Ohmart, 2008; Flor & Singleton, 2011; Matous & Todo, 2018; Zhou et al., 2020; Faridi et al., 2021; Ataei et al., 2022; Cui & Liu, 2022; Jowett et al., 2022; Li & Jin, 2022; Liu, R. Shi et al., 2022 ; Liu, K. Shi, et al., 2022 ; Gao et al., 2023; Liu et al., 2023; Xiuling et al., 2023; Yang et al., 2023), and the majority of them found positive effect on various pro-environmental behaviors. Four studies focused on agrochemical use: Matous and Todo (2018) compared the same technical training given at various distances from farmers' hometowns in Indonesia and found that further training has the highest effect on organic fertilizer use. This study is highly interesting, as the authors added the influence of the distance between training and farmers' hometowns and thus the collaboration between people with different farming habits. Cui and Liu (2022) found a positive effect of technical services provided by the government on farmers' chemical fertilizers reduction behaviors in China, which was also found by both Liu, K. Shi et al. (2022) and Yang et al. (2023), who both examined Chinese farmers' organic fertilizers use when participating in technical trainings. Technical trainings provided by government-affiliated agricultural technicians in China were also found to decrease the use of pesticides by Zhou et al. (2020), and technical trainings provided by agricultural cooperatives, which group various farmers together, have also a positive effect on biopesticide adoption in higher educational-level group, as found by Liu, R. Shi et al. (2022). Xiuling et al. (2023) compared various types of technical training, focusing on online versus offline trainings, and found an overall positive impact on farmers' water-saving irrigation technology adoption, depending on farmers' demographics such as age, education level, and farm size. This was confirmed by Gao et al. (2023), who compared traditional versus new agricultural technology trainings and also found a positive impact of both trainings, depending on the same demographics. Finally, Liu et al. (2023) also focused on Chinese farmers and found that agricultural extension training attendance had no impact on farmers' rice-crayfish integrated system adoption. Land management practices were also found to be positively influenced by technical trainings in other countries: Beedell and Rehman (2000) focused on advisory groups providing technical trainings to farmers in the United Kingdom and found that participants have consistently higher self-reported pro-environmental behaviors than non-participants. Technical trainings held by the Ministry of Agriculture has a positive effect on water and soil conservation measure adoptions in Iran, as found by Faridi et al. (2021), and also on general intentions to adopt practices of conservation agriculture, as found by Ataei et al. (2022). Lubell and Fulton (2007) looked at technical trainings provided by experts from local agencies in the USA and found a positive effect on best agricultural management practices adoption, such as orchard plantation. Seven studies focused on pest management practices: Bager and Proost (1997) and Thomas et al. (1988) studied the effect of consulting with an extensionist and scouting services provided by specialists, respectively. Bager and Proost (1997) found a reduction in pesticide use for farmers in close contact with extensionists in Denmark, but not in the Netherlands, while Thomas et al. (1988) found a positive effect on the advised integrated pest management practices in the USA. Ohmart (2008) studied the effect of a workbook given to farmers to self-assess their integrated farming practices in the USA and found an increase in integrated pest management use after this workbook was implemented. Flor and Singleton (2011) studied the impact of a campaign promoting Ecological Based Rodent Management (EBRM) practices in the Philippines and found that farmers participating in the intensive campaign, comprising consultations with rat experts, visits by extension staff, demonstrations of the recommended methods and exposure to the promotional material have a significant and positive impact on farmers' EBRM adoption. Li and Jin (2022) and Yang et al. (2023) both focused on Chinese farmers' pesticide use. While Yang et al. (2023) found a positive impact of technical trainings provided by the government on farmers' biopesticide use, Li and Jin (2022) found no effect of technical training participation. Finally, Jowett et al. (2022) found that technical training participation had a positive impact on future intentions to adopt integrated pest management practices in the United Kingdom.

Overall, technical training seems to be effective in promoting farmers' pro-environmental behaviors. There is no difference between symmetrical and asymmetrical collaborations, both having positive effects. However, there is a bias towards asymmetrical collaboration in this category, as many more studies focused on it compared to symmetrical ones.

3.3.3. Collaboration among farmers

Nine studies focused on collaboration among farmers, be it through cooperation with other farmers (Faridi et al., 2021), common management of lands (Deng et al., 2022; Di Falco & Van Rensburg, 2008; Li & Jin, 2022; Liu et al., 2023; Sarkar et al., 2022; Yang et al., 2023) or study groups (Bager & Proost, 1997; Ohmart, 2008). All papers from this category were classified as symmetrical collaboration.

Four papers measured collaboration in a self-reported way (Faridi et al., 2021; Li & Jin, 2022; Liu et al., 2023; Yang et al., 2023), asking farmers to state whether they cooperate with other farmers or not, or whether they are members of a cooperative. Faridi et al. (2021) found a marginally significant positive effect of collaboration on the water and soil conservation measures adoption. Li and Jin (2022) and Liu et al. (2023) also found that cooperative membership had a positive impact on pesticide use and rice-crayfish integrated system adoption, respectively.

Also when not self-reported, cooperative membership was found to have a positive effect on groundwater protection behaviors by Deng et al. (2022). However, Yang et al. (2023) found no impact of cooperative membership on organic fertilizer use or on biopesticide use. Two studies focused on the effect of collective management on farmers' pro-environmental behaviors (Di Falco & Van Rensburg, 2008; Sarkar et al., 2022) and in both studies, groups of farmers manage their land together and make decisions together. Sarkar et al. (2022) focused on cooperative organizations and their effect on farmers' intentions to adopt environmentally friendly technology and found positive results. Di Falco and Van Rensburg (2008) focused on common grazing resource management in Ireland and found that collaboration in these commonages positively influences livestock load, involving a decrease in livestock load with collaboration. The effect of study groups is also found to be positive, as shown by Bager and Proost (1997) and Ohmart (2008), who reported a significant effect on pesticide use and pest-management, respectively. The study groups were organized by a third party in Ohmart's (2008) study. The only not significant result was for farmers from the Netherlands in the study of Bager and Proost (1997), who found that group discussion had a positive effect on farmers' attitudes and knowledge towards pesticide use, but not on behaviors per se.

In sum, collaboration among farmers seems to be a promising tool to promote pro-environmental behaviors, as most of the studies found a positive effect. However, there is a lack of studies focusing on this, as shown by the low number of reviewed articles classified in this category.

3.3.4. Peer influence

The effect of peers on farmers' pro-environmental behaviors has been studied in thirteen of the reviewed papers (Buyinza et al., 2020; Byerly et al., 2021; Cui & Liu, 2022; Gao et al., 2023; Huang et al., 2016; Li & Jin, 2022; Liu et al., 2023; Ma et al., 2022; Matous, 2015; Matous & Todo, 2018; Vu et al., 2020; Yang et al., 2023; Zhou et al., 2020) and the majority found a significantly positive effect. This category of collaboration is slightly different from the others, as there is not always a proper interaction between farmers. However, it is still interesting to review such studies because farmers are indirectly influenced by their peers, as in some studies farmers are positively interdependent in terms of information exchange, even if they are not directly interacting. It was thus decided to keep these studies, even if they do not exactly fit the definition of direct collaboration. Peer influence is measured in different ways, from considering neighbors' pro-environmental behaviors in farmers' decision-making (Buyinza et al., 2020; Cui & Liu, 2022; Gao et al., 2023; Huang et al., 2016; Liu et al., 2023; Ma et al., 2022; Zhou et al., 2020), visioning a video of farmers relating their experience with organic fertilizer use (Vu et al., 2020), the influence of discussions among farmers (Li & Jin, 2022; Matous & Todo, 2018; Yang et al., 2023) or farmers' self-reported source of information concerning pro-environmental practices (Byerly et al., 2021; Matous, 2015).

Seven articles measured peer influence in a self-reported way (Byerly et al., 2021; Cui & Liu, 2022; Li & Jin, 2022; Liu et al., 2023; Ma et al., 2022; Matous, 2015; Yang et al., 2023). Byerly et al. (2021) asked farmers to state their source of information for sustainable practices, while Matous (2015) asked them to specifically name the people from whom they seek advice to create a social network of the interactions between farmers but also with other people, such as experts. Byerly et al. (2021) found a positive effect of peer influence on biodiversity management practices adoption. In the case of Matous (2015), they analyzed the internal, external, and reciprocal links among different groups of farmers in Indonesia, functioning as organizations and comprising approximately 20 farmers per group. He found that a lack of reciprocal links and extra-group links are related to a lack of conservation efforts and unproductive practices, respectively. Whether farmers exchange with peers was found to have a positive impact on organic fertilizer use depending on farm size by Yang et al. (2023), however, no effect was found on pesticide use by Li and Jin (2022). In the case of Cui and Liu (2022), Ma et al. (2022), and Liu et al. (2023), farmers had to state whether their surroundings (neighbors, friends, relatives) adopted various pro-environmental behaviors such as chemical fertilizer reduction or rice-crayfish integrated system adoption, and all found positive impact on farmers' own pro-environmental behaviors, depending on the farm scale for Cui and Liu (2022). The effect of neighbors was found to be highly important in four studies (Buyinza et al., 2020; Gao et al., 2023; Huang et al., 2016; Zhou et al., 2020). In addition to testing the effect of direct technical training on farmers, Zhou et al. (2020) tested the effect of neighbors' technical training on farmers and found that when their neighbors participated in the training, farmers decreased their pesticide use. In the same trend, Buyinza et al. (2020) investigated how neighbors to farmers who actively participated in a conservation project were influenced and found that social norms have a high effect on intentions to integrate trees into coffee plantations. In the case of Huang et al. (2016), they based all their analysis on a model simulation, taking into account neighbors' behavior concerning bioenergy crop adoption, and found that farmers tend to manage their land in the same way as their neighbors. Finally, Gao et al. (2023) analyzed how the number of neighbors adopting fertigation technology affected the time to adopt them and found an overall positive effect, depending on farmers' age, education level, and farm size. Matous and Todo (2018) analyzed the social networks of farmers according to the distance to the training site, and found that farmers trained further were more trusted by their non-trained peers concerning organic fertilizer adoption, because they had access to new knowledge not available in their communities. Lastly, Vu et al. (2020) focused on the effect of a 3-min video of farmers sharing their experience with organic fertilizer use and found that farmers are more likely to shift their fertilizer use to organic one after watching the testimony.

Overall, farmers seem to be highly influenced by their peers, tending to adapt their farming practices accordingly. This last category is more difficult to classify between symmetrical and asymmetrical collaboration, as no exact details on the interaction between farmers and peers were given. However, we considered that when farmers are discussing together practices (Li & Jin, 2022; Matous & Todo, 2018), referring to their source of information (Byerly et al., 2021; Matous, 2015), or when they are taking into account their neighbors' behaviors (Buyinza et al., 2020; Cui & Liu, 2022; Gao et al., 2023; Huang et al., 2016; Liu et al., 2023; Ma et al., 2022; Yang et al., 2023; Zhou et al., 2020), the collaboration is symmetrical. On the contrary, when no clear interaction happens, as in the case of watching a video (Vu et al., 2020), the collaboration was defined as asymmetrical.

3.3.5. Countries development status

Interestingly, differences emerged when comparing research conducted in developed and developing countries. We observed that developed countries place a greater emphasis on program participation, with 12 studies dedicated to this aspect compared to only 4 for developing countries. On the other hand, developing countries studied more technical trainings, with 15 articles exploring this facet, in contrast to 7 in developed countries. Concerning the type of collaboration, developing countries are more focused on symmetrical collaboration, as evidenced by 21 articles against 10 for developed countries. Asymmetrical collaboration shows a more balanced distribution, with 15 studies in developing countries and 12 in developed ones. Additionally, we noted a temporal difference in research distribution. Older papers tend to be concentrated in developed countries, while younger publications are more prevalent in developing countries.

4. Discussion

This review has analyzed an increasing body of literature on the effect of collaboration on farmers' pro-environmental behaviors. Empirical research has focused on various types of collaboration, which were classified into four groups: program participation, technical trainings, collaboration among farmers, and peer influence. Overall, collaboration has a positive effect on farmers' pro-environmental behaviors, as 33 studies had strictly positive results, while the other 11 found either no effect or various effects depending on the pro-environmental behaviors or on the program studied (Table 2), confirming the first hypothesis stating that collaboration has a positive effect on farmer's pro-environmental behaviors.

It is worth noting that none of the studies included in the present review reported a negative effect of collaboration on pro-environmental behaviors. However, this could be due to potential confounding factors or methodological limitations of the studies, as highlighted in Table 1. One potential source of bias is the presence of selection bias among various included studies, especially the ones about program participation. Moreover, the majority of reviewed studies relied on self-reported measures to assess pro-environmental behaviors. Although self-reporting is a prevalent method for behavior measurement in the current literature, its validity is still debated, as discussed in the review by Kormos and Gifford (2014) and identified by Koller et al. (2023). Additionally, six studies included in the present review used intentions as a proxy for actual pro-environmental behaviors. While intentions are known to be linked to behaviors as reported by the Theory of Planned Behaviors by Ajzen (1991), there is a gap between intentions to behave and actual behaviors, as reviewed by Sheeran and Webb (2016) and found for farmers by Zhou et al. (2023). Given these considerations, it is imperative to keep in mind the potential disparities between reported intentions and observed behaviors when drawing conclusions from the studies.

No clear difference could be highlighted between symmetrical and asymmetrical collaborations in the various categories, both having positive and null impacts, rejecting the second hypothesis stating that the proportion of studies reporting a positive effect would be larger in studies focusing on symmetrical collaboration. However, a lack of symmetrical collaborations was highlighted in technical trainings.

The studies varied in terms of collaboration, pro-environmental behaviors measured, or type of analysis done, making it difficult to draw overall conclusions. Such high variability among studies shows that they do not belong to an established field with uniform methods, measures, and protocols, but on the contrary, to a whole new subject that is studied in various ways and without a clear experimental approach. Moreover, few studies fitted the inclusion criteria, showing the emergence of this subject in the scientific literature. This review is thus the first to summarize the effect of collaboration on farmers' pro-environmental behaviors, at least to our knowledge. The analysis done is thus purely qualitative, allowing a sensible synthesis, but preventing the estimation of the relative strength of the different categories and types of collaboration in determining farmers' pro-environmental behaviors.

Some reviewed studies found no effect on farmers' pro-environmental behaviors, but on other factors, such as knowledge (Lentijo & Hostetler, 2013), engagement in other collaborative activities (Petursdottir et al., 2017), or awareness of the importance of pro-environmental behaviors such as restoration (Petursdottir et al., 2017). Even if it does not reach behavioral change yet, these results are promising as the collaboration has a positive effect on factors that could influence behaviors. Indeed, it is known that knowledge and involvement affect the behaviors (Meinhold & Malkus, 2005), suggesting that, in the long term, collaboration may positively influence the behaviors as well.

Within studies finding a positive effect of collaboration, we highlighted several recurring factors that may have a major role to play in promoting farmer's pro-environmental behaviors. One of them is the importance of farmer's proactive engagement. This is particularly highlighted by Drescher et al. (2019), who showed that only programs involving farmers in the management plan and in the long-term have an impact on their conservation behaviors. Being engaged in the decision-making, farmers are more concerned and feel more connected to the environment, which increases their pro-environmental behaviors. This was shown in a meta-analysis by Mackay and Schmitt (2019), who examined whether connection to nature could promote pro-environmental behaviors, analyzing both correlational data and experimental manipulations. They found a positive association between nature connection and pro-environmental behaviors, across various measurements, samples, and demographic characteristics. Pro-active engagement will also increase farmers' awareness and knowledge about the environment and the importance of preserving it, which is a key point in increasing pro-environmental behaviors. As found by Lentijo and Hostetler (2013), one of the main barriers to conservation practices adoption is a lack of environmental awareness, together with a lack of environmental knowledge. Regarding this, it is essential to take into consideration farmer's expertise and to involve them in the decision-making when planning collaborations with them. It is also essential to give them access to information about the environment and its conservation, increasing the communication between the various actors of the collaboration.

Linked to their engagement, it is also essential to increase farmers' awareness of the effect of such collaboration. As described by Knook et al. (2020), farmers participating to Participatory Extension Programs show higher levels of pro-environmental practices adoption but did not attribute this change to their participation. Increasing their consciousness of the utility of such programs will promote a sense of concreteness to their actions, which may have a positive effect on their intentions to behave pro-environmentally (Van Lange & Huckelba, 2021). This could be emphasized through collaboration with scientists, who can directly measure the impact of pro-environmental behaviors on the ecosystem. They can then give direct feedback to farmers, increasing their awareness of the utility and impacts of their efforts. However, this type of collaboration seems to be understudied, as only one study focusing on this type of collaboration was found in the present review (Forté-Gardner et al., 2004). There is thus a clear need for empirical research on the effect of collaboration between scientists and farmers on the latter's pro-environmental behaviors. Future research could also consider collaborations involving scientists, farmers, but also non-scientists (Woutersen et al., 2022), and assess the effects of such collaborations on pro-environmental behavior.

All reviewed studies had a clear connection between collaboration and behavior, except for one which was undefined. As the majority of studies found a positive effect, it is hard to draw conclusions on the difference between direct and related connections. However, it is interesting to note that direct connection seems to be important, as highlighted in some studies, especially by Goodale et al. (2015) who found that only practices promoted by the program are positively influenced by program participation. This is consistent with Ajzen's (1988) principle of compatibility, whereby the constructs (e.g., the content of a training course) measured in association with a specific behavior should involve the same target (see also Sok, Borges, Schmidt, & Ajzen, 2021). For actions to be concrete and relevant, the goal of the collaboration must have a clear link with farmers' practices and behaviors. Farmers need to understand why they are acting in a certain way and what is the goal of their actions. Future collaborations with farmers should thus make sure that the advice given is relevant and achievable. This is supported by studies focusing on several different sustainable practices, not interconnected with one another and not directly linked to the collaboration, which found null results (Boz, 2016; Goodale et al., 2015; Lentijo & Hostetler, 2013; Li & Jin, 2022; Liu et al., 2023; Márquez-García et al., 2018; McGinty et al., 2008; Petursdottir et al., 2017). It is thus important to increase the relevance between advice and practices.

Another interesting result is the effect of peers on farmers' pro-environmental behaviors. Farmers seem to be highly reliant on their peers, be it from study groups, cooperation between them, or mere exposure to neighbors' behavior. This was already demonstrated that in-group interactions are highly efficient in promoting pro-environmental attitudes and behaviors in various studies (reviewed in Fielding &

Hornsey, 2016). This shows the importance of collective actions and management in the agricultural world, as suggested by Pretty (2003) and Batáry et al. (2015). Knowing that governmental programs' objectives to decrease biodiversity loss are not efficient and not specific enough (Batáry et al., 2015; Kaligarič et al., 2019), there is an opportunity to improve their functioning, shifting their focus from individual level to collaborative projects. This would allow the progression from disconnected actions to increased interactions between farms and ecological structures, achieving objectives at the landscape scale in contrast to the farm scale (Whittingham, 2007; EEA, 2010; Pe'er et al., 2014). Focusing on collective and collaborative endeavors and raising awareness among groups of farmers could lead more easily and efficiently to environmental changes, especially knowing that social norms have a positive impact on pro-environmental behaviors (Farrow et al., 2017) and that peer influence is highly important in farmers' decision-making.

Our systematic review encompasses studies from both developed and developing countries. As the goal of the review was to provide a comprehensive overview of the scientific literature, no selection based on the country was made. However, it is essential to keep in mind that pro-environmental behaviors are highly influenced by the cultural context, as reviewed by Tam and Milfont (2020). This was also demonstrated by Wang et al. (2023) for farmers. Moreover, farming systems are radically different between developing and developed countries. Thus, findings from developed countries are not necessarily generalizable to developing ones, and vice versa. These regional nuances underscore the need for context-specific approaches in collaborative pro-environmental initiatives. Interestingly, we found differences in collaboration groups according to the development status of the countries. Overall, developing countries focused more on technical trainings, while developed countries studied more program participation. This potentially highlights the different ways of action according to the development status. Moreover, we found that older studies are concentrated in developed countries, while more recent studies are made in developing countries, highlighting an increased interest in sustainable farming systems in developing countries.

Overall, the results of this review allow a first analysis of what is currently studied on the collaboration between farmers and other people. Collaboration is a mean to increase farmers' pro-environmental behaviors, even if it is essential to keep in mind that effects are not always fond with experimental designs and pre-post measures, which would allow to assess efficacy in terms of behavior change. Future research can expand this analysis in various ways. First, only peer-reviewed articles were included, as the goal was to estimate the current state of knowledge on the impact of collaboration on farmers' pro-environmental behaviors and what is lacking in the empirical research. Through a meta-analysis, it would be possible to take into account other types of literature, such as grey literature, increasing the different types of collaboration considered, decreasing the publication bias towards positive results, and assessing quantitatively the results. Moreover, most of the articles reviewed are from journals related to environmental, biological, agricultural, and social sciences, and only a few of them are related to economics, always with a focus on ecology. This leads to a bias toward ecological studies, together with the fact that most of the studies focus on conservation programs. However, farmers are subject to various pressures, in particular from industries, consumers, or for financial reasons, pushing them towards anti-environmental behaviors. They are thus facing a strong dilemma between increased yields and reduced impact on the environment. It would be interesting to analyze the effect of such pressures on their behaviors, to estimate farmers' struggle, and to consider all impacting factors in farmers' decision-making. However, these types of collaboration seem to be under-studied, or at least were not reflected in our search.

Finally, farmers are part of a specialized group within society, characterized by their close relationship with and responsibilities towards the natural environment. Their whole profession and decision-making processes are deeply entwined with the environment. This intrinsic connection makes them peculiar as compared with other population groups. As a result, findings regarding pro-environmental behaviors among farmers may not readily extend to other groups of the population, such as urban residents or industrial workers. Therefore, while collaboration may yield positive results within the farming community, it is essential to exercise caution when extrapolating these findings to broader societal contexts.

5. Conclusion

The objective of this paper was to assess the role of collaboration in promoting farmers' pro-environmental behaviors, focusing on symmetrical versus asymmetrical collaboration. This approach gives insights about what could be relevant to developing future research directions, but also how collaborations between experts from different fields can be improved. This review found an overall positive effect of collaboration on farmers' pro-environmental behaviors, and no negative effect, which is highly encouraging for future collaborations. However, no difference between symmetrical and asymmetrical collaboration was found. Summarizing the most impacting factors, future collaborations should focus on proactively involving farmers in the decision process. They should concentrate on groups of farmers and not individually, as farmers are highly reliant on their peers. Moreover, it is important to clearly communicate the objectives of the collaboration and to target precise behaviors that are achievable for farmers. And finally, it is essential that farmers are aware of the positive impacts of such collaboration on the environment, to motivate them towards pro-environmental behaviors.

CRediT authorship contribution statement

Estelle Milliet: Conceptualization, Data curation, Investigation, Methodology, Writing – original draft, Writing – review & editing, Formal analysis, Project administration, Visualization, Software. **Céline Plancherel:** Conceptualization, Data curation, Writing – review & editing. **Alexandre Roulin:** Conceptualization, Funding acquisition, Supervision, Writing – review & editing. **Fabrizio Butera:** Conceptualization, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare no competing interests.

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Appendix A. Supplementary data

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Chapter 2

The relationship between a barn owl (Tyto alba) conservation project involving scientist-farmer collaboration and farmers' attitudes and behaviors towards science and the environment in Switzerland

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Abstract

In light of agriculture's significant contribution to global environmental crisis, farmers play a crucial role in biodiversity conservation. It is thus important to explore the drivers motivating them towards sustainable practices. Collaboration between farmers and scientists is a promising tool to promote pro-environmental practices, yet empirical evidence on the outcomes of such collaborations remains sparse. In this study, we aim to empirically assess the association between a long-term scientist-farmer collaboration and farmers' attitudes and behaviors towards science and the environment. Using survey data collected across three consecutive years, we compared farmers collaborating in a barn owl (*Tyto alba*) conservation project with non-collaborators. Our findings reveal a complex interplay between collaboration and farmers' social-psychological constructs. Collaborators exhibited significant improvement in trust towards science, particularly between the first and second surveys, while non-collaborators showed gradual improvements. Both groups enhanced their pro-environmental attitudes over time. Finally, collaboration was not associated with self-reported pro-environmental behaviors, which improved across all farmer groups over time. Moreover, our analysis suggests that self-reported pro-environmental attitudes and behaviors can predict attitudes towards science. This study underscores the value of collaboration with scientists in enhancing farmers' attitudes towards science. It also highlights the intricate relationships between attitudes towards science and pro-environmental attitudes and behaviors.

Keywords: agriculture, biodiversity conservation, collaboration between farmers and scientists, ecology, social psychology, sustainable practices

1. Introduction

Farmers play an essential role in sustainable development and biodiversity conservation (de Snoo et al., 2013; Riley, 2011), and scientist-farmer collaborations can bridge the gap between scientific research and practical agricultural application (Amel et al., 2017; Bennett et al., 2017b; Farwig et al., 2017). However, despite the recognized importance of these collaborations, there is a lack of empirical research examining the direct outcomes of such partnerships, particularly their association with attitudes and behaviors towards science and the environment among farmers. A recent review has tackled this issue from a theoretical point of view and found that collaboration generally promotes pro-environmental behaviors among farmers (Milliet et al., 2023). However, collaboration with scientists is notably lacking (Farwig et al., 2017; Milliet et al., 2023), despite the fact that bringing scientists with practitioners has been found to be highly efficient to implement new practices and technologies (Hoffmann et al., 2007). This paper aims to fill this empirical gap by examining the association between a long-term scientist-farmer collaboration and farmers' attitudes and behaviors towards science and the environment.

Collaboration between scientists and the general public

Collaboration is a fundamental aspect of human society. When individuals with diverse educational and research backgrounds collaborate, they can address problems requiring resources and knowledge from multiple disciplines, achieving common goals (Kelly et al., 2023). Throughout history, collaboration has been particularly crucial to the advancement of science and technology, such as collaboration among researchers, but also with industries or local population, across various disciplines, organizations, and cultures, allowing to tackle increasingly complex challenges (Cheruvelil et al., 2014; Daily et al., 1999; Hall et al., 2018; Tengö et al., 2014). Local knowledge and expertise can significantly help scientists in their research. For instance, biologists are working with local communities to inventory exotic species in tropical rain forests (Basset et al., 2004; Janzen, 2004; Novotny et al., 1997; Pfeiffer & Uril, 2003; Sheil & Lawrence, 2004) or to discover regional settlement and archaeological structure in the Amazonia (Heckenberger et al., 2003). However, collaboration between scientists and local people should not only be helpful to scientific research but should also be used as a tool promoting public understanding of science and raising awareness about specific scientific studies (Bonney et al., 2016).

In the actual context of climate change and biodiversity crisis, collaboration between scientists and lay-people can be especially instrumental for addressing environmental problems (Bodin, 2017). Indeed, the latest Intergovernmental Panel on Climate Change report is unmistakable: the negative impact of human activities on the environment is tremendous, including air and water pollution, habitat destruction, and the extinction of various species (IPCC, 2022). Regarding this environmental crisis, it is essential to understand not only how humans interact with their environment, as proposed by Newell et al. (2014), but also to study strategies for influencing and driving human behaviors towards eco-friendlier ones (Amel et al., 2017). This includes examining the mechanisms by which we can encourage pro-environmental behaviors and understanding the factors that motivate individuals to adopt attitudes and behaviors that support nature conservation (Clayton & Brook, 2005). Collaboration with scientists can be an essential tool to promote environmentally friendly practices and enhancing awareness and motivation towards nature conservation (Bennett et al., 2017a). Indeed, engaging with scientists provides individuals with a deeper understanding of environmental challenges and scientific solutions, which is likely to promote pro-environmental behaviors (Lyons & Breakwell, 1994). However, simply communicating scientific findings is not enough to initiate behavioral change, as argued by Perga et al. (2023). Active public involvement in research projects is essential because it builds a comprehensive understanding of outcomes, increasing the likelihood of adopting recommended behaviors (Farwig et al., 2017).

Collaboration between scientists and farmers

While every individual can take steps to reduce their environmental impact, certain professions, such as farmers, have a particularly high contribution to the environment. Agricultural fields can provide many ecosystem services, such as regulation of water, increased biodiversity, and soil protection (Swinton et al., 2007; Wittwer et al., 2021). Therefore, farmers have a key role to play in protecting the environment by adopting more sustainable farming practices, and it is crucial to understand what motivates them towards such practices (de Snoo et al., 2013). Collaboration between farmers and scientists could be a central tool for promoting pro-environmental behaviors in farmland (Amel et al., 2017;

Bennett et al., 2017b; Farwig et al., 2017). This type of partnership goes beyond traditional scientific collaboration, which has traditionally been limited to academic or professional circles and is often isolated from the broader community (Farwig et al., 2017). In addition to promoting pro-environmental behaviors, scientist-farmer interactions can also promote farmers' positive perception of and trust in science. This is particularly important as trust in science may be related to pro-environmental behaviors. Indeed, research found that individuals who trust scientists on issues related to climate change are more likely to engage in pro-environmental behaviors (reviewed by Cologna & Siegrist, 2020). Increased trust in science can help them understand better the importance of the environment and the consequences of its degradation, which could in turn lead to greater pro-environmental behaviors (Duerden & Witt, 2010; Hsu, 2004). Farmers are no exception, as it has been found that they are more willing to implement measures promoting biodiversity when they have a thorough understanding of on-farm biodiversity through specific advice (Gabel et al. 2018). As individuals become better informed about the issues at hand, they are more likely to make conscious choices and take action to protect the environment.

Therefore, by promoting collaboration between farmers and scientists, not only is it possible to promote farmers' pro-environmental behaviors, but also improve their trust in science which could further encourage their pro-environmental behaviors. It can particularly benefit both groups by facilitating the exchanges between them, leading to mutual benefits, and bridging the gap between environmental science and practical farming practices. On the one hand, farmers can gain a deeper understanding of environmental issues and practices, which can increase their attitudes towards science and their pro-environmental behaviors. They would also feel more connected to nature being involved in a conservation project, leading to pro-environmental behaviors (Mackay & Schmitt, 2019). On the other hand, scientists can gain insight into the real-world challenges and constraints faced by farmers, informing their research and conservation efforts. This mutual exchange can lead to the development of more effective and sustainable agricultural practices (Duveen & Psaltis, 2008; Johnsen & Ford, 2002), ultimately helping farmers and scientists to work together to mitigate the impacts of agriculture on the environment.

The present research

In this study, we aim to examine the case of a long-standing collaboration between scientists at a Swiss University and local Swiss farmers to conserve a wild population of barn owls (*Tyto alba*) by installing artificial nest boxes on farmers' barns. Over the past 30 years, this collaboration has allowed scientists to work closely with farmers, demonstrating how data are collected on the field and regularly communicating with them about barn owl clutches in their nest boxes. The objective of the present study is to estimate whether being a collaborator, versus not, in this project is related to farmers' attitudes and behaviors towards science and the environment. The study tracked such attitudes and behaviors over a three-year period from 2020 to 2022. Additionally, we examined how these factors – farmers' attitudes towards science and pro-environmental attitudes and behaviors – are associated with each other during this period. Our hypothesis is that this long-term collaboration should have a positive association with both attitudes towards science (H1) and self-reported pro-environmental attitudes and behaviors (H2). Moreover, as discussed earlier, we expect attitudes towards science to be positively associated with pro-environmental attitudes and behaviors (H3). To estimate this, around 200 Swiss farmers, both collaborators with the research group and non-collaborators in the same region, were interviewed three years in a row with self-reported questionnaires. The longitudinal design was devised to mitigate the non-random assignment of farmers in the two groups.

2. Methods

For this study, survey data were used to investigate the association between scientist-farmer collaboration, on the one hand, and attitudes and behaviors towards science and the environment of farmers, on the other hand, for three years (2020, 2021, 2022). As an example of collaboration between scientists and farmers, we used the specific case of a research group from our university, in Switzerland, which collaborates with local farmers. Using a stratified non-random sampling, we compared farmers who collaborate with the research group with farmers who do not.

2.1 Collaboration between farmers and scientists

In this study, we focused on a specific collaboration between scientists and farmers that has been ongoing for more than 30 years. Since the 1990s, our research group worked with farmers to protect and study a population of free-living barn owls. For years, these birds adapted to breed in traditional barns and other man-made structures (Roulin, 2020). However, with human development such as urbanization and renovation, many old farms where barn owls used to inhabit have disappeared. A simple solution to this problem is to install nest boxes in rural buildings. In the study area, which is located in the Swiss plateau and covers approximately 1'000 km^2, over 300 nest boxes have been fastened against the walls of barns belonging to local farmers, in accordance with them. Scientists visit the nest boxes at least once a month from March to August each year following a strict protocol (Frey et al., 2011), allowing for possible interactions with the farmers.

2.2 Sampling and survey

A total of 482 farmers in western Switzerland (State of Vaud and Fribourg) were invited to participate in this study by responding to a self-administered questionnaire three years in a row (2020, 2021 and 2022), either on paper or online (Table S1). Respondents were all farmers with their farms located on the Swiss Plateau (Fig. 1). Of these 482 farmers, 273 were collaborators, i.e. farmers from the address book of the barn owl project. The non-collaborators (N = 209) were drawn from a list of farmers from state of Vaud, but included farmers located within the same area as collaborators. They were then paired to collaborators and an equivalence analysis was performed to ensure the comparability of the datasets (see section 3.2). We contacted all farmers by phone to explain the goal of the study, and to ask them if they were willing to participate before receiving the questionnaire. The questionnaires were then sent to 156 collaborators and 128 non-collaborators who agreed to participate at the end of January 2020, 2021, and 2022, either by email with a link to open the online survey, or by postal mail with a provided stamped envelope for return (Table S1). Farmers had one month to respond, and a reminder was sent to the non-respondents two weeks after sending the questionnaire. To avoid any mode effect, as recommended by Dillman et al (2014), and to get a unified mode construction of the survey, the same questions were asked on paper and online. Moreover, to estimate the evolution of their responses, the same questionnaire was used for all three years.

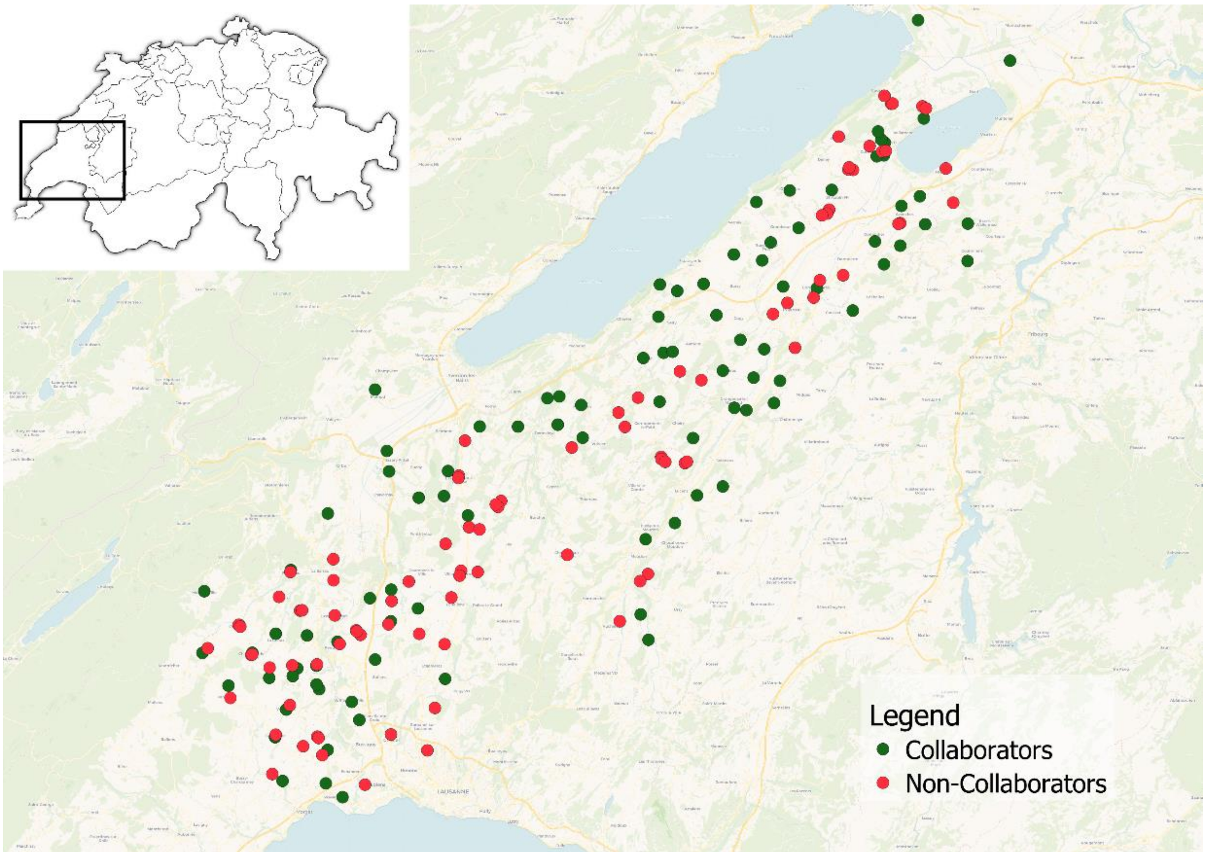

Figure 1: Study area in western Switzerland: Collaborating farmers, who have a barn owl nest box fastened on their farms, are indicated in green and non-collaborating farmers in orange.

2.3 Questionnaire

The questionnaire was divided in 5 parts (see Sup.mat. III for complete list of questionnaire items), inquiring into: (1) Sociodemographic questions to gather data about the respondents (age, gender, civil status, etc.); (2) Questions about their farm (type of agriculture, size of the farm, number of employees, etc.); (3) Questions related to their attitudes towards science. Farmers had to indicate their level of agreement with nine statements concerning science and scientific work on a 5-point Likert scale with options ranging from 5 (*Strongly agree*) to 1 (*Strongly Disagree*), allowing to extract their attitudes towards science. Since this is highly context-specific, we developed our own scale to measure this construct in French (Table S2); (4) Questions related to their attitudes and behaviors towards the environment. Among other questions, farmers had to indicate their level of agreement with 25 statements concerning the environment on a 6-point Likert scale with options ranging from 6 (*Strongly Agree*) to 1 (*Strongly Disagree*). In this case, we used existing scales, notably the New Ecological Paradigm (NEP) scale (Dunlap et al., 2000; Milfont & Duckitt, 2010), supplemented with additional items made by the researchers to add specific agricultural pro-environmental behaviors (based on

Graf et al., 2016) (Table S2). The translation of items from English to French was primarily based on available translated versions (Moussaoui et al., 2016; Schleyer-Lindenmann et al., 2016) (Table S2). For items where translations were not available, or to ensure context-specific relevance, translations were conducted by the research team (Table S2). The statements were divided in three topics: i) Pro-environmental attitudes, defined as perspectives, or values, that farmers hold towards the environment and ecological conservation, including beliefs about human intervention in nature, skepticism towards environmental crisis, prioritization of economic over environmental concerns, and perceptions of climate change; ii) Pro-environmental behaviors, defined as the self-reported behaviors on farm that are favorable for the environment (such as mowing methods), as well as general pro-environmental behaviors (such as power or electricity saving); iii) Perceived collective efficacy of a pro-environmental behavior, defined as the extent to which farmers believe in their ability to reduce agricultural impact on the environment as a farmer community; and (5) Questions related to the research group working with barn owls. The latter was the only differing part between collaborators and non-collaborators, with collaborators having more detailed questions about their relationship with the scientists, while non-collaborators were just asked if they ever heard about the research group (see Sup.mat III b & c).

The participants were informed that the survey was designed to study the relationship between farmers and scientists. The confidentiality as well as the duration of the project were also clearly explained. Online participants generally completed the online questionnaire within 25 minutes. They were thanked for their participation and received a written debrief 9 months later.

2.4 Transparency and openness

We report all data exclusions, and all manipulations following JARS (Appelbaum et al., 2018). All statistical analyses were conducted with R 4.2.1 (R Core Team, Vienna, Austria), with RStudio (RStudio Team, 2020) as graphic user interface. Models were fitted, checked for collinearity between predictors and assumptions were verified using the *performance* package (Lüdecke et al., 2021) and by visually inspecting the residual diagnostic plots. The effects were considered as significant when their p-values were smaller than .05.

This study's design, hypotheses and analyses were not pre-registered. The sample size was determined by the size of the sample of farmers who participated in the barn owl project. Raw imputed data, and log files of the analyses are available on the Open Science Framework (OSF) page of the project.

For the sake of full disclosure, it should be noted that this study also included analyses beyond the scope of this paper. These additional analyses included evaluating the effect of a targeted communication on farmers' attitudes towards science and the environment through the distribution of a booklet containing scientific facts about barn owls. Furthermore, we offered farmers the opportunity to install raptor perches in their fields to assess their commitment to biodiversity conservation. Finally, to enhance the comparative analysis, we included responses from a new group of non-collaborators in the final survey wave. However, results from these supplementary analyses are not discussed in the present article. For interested reader, please contact the corresponding author.

3. Results

All data were anonymized before any analysis, by giving an ID to each farmer that was then kept throughout the three survey waves. The randomness of missing data was checked using the Little's missing completely at random test using the *mcar_test* function from the package *naniar* (Tierney & Cook, 2023) (Table S4). These analyses confirmed that missing data were random, justifying the use of imputations to obtain a complete dataset for the three-years study period. We thus applied predictive mean matching for imputations on missing data, focusing specifically on the items that were to be analyzed subsequently. This imputation was performed using the *mice* function from the *mice* package (van Buuren & Groothuis-Oudshoorn 2011). Notably, missing data constituted 1% of observations for attitudes towards science and 4% for attitudes and behaviors towards the environment.

3.1 Response rate

The response rate for the first survey was 68.7%, as 195 farmers responded completely (103 collaborating and 92 non-collaborating, see Table S1-a). The second survey was sent only to the respondents of the first one (N = 211), and the response rate was 59.2%, as 125 farmers responded (68 collaborators, 57 non-collaborators, see Table S1-b). Finally, the response rate of the third survey was 54.4%, as 206 surveys were sent and 112 farmers responded (64 collaborators, 48 non-collaborators, see Table S1-c). After removing farmers that answered only once (N = 65), and performing imputations for the missing data, a total of 133 farmers' answers were used in the analysis for the first survey, 120 for the second survey and 107 for the third.

3.2 Equivalence analysis and sample description

After applying Bonferroni corrections to account for multiple testing, no significant differences were identified between collaborators and non-collaborators across demographic or agricultural variables, allowing accurate comparison of the two samples (see sup. mat. V). However, it is noteworthy that the datasets were biased towards men (Collaborators: 15 women and 79 men; non-collaborators: 3 women and 91 men). To account for this, analyses were performed both on the entire sample and on a male-only subset. As findings were consistent, it was decided to keep the whole sample.

In terms of farm characteristics, the data revealed a predominance of large farms, with more than half of the respondent having farms exceeding 40 hectares. Despite the size of these farms, the number of employees was low, with nearly 70% of the respondents working with one or two people, in majority family members, and 12% working alone. The farm types in our sample varied, with a majority working on large crops, followed by a combination of diverse agricultural practices, such as cattle farm and crop for example. Concerning the production system, the majority of respondents practiced either in conventional farming (26%) or under the IP-Suisse label[1] (25%) or both (30%), and a smaller proportion of the farmers are operating under the organic label (14%).

3.3 Measurement reliability and validity

To establish construct validity for both "attitudes towards science" and "attitudes and behaviors towards the environment" across the three time points, exploratory factor analyses were conducted using *psych* package (Revelle, 2023). The reliability of the subscales was evaluated, and items that did not align with any factor or that reduced overall reliability were systematically removed. In the end, four factors were identified: "trust towards science",

[1] The IP-Suisse certification label is awarded to Swiss farmers who adhere to integrated production methods. These methods are designed to promote sustainable agricultural practices that exceed statutory environmental protection requirements. The label signifies a commitment to environmentally friendly, animal-friendly, and resource-conserving farming techniques. For more information, see https://www.ipsuisse.ch

“perceived limitation of science”, “ecological attitudes”, and “pro-environmental behaviors”. All details of the analyses can be found in supplementary material VI.

3.4 Effects of collaboration on attitudes towards science and attitudes and behaviors towards the environment

For each farmer and across all survey waves, we calculated the mean score for the items comprising each of the above factors. We then used these mean scores as response variable in linear mixed model using the function *lmer* from the package *lme4* (Bates et al., 2015). Collaboration status in interaction with the survey wave (first, second or third) were used as independent variables, and farmer ID as random intercept. Then, pairwise comparisons were performed using the *emmeans* function from the package *emmeans* (Lenth, 2022) with a *Bonferroni* correction for multiple testing, grouping first by collaboration group to get the evolution over the survey waves and then by survey to compare between the two groups at each survey.

3.4.1 Attitudes towards science

Trust towards science

First, we estimated the interaction between collaboration and survey wave on farmers’ trust towards science (Table 1). The results revealed a significant effect of the survey wave, $F(2, 354) = 33.35, p < .01$, indicating that trust towards science significantly varied across the three surveys. While the effect of collaboration status alone was marginally significant, $F(1, 354) = 2.78, p = .097$, there was a significant interaction between collaboration status and survey waves, $F(2, 354) = 9.32, p < .01$. This indicates that the evolution of trust towards science differed between collaborators and non-collaborators over time (Table 1B).

For collaborators, from the first to the second survey, their trust towards science increased by 1.25 standard deviations, and by 1.22 standard deviations from the first to the third survey. However, no significant change was observed between survey 2 and survey 3 (Table 1C). In contrast, for non-collaborators, their trust towards science increased by 0.53 standard deviations from the first to the third survey, while the changes from survey 1 to survey 2 and from survey 2 to survey 3 were not statistically significant (Table 1C). This was confirmed in the analyses at each survey wave (Table 1C). In the first survey, non-collaborators had trust level 0.39 standard deviations higher compared to collaborators. In the second survey, collaborators exhibited trust levels 0.59 standard deviations higher than non-collaborators. However, no difference emerged in the third survey.

In summary, while collaborators showed a pronounced increase in trust towards science from the first to the second survey before stabilizing, non-collaborators showed a more gradual increase, which became statistically significant only when comparing the first and the last surveys (Fig. 2A).

Perceived limitations of science

Then, we analyzed the effect of the interaction between collaboration and survey wave on the second factor for attitudes towards science, which relates to farmers' perceived limitations of science (Table 2). A higher score in this factor signifies a more negative view of science. The results showed an overall significant effect of the collaboration status, $F(1, 134) = 11.87, p < .01$, indicating distinct attitudes between collaborators and non-collaborators. The effect of the survey wave alone did not reach significance, $F(2, 246) = 2.27, p = .105$, nor did the interaction between survey wave and collaboration status, $F(2, 246) = 1.95, p = .144$ (Table 2B).

The analyses per survey wave (Table 2C) revealed that no differences were found in the first survey, but collaborators had levels of perceived limitations 0.45 standard deviations lower compared to non-collaborators in the second survey. This difference was also observed in the third survey, but to a lesser extent, with collaborators having scores 0.33 standard deviation lower than non-collaborators. However, these differences are only descriptive as no interaction effect was found.

In summary, collaborators displayed an overall lower level of perceived limitations of science (Fig. 2B).

Table 1: Self-reported trust towards science: (A) Descriptive statistics for the self-reported trust towards science for each survey and collaboration group; (B) Results of fitting linear mixed model, with collaboration status, survey wave and their interaction as fixed factors, and farmer ID as random intercept. (C) Results of fitting pairwise comparisons on the linear mixed model between survey within each collaboration groups as well as within each survey between collaboration groups. Significant results are indicated in bold.

(A)	**Descriptive statistics for trust towards science**				
Survey	*Collaboration status*	*Mean*	*SE*	*Lower CI*	*Upper CI*
1	Collaborators	2.77	0.108	2.56	2.99
	Non-Collaborators	3.16	0.117	2.93	3.39
2	Collaborators	4.02	0.114	3.80	4.24
	Non-Collaborators	3.43	0.124	3.19	3.67
3	Collaborators	3.99	0.118	3.76	4.22
	Non-Collaborators	3.70	0.136	3.44	3.97

(B)	**Linear mixed model**				
Variables		*Estimate*	*SE*	*df*	*t-ratio*	*p.value*
(Intercept)	2.773	0.108	354	25.864	<0.01
Second survey wave (S2)	**1.247**	**0.157**	**354**	**7.94**	**<0.01**
Third survey wave (S3)	**1.216**	**0.160**	**354**	**7.61**	**<0.01**
Non-collaborators	**0.385**	**0.160**	**354**	**2.41**	**0.016**
S2: Non-collaborators	**-0.975**	**0.232**	**354**	**-4.21**	**<0.01**
S3: Non-collaborators	**-0.671**	**0.240**	**354**	**-2.79**	**<0.01**

(C)	**Pairwise comparisons**					
Contrasts		*Estimate*	*SE*	*df*	*t-ratio*	*p.value*
Collaborators	**S1 vs S2**	**1.247**	**0.157**	**239**	**7.94**	**<0.01**
	S1 vs S3	**1.216**	**0.160**	**245**	**7.761**	**<0.01**
	S2 vs S3	-0.032	0.164	256	-0.19	1.00
Non-collaborators	S1 vs S2	0.272	0.171	235	1.59	0.337
	S1 vs S3	**0.545**	**0.179**	**250**	**3.04**	**<0.01**
	S2 vs S3	0.273	0.184	263	1.49	0.416
Collaborators vs Non-collaborators	**S1**	**0.385**	**0.160**	**354**	**2.41**	**0.016**
	S2	**-0.590**	**0.168**	**354**	**-3.51**	**<0.01**
	S3	-0.285	0.179	354	-1.59	0.113

Table 2: Self-reported perceived limitations of science: (A) Descriptive statistics for the self-reported perceived limitation of science for each survey and collaboration group; (B) Results of fitting linear mixed model, with collaboration status, survey wave and their interaction as fixed factors, and farmer ID as random intercept. (C) Results of fitting pairwise comparisons on the linear mixed model between survey within each collaboration groups as well as within each survey between collaboration groups. Significant results are indicated in bold.

(A)	**Descriptive statistics for perceived limitations of science**				
Survey	*Collaboration status*	*Mean*	*df*	*Lower CI*	*Upper CI*
1	Collaborators	3.15	352	2.98	3.32
	Non-Collaborators	3.24	352	3.05	3.43
2	Collaborators	3.16	353	2.98	3.35
	Non-Collaborators	3.61	353	3.41	3.81
3	Collaborators	3.10	353	2.91	3.29
	Non-Collaborators	3.42	354	3.21	3.64

(B)	**Linear mixed model**				
Variables	*Estimate*	*SE*	*df*	*t-ratio*	*p.value*
(Intercept)	3.148	0.088	351.99	35.74	<0.01
Second survey wave (S2)	-0.016	0.124	238.63	0.13	0.899
Third survey wave (S3)	-0.049	0.126	243.81	-0.39	0.699
Non-collaborators	0.093	0.130	351.86	0.72	0.475
S2: Non-collaborators	0.355	0.183	236.42	1.94	0.054
S3: Non-collaborators	0.232	0.190	246.50	1.22	0.223

(C)	**Pairwise comparisons**					
Contrasts		*Estimate*	*SE*	*df*	*t-ratio*	*p.value*
Collaborators	S1 vs S2	-0.016	0.124	237	-0.127	1.00
	S1 vs S3	-0.049	0.126	242	0.387	1.00
	S2 vs S3	-0.065	0.130	253	0.498	1.00
Non-collaborators	**S1 vs S2**	**0.371**	**0.135**	**233**	**-2.753**	**0.019**
	S1 vs S3	0.183	0.142	247	-1.288	0.596
	S2 vs S3	-0.188	0.146	259	-1.291	0.594
Collaborators vs Non-collaborators	S1	-0.093	0.130	352	-0.720	0.475
	S2	**-0.448**	**0.137**	**353**	**-3.270**	**<0.01**
	S3	**-0.325**	**0.146**	**353**	**-2.220**	**0.027**

3.4.2 Attitudes and behaviors towards the environment

Pro-environmental attitudes

Then, we examined the factor relating to farmers' pro-environmental attitudes (Table 3). In order to facilitate clearer interpretation of the results, the score, which originally measured negative pro-environmental attitudes, was reversed. This adjustment means that higher values of pro-environmental attitudes represent more positive perception of environmental matters. Results showed a significant effect of survey wave, $F(2, 237) = 35.69, p < .01$, indicating notable changes in pro-environmental attitudes over time. No significant effect of collaboration status was found, $F(1, 129) = 0.16, p = .69$, but a significant interaction between the two, $F(2, 237) = 3.14, p = .045$. This indicate that the trajectory of attitude change differed between collaborators and non-collaborators (Table 3B).

For collaborators, from the first to the second survey, their pro-environmental attitudes increased by 0.94 standard deviations, and by 0.83 standard deviations from the first to the third survey, meaning that their attitudes improved over time. However, the change between survey 2 and survey 3 was minimal and not statistically significant (Table 3C). For non-collaborators, their pro-environmental attitudes increased by 0.45 standard deviations from the first to the second survey and by 0.62 standard deviation from the first to the third survey. As with collaborators, no significant change was observed from survey 2 to survey 3 (Table 3C).

Comparing the groups at each survey wave, there was a tendency only in the first survey, collaborators having scores 0.27 standard deviation lower than non-collaborators ($p = .06$). However, this difference was not observed in the second or third survey (Table 3C).

Overall, both collaborators and non-collaborators enhanced their pro-environmental attitudes over time (Fig. 2C).

Table 3: Self-reported pro-environmental attitudes: (A) Descriptive statistics for the self-reported pro-environmental attitudes for each survey and collaboration group; (B) Results of fitting linear mixed model, with collaboration status, survey wave and their interaction as fixed factors, and farmer ID as random intercept. (C) Results of fitting pairwise comparisons on the linear mixed model between survey within each collaboration groups as well as within each survey between collaboration groups. Significant results are indicated in bold.

(A)	**Descriptive statistics for pro-environmental attitudes**				
Survey	*Collaboration status*	*Mean*	*df*	*Lower CI*	*Upper CI*
1	Collaborators	3.46	0.097	3.27	3.65
	Non-Collaborators	3.73	0.105	3.52	3.94
2	Collaborators	4.39	0.102	4.19	4.59
	Non-Collaborators	4.18	0.111	3.96	4.40
3	Collaborators	4.29	0.105	4.08	4.49
	Non-Collaborators	4.35	0.121	4.11	4.59

(B)	**Linear mixed model**				
Variables	*Estimate*	*SE*	*df*	*t-ratio*	*p.value*
(Intercept)	3.458	0.097	342.9	35.68	<0.01
Second survey wave (S2)	**0.936**	**0.131**	**230.2**	**7.15**	**<0.01**
Third survey wave (S3)	**0.829**	**0.134**	**234.9**	**6.21**	**<0.01**
Non-collaborators	0.270	0.143	342.3	1.88	0.06
S2: Non-collaborators	**-0.484**	**0.193**	**228.2**	**-2.50**	**0.013**
S3: Non-collaborators	-0.209	0.201	237.3	-1.04	0.299

(C)	**Pairwise comparisons**					
Contrasts		*Estimate*	*SE*	*df*	*t-ratio*	*p.value*
Collaborators	**S1 vs S2**	**0.936**	**0.131**	**234**	**7.142**	**<0.01**
	S1 vs S3	**0.829**	**0.134**	**239**	**6.205**	**<0.01**
	S2 vs S3	-0.107	0.137	248	-0.778	1.00
Non-collaborators	**S1 vs S2**	**0.452**	**0.142**	**231**	**3.179**	**<0.01**
	S1 vs S3	**0.620**	**0.150**	**243**	**4.127**	**<0.01**
	S2 vs S3	0.168	0.154	254	1.088	0.833
Collaborators vs Non-collaborators	S1	0.270	0.143	343	1.884	0.061
	S2	-0.214	0.151	347	-1.422	0.156
	S3	0.061	0.160	350	0.380	0.704

Self-reported pro-environmental behaviors

Finally, we analyzed the last factor, which relates to farmers' self-reported pro-environmental behaviors (Table 4). Results showed a significant effect of survey wave, $F(2, 242) = 56.38, p < .01$, demonstrating an overall improvement in self-reported pro-environmental behaviors across the survey waves. However, the effect of collaboration status, $F(1, 128) = 0.79, p = .37$, and the interaction between the two, $F(2, 242) = 1.26, p = .29$, were not significant (Table 4B). Collaborators' self-reported pro-environmental behaviors increased by 1.13 standard deviations from the first to the second survey, and by 1.21 standard deviation from the first to the third survey. However, the change from survey 2 to survey 3 was not statistically significant (Table 4C). The same effects were found for non-collaborators, with an increase by 0.79 standard deviation from survey 1 to survey 2 and by 0.96 standard deviations from survey 1 to survey 3, but no change from survey 2 to survey 3. Comparisons between the two groups at each survey did not reveal significant differences in self-reported pro-environmental behaviors (Table 4C).

Overall, these findings highlight a positive trend in self-reported pro-environmental behaviors over time, with similar patterns of improvement observed between collaborators and non-collaborators (Fig. 2D).

Table 4: Self-reported pro-environmental behaviors: (A) Descriptive statistics for the self-reported pro-environmental behaviors for each survey and collaboration group; (B) Results of fitting linear mixed model, with collaboration status, survey wave and their interaction as fixed factors, and farmer ID as random intercept. (C) Results of fitting pairwise comparisons on the linear mixed model between survey within each collaboration groups as well as within each survey between collaboration groups. Significant results are indicated in bold.

(A)	**Descriptive statistics for self-reported pro-environmental behaviors**				
Survey	*Collaboration status*	*Mean*	*SE*	*Lower CI*	*Upper CI*
1	Collaborators	3.49	0.106	3.28	3.70
	Non-Collaborators	3.77	0.115	3.55	4.00
2	Collaborators	4.62	0.111	4.40	4.84
	Non-Collaborators	4.56	0.121	4.33	4.80
3	Collaborators	4.70	0.115	4.47	4.92
	Non-Collaborators	4.74	0.133	4.48	5.00

(B)	**Linear mixed model**				
Variables	*Estimate*	*SE*	*df*	*t-ratio*	*p.value*
(Intercept)	3.491	0.106	353.0	32.99	<0.01
Second survey wave (S2)	**1.133**	**0.150**	**234.1**	**7.53**	**<0.01**
Third survey wave (S3)	**1.205**	**0.153**	**239.5**	**7.87**	**<0.01**
Non-collaborators	0.282	0.156	352.9	1.81	0.072
S2: Non-collaborators	-0.342	0.222	231.8	-1.54	0.125
S3: Non-collaborators	-0.241	0.230	242.4	-1.05	0.296

(C)	**Pairwise comparisons**					
Contrasts		*Estimate*	*SE*	*df*	*t-ratio*	*p.value*
Collaborators	**S1 vs S2**	**1.133**	**0.151**	**238**	**7.52**	**<0.01**
	S1 vs S3	**1.205**	**0.153**	**243**	**7.86**	**<0.01**
	S2 vs S3	0.072	0.157	254	0.46	1.00
Non-collaborators	**S1 vs S2**	**0.791**	**0.164**	**234**	**4.84**	**<0.01**
	S1 vs S3	**0.964**	**0.172**	**248**	**5.6**	**<0.01**
	S2 vs S3	0.173	0.176	260	0.98	0.98
Collaborators vs Non-collaborators	S1	0.282	0.156	353	1.81	0.072
	S2	-0.059	0.165	353	-0.36	0.718
	S3	0.041	0.175	354	0.24	0.814

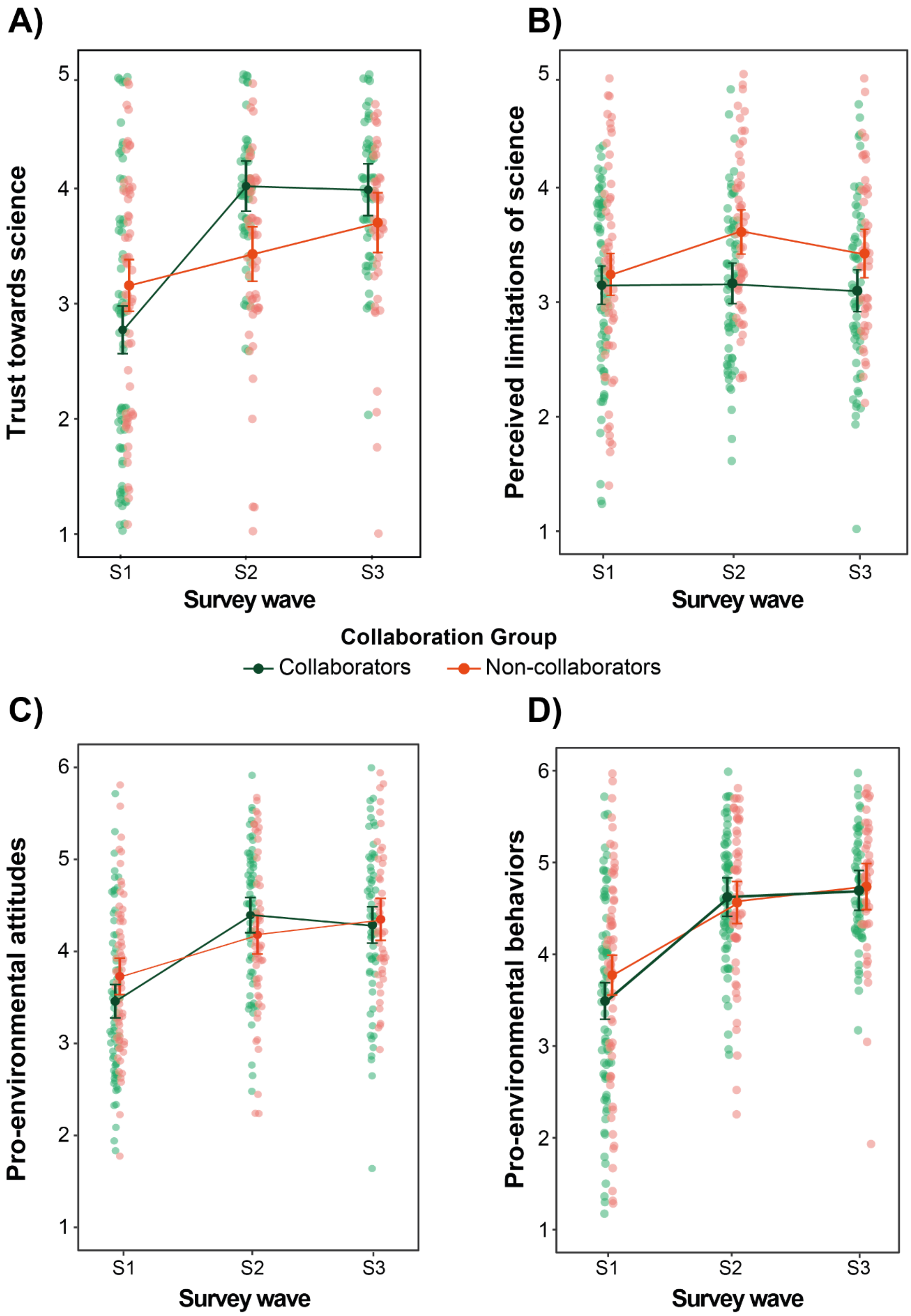

Figure 2: Evolution of the four factors scores over time: *Score for (A) trust towards science; (B) perceived limitation of science; (C) pro-environmental attitudes; and (D) pro-environmental behaviors from first to third survey for collaborators (green) and non-collaborators (orange). Light colored dots represent the raw data, while dark dots indicate the average score predicted and the bars the 95% confidence interval.*

3.5 Reciprocal relationship between attitudes towards science and attitudes and behaviors towards the environment

To investigate the reciprocal relationship attitudes towards science and attitudes and behaviors towards the environment have on each other, we used longitudinal cross-lagged path models. Each factor was modelled by the previous score of the other factors at the previous time point as well as its own score at the previous time point using first-order auto-regressive effects. Four distinct cross-lagged models were conducted: (1) Trust towards science and pro-environmental attitudes, (2) Trust towards science and pro-environmental behaviors; (3) Perceived limitations of science and pro-environmental attitudes; (4) Perceived limitations of science and pro-environmental behaviors. The analyses were conducted in two stages. First, an overall cross-lagged model was fit with *FIML* estimation for missing data using the *sem* function from the *sem* package (Fox et al., 2022). Second, to determine if the collaboration had an effect, a second model was fitted accounting for each collaboration group to examine potential differences in the associations between each factor by collaboration group. The two models were then compared using a chi-squared difference test to estimate which have the better fit. Model fit was evaluated using χ^2, the comparative fit index (CFI), the Tucker-Lewis index (TLI), and the root mean square error of approximation (RMSEA). CFI and TLI values above 0.95 indicate a close fit (Hu & Bentler, 1999), and an RMSEA value of less than 0.08 indicates a fair fit (Browne & Cudeck, 1992).

3.5.1 Effect of collaboration

In each case, the simpler model, which does not account for collaboration status, was consistently preferred over the more complex model, accounting for collaboration status. The results indicate no significant improvement in model fit by incorporating collaboration status as a differentiating factor, suggesting that collaboration status does not significantly influence the dynamics being investigated (Table 5). The results described in the following section thus correspond to the overall model, without accounting for the collaboration group.

Table 5: Results of chi-squared difference test: Results of fitting a chi-squared difference test using the *anova* function in R, across each analyzed factor combination. Each row pair represents a comparison between a simpler model, not accounting for the collaboration status, and a complex model, accounting for collaboration status. For both model types, we report the chi-square value, together with the chi-square difference, difference in degree of freedom, RMSE value and the associated p.value.

Model	χ^2	$\Delta\chi^2$	Δdf	RMSEA	p.value
Trust towards science – Pro-environmental attitudes					
Simpler model	$\chi^2(4)=9.27$	5.34	4	0.05	0.25
Complex model	$\chi^2(8)=14.61$				
Trust towards science – Pro-environmental behaviors					
Simpler model	$\chi^2(4)=3.72$	5.59	4	0.05	0.23
Complex model	$\chi^2(8)=9.31$				
Perceived limitations of science – Pro-environmental attitudes					
Simpler model	$\chi^2(4)=5.72$	6.47	4	0.07	0.17
Complex model	$\chi^2(8)=12.19$				
Perceived limitations of science – Pro-environmental behaviors					
Simpler model	$\chi^2(4)=4.63$	1.06	4	0.0	0.90
Complex model	$\chi^2(8)=5.69$				

3.5.2 Trust towards science – Pro-environmental attitudes

In the first cross-lagged model, we examined the relationship between farmers' trust towards science (Trust) and their pro-environmental attitudes (Att) (Fig. 3A). This model displayed an acceptable fit to the data (Table 6), although the RMSEA was slightly higher than the conventional threshold. We observed that initial levels of trust towards science did not significantly predict later pro-environmental attitudes, nor did initial pro-environmental attitudes significantly predict trust towards science in the second survey. This suggests an independent temporal evolution of these constructs over the first two periods examined. However, pro-environmental attitudes in the second survey positively predicted trust towards science in the third survey, with one-point increase in attitudes leading to a 0.24-point increase in trust. Both trust towards science and pro-environmental attitudes demonstrated significant stability over time, indicating that farmers' opinions are relatively consistent across the measurement waves.

3.5.3 Trust towards science – Pro-environmental behaviors

The second cross-lagged model explored the relationship between farmers' trust towards science (Trust) and their self-reported pro-environmental behaviors (PEB) (Fig. 3B) and demonstrated an excellent fit (Table 6). Results indicated that trust towards science did not significantly predict later self-reported pro-environmental behaviors. Conversely, self-reported pro-environmental behaviors at the second survey tended to positively predict trust towards science at the third survey, with a one-point increase in PEB in survey 2 leading to a 0.23-point increase in trust towards science in survey 3 ($p = .07$). But this pattern was not observed between survey 1 and 2. As previously, both measures demonstrated stability over time.

3.5.4 Perceived limitations of science – Pro-environmental attitudes

In the third model, perceived limitations of science (Limit) and pro-environmental attitudes (Att) were analyzed (Fig. 3C) and demonstrated a good fit to the data (Table 6). The results showed that initial pro-environmental attitudes positively predicted perceived limitations towards science, with a one-point increase in pro-environmental attitudes leading to a 0.18-point increase in perceived limitations of science in survey 2. This suggests that pro-environmental attitudes were associated with more negative perceptions of science. However, the opposite was found from survey 2 to survey 3, with a one-point increase in pro-environmental attitudes leading to a 0.20-point decrease in perceived limitations of science in survey 3, suggesting an opposite trend. Perceived limitation towards science did not predict pro-environmental attitudes. Again, both factors demonstrated a high degree of stability.

3.5.5 Perceived limitations of science – Pro-environmental behaviors

The final model assessed the dynamics between perceived limitations of science (Limit) and pro-environmental behaviors (PEB) (Fig. 3D) and showed an excellent fit to the data (Table 6). Perceived limitations of science did not predict later self-reported pro-environmental behaviors. However, earlier self-reported pro-environmental behaviors were significantly predictive of later perceived limitations towards science, with a one-point increase in PEB in survey 1 leading to a 0.16-point increase in perceived limitations in survey 2. This suggest that initial engagement in pro-environmental behaviors was positively associated with subsequent perceptions of the limitations of science. However, this was not consistent from survey 2 to survey 3, nor in the reverse direction. As previously, a strong stability of the two factors was observed over time.

Table 6: Cross-lagged models fit: Fit indices (CIF, TLI and RMSEA) of the cross-lagged models performed on the four factors relating to farmers' attitudes towards science and attitudes and behaviors towards the environment.

Model	**CFI**	**TLI**	**RMSEA**
Trust towards science – Pro-environmental attitudes	**0.961**	**0.855**	**0.098**
Trust towards science – Pro-environmental behaviors	**1.00**	**1.02**	**0.0**
Perceived limitations of science – Pro-environmental attitudes	**0.99**	**0.94**	**0.056**
Perceived limitations of science – Pro-environmental behaviors	**0.99**	**0.99**	**0.034**

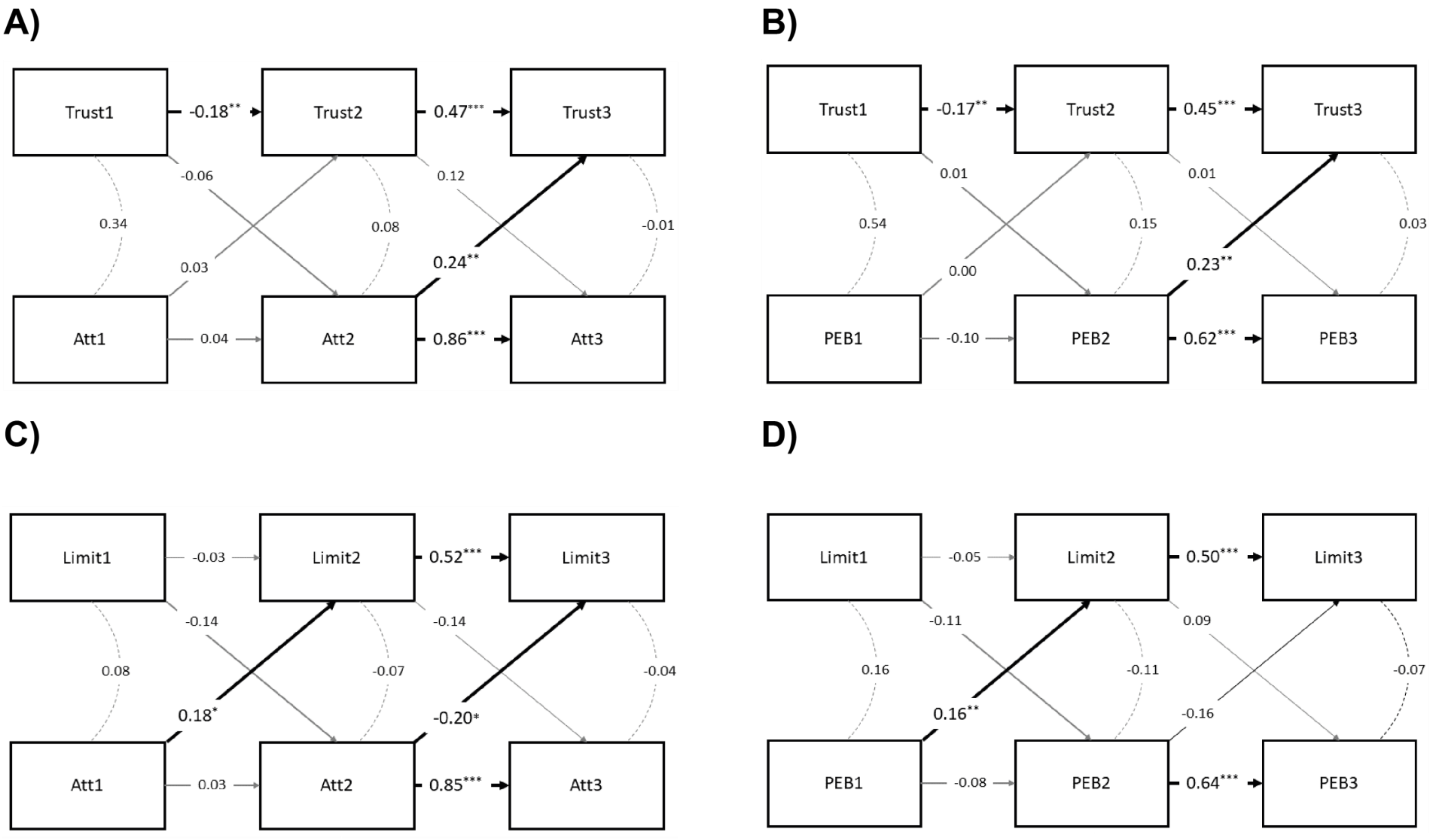

Figure 3: Results of the cross-lagged models: Cross-lagged effects model between (A) Trust towards science and pro-environmental attitudes; (B) Trust towards science and pro-environmental behaviors (PEB); (C) Perceived limitations of science and pro-environmental attitudes; and (D) Perceived limitations of science and pro-environmental behaviors (PEB). Path coefficients are standardized values and thick lines represent significant paths (***<.001; **<.01; *<.05). Dashed lines represent the covariances between the two factors for each survey.

4. Discussion

Agriculture contributes significantly to the environmental crisis, accounting for up to 22% of global greenhouse gases emissions (IPCC, 2023). Farmers thus play an essential role as primary agents of change, and understanding the drivers behind their adoption of sustainable practices is essential to mitigate agriculture's impact on the environment. Collaboration between ecologists and farmers has emerged as a promising approach to promote engagement in sustainability among farmers (Bodin, 2017; Tengö et al., 2014). This study examines the dynamics of such scientist-farmer collaboration, focusing on a collaboration between Swiss farmers and a research group from a mid-sized Swiss University for the conservation of the barn owl. The aim was to determine the association between involvement in this conservation project and farmers' attitudes and behaviors towards science and the environment, by comparing collaborating farmers with non-collaborators. Our analysis focuses on four different factors: farmers' trust towards science and perceived limitations of science, as well as pro-environmental attitudes and behaviors. This longitudinal case study reveals significant shifts over time in these dimensions, though at different rates between collaborators and non-collaborators, highlighting the complex interplay between environmental initiatives and social-psychological factors among the farming community.

Attitudes towards science

To the best of our knowledge, this study is the first to evaluate the association between participation in a conservation project with scientists and farmers' attitudes towards science. Given that collaborators have been in contact with scientists — witnessing the methodologies employed, data collection processes in the field, and being updated annually on the research group's findings— our first hypothesis was that these farmers would exhibit more positive attitudes towards science than non-collaborators.

This was not as straightforward in our results. Collaborators, initially displaying lower levels of trust than non-collaborators, experienced a significant increase from the first to the second survey, and stabilized thereafter. This change may reflect initial discontent among collaborators, possibly due to feeling under-engaged in the conservation project with the scientists. As their involvement increased with the surveys, it apparently strengthened their trust towards science. In contrast, non-collaborators exhibited a more uniform and gradual increase in trust over time.

Regarding perceived limitations of science, both collaborators and non-collaborators had similar perceptions, indicating that initial collaboration status did not significantly associate with their attitudes. Over time, a slight yet consistent deterioration was noted among non-collaborators, in contrast to the slight improved perspective of collaborators. This gradual shift led to a noticeable disparity between the two groups, suggesting that continuous collaboration might subtly enhance how farmers perceive scientific research.

This observation aligns with Bäckstrand (2003), who argues that direct engagement with scientific research can demystify science and promote a more nuanced appreciation of its capabilities and limitations. However, the findings indicate that for farmers to gain a positive view of science, their involvement in a scientific project must be meaningful. In this study, the level of farmers' involvement in the conservation project is largely determined by the farmers themselves. The interaction with the research group primarily consists of using their barns for nest box installations. The researchers maintain communication with the farmers to coordinate access and inform them of their visits. Beyond these interactions, any deeper engagement from the farmers, such as participating in or observing fieldwork, is purely voluntary and based on their personal commitment and interest. Although involvement in the barn owl conservation project seems to be positively associated with positive attitudes towards science, the effects are moderate, and the findings are nuanced. The initial lower trust level among collaborators may reflect superficial involvement, which may lead in turn to skepticism. Future research could benefit from a more detailed exploration of the dynamics of scientist-farmer collaboration, particularly examining attitudes pre- and post-collaboration, and encouraging greater involvement of the farmers in the research questions and process. The present study's insights, while valuable, underscore the complexity of gauging the influence of such collaborations on farmers' attitudes towards science, and emphasize the importance to integrate them as proactive actors, and not merely facilitators.

Attitudes and behaviors towards the environment

In addressing our second hypothesis, which stated that long-term collaboration would be positively associated with pro-environmental attitudes and behaviors, the findings suggest a nuanced relationship. Collaboration was positively associated with pro-environmental attitudes depending on time of survey, and both collaborators and non-collaborators showed significant increases from the first to the second and third survey. Regarding the self-reported pro-environmental behaviors, all farmers, regardless of their collaboration status, showed significant improvement in their behaviors over time. This trend is not only promising but also indicative of Swiss farmers' commitment to environmental conservation and sustainable practices. Notably, this increase may reflect more than just environmental consciousness, it is possible that participating in the survey itself acted as a trigger for reflection and subsequent behavior change. Responding to the survey questions may have served to raise awareness among farmers or caused them to reconsider their practices and the impacts of their actions, effectively reinforcing their commitment to sustainable farming. Furthermore, a large proportion of the farmers in this study are already actively engaged in eco-friendly farming. A majority of the respondents operate under certifications such as IP-Suisse or organic farming labels, which impose specific requirements for on-farm biodiversity and environmental conservation. These numbers follow the Swiss statistical data (OFS, 2023). This level of engagement highlights the existing baseline of conservation practices among Swiss farmers, emphasizing their crucial role in conservation.

However, no significant association between collaboration and pro-environmental behaviors was found. This may suggest that the behaviors assessed through the surveys were not sufficiently aligned with the specific conservation objectives of the barn owl project. The surveyed behaviors, while indicative of general pro-environmental behaviors, do not directly correlate with the targeted actions that could directly affect the barn owl and thus be influenced by the research group, such as the use of pesticides, the plantation of wildflower strips or hedges, or the installation of raptor perches. Future research should concentrate on these more precise behaviors to more accurately assess the influence that scientists could have on encouraging farmers to adopt specific behaviors related to the scientific research performed. This is consistent with the findings of Lentijo & Hostetler (2013), who studied the effects of a bird conservation project and discovered a positive effect on farmers' knowledge of birds, but not on their conservation practices. Conversely, Josefsson et al. (2017) found that Swedish farmers' intentions to implement sustainable practices were positively associated with their active participation in a bird conservation program. This program was marked by regular bird surveys, specific expert advice, and on-site farm visits. The contrast in findings between these studies might be attributed to the varying levels of farmers' engagement. In our research, the degree of contact between farmers and scientists was left to the farmers' choice, which may have resulted in less direct involvement compared to the proactive model seen in Josefsson et al. (2017). This is further supported by the study of Forté-Gardner et al. (2004), which examined a field experiment involving both scientists and farmers and found a positive association with farmers' intentions to adopt sustainable practices. The effectiveness of conservation projects in changing farming practices may depend on the extent of farmer engagement, ranging from passive receipt of information to active participation. Therefore, enhancing the proactive involvement of farmers in conservation projects could be key to realizing the full potential of scientific collaboration in promoting sustainable agricultural practices.

Association between attitudes towards science and attitudes and behaviors towards the environment

Finally, our third hypothesis expected attitudes towards science to positively predict pro-environmental attitudes and behaviors. Our findings revealed unexpected dynamics among the four factors evaluated. Contrary to our initial assumption, we observed that pro-environmental attitudes and behaviors predicted attitudes towards science rather than the contrary.

Our analysis revealed that both pro-environmental attitudes and, to a lesser extent, self-reported pro-environmental behaviors predicted trust towards science. Pro-environmental attitudes were found to positively relate with trust towards science. This suggests that farmers who hold more favorable views towards ecological matters are also likely to exhibit greater trust in scientific research and findings. This finding aligns with the dynamics observed for pro-environmental behaviors, where an increase in such behaviors positively correlated with higher trust. This correlation suggests that engaging in pro-environmental practices may enhance farmers' trust in scientific research and its ability to address ecological challenges. Further investigation is needed to understand how various aspects of environmental engagement influence trust in science, and how to promote this trust in the face of growing ecological concerns.

For perceived limitations of science, our analysis indicated different relation with pro-environmental attitudes. While initial pro-environmental attitudes were related to increased perceived limitations of science in the second survey – suggesting a less favorable view of science – the relation in the third survey presented a contrasting picture. Here, a rise in pro-environmental attitudes corresponded with a decreased perception of science's limitations. This reversal could indicate that as farmers' pro-environmental attitudes continued to mature over time, their perceptions of scientific limitations diminished, possibly indicating a more integrated understanding of how science can contribute to addressing ecological issues. This change suggests a complex relationship between pro-environmental attitudes and perceptions of science, but also the dynamic nature of farmers' perceptions of science, especially in the context of environmental issues. This observation highlights the need for ongoing dialogue between the scientific community and farmers to address and clarify the potential and limitations of science in addressing complex environment issues, as well as the need for further research in the relationships between attitudes towards science and towards the environment.

Regarding self-reported pro-environmental behaviors, higher levels were associated with greater perceived limitations of science. This outcome may indicate a paradox where engaging in pro-environmental practices increases awareness of the scope of environmental challenges, leading to greater questioning of scientific solutions and their perceived limitations. It suggests that active environmental engagement may cultivate a more discerning perspective on the limitations of scientific approaches.

These findings suggest a complex web of relationships between farmers' trust in science, perceived limitations of science, and pro-environmental attitudes and behaviors. Rather than linear relationships where positive attitudes towards science directly lead to pro-environmental actions, our results indicate more intricate links. This highlights the necessity for additional research on the relationship between these social-psychological factors. It is essential to comprehend these dynamics to design effective communication strategies and interventions that can bridge the gap between scientific research and farmers' perceptions. This will ultimately lead to a more collaborative and informed approach to addressing environmental challenges and could inform more effective strategies for promoting sustainable practices in the agricultural sector.

It is important to note that the COVID-19 pandemic began shortly after our first survey was completed, which may have significantly influenced the results of subsequent surveys. The pandemic has highlighted the importance of science and scientific research in addressing public health emergencies, potentially altering public perceptions of science and environmental priorities (Pagliaro et al., 2021; Plohl & Musil, 2021). The pandemic may have increased awareness among the farming community of the interdependence of human health, agriculture, and ecological sustainability (Beckman & Countryman, 2021; Siche, 2020; Sridhar et al., 2023), potentially influencing attitudes towards science and pro-environmental attitudes and behaviors. Considering the timing of the COVID-19 outbreak, it is important to carefully consider its implications on the shifts in attitudes and behaviors noted among the study participants, especially between the first and second surveys.

5. Conclusion

The urgent need to preserve biodiversity requires new approaches to collectively behave in an eco-friendlier way. Agriculture being confronted with several challenges as far as nature conservation is concerned, studying farmer's behavior is of the utmost importance to promote the implementation of environmentally friendly farming methods. Farmers have a key role to play in fighting against climate change and, in this research, we showed that scientist-farmer collaboration can be a tool to improve attitudes towards science. However, we could not detect any relation with pro-environmental attitudes and behaviors. The trends observed underscore the importance of inclusive, participatory research approaches and the need for targeted strategies to enhance specific conservation behaviors.

Ethic Statement

This study involved human participants and was reviewed and approved by the Ethics Committee of the University of Lausanne. The participants provided their written informed consent to participate to the study.

Material access

Open Science Framework link:

https://osf.io/hv8p4/?view_only=58938de889604b7d9a53d4a9792b112d

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Supplementary material

Supplementary material I – Response rate

Table S1-a: Response rate at first survey

MAIL	**Proposed by phone**	**Sent**	**Responded**	**Response rate**
Collaborators	273	60	32	53.3%
Non-Collaborators	209	54	44	81.5%
EMAIL				
Collaborators	-	96	71	74.0%
Non-Collaborators	-	74	48	64.9%
TOTAL	482	284	195	68.7%

Table S1-b: Response rate at second survey

MAIL		Sent	Responded	Response rate
Collaborators	Booklet	7	5	71.4%
	No booklet	2	2	100%
Non-Collaborators	Booklet	9	5	55.6%
	No booklet	9	4	44.5%
EMAIL				
Collaborators	Booklet	51	34	66.7%
	No booklet	51	27	41.2%
Non-Collaborators	Booklet	41	26	63.4%
	No booklet	41	22	53.7%
TOTAL		211	125	49.2%

Table S1-c: Response rate at third survey

MAIL	Sent	Responded	Response rate
Collaborators	9	7	77.8%
Non-Collaborators	18	7	38.9%
EMAIL			
Collaborators	99	57	57.6%
Non-Collaborators	80	41	51.3%
TOTAL	206	112	54.4 %

Supplementary material II – Survey items

*Table S2 : Questionnaire items used to for factor analyses. Negative statements are indicated with an *.*

Item N°		English Source	French Source
Attitudes towards science			
1	*The work of researchers at the University of Lausanne enables essential discoveries.*	Researcher-translated	Researcher-made
2	*Researchers do not work on concrete enough subjects.**	Researcher-translated	Researcher-made
3	*Researchers knowledge is too theoretical.**	Researcher-translated	Researcher-made
4	*Communication of researchers with general public is too complicated.**	Researcher-translated	Researcher-made
5	*Communication of researchers with general public is not sufficiently developed.**	Researcher-translated	Researcher-made
6	*The knowledge produced at the University of Lausanne is trustworthy.*	Researcher-translated	Researcher-made
7	*University scientists are experts in their field.*	Researcher-translated	Researcher-made
8	*Advice provided by the University is not feasible.**	Researcher-translated	Researcher-made
9	*Scientists are too disconnected from field work**	Researcher-translated	Researcher-made
Opinion towards the environment			
1	*Humans have the right to modify the natural environment to suit their needs.**	Dunlap et al, 2000	(Schleyer-Lindenmann et al., 2016)
2	*The balance of nature is strong enough to cope with impacts of modern industrial nations.*	Dunlap et al, 2000	(Schleyer-Lindenmann et al., 2016)
3	*The so-called "ecological crisis" facing humankind has been greatly exaggerated.**	Dunlap et al, 2000	(Schleyer-Lindenmann et al., 2016)
4	*I would like to join and actively participate in an environmentalist group.*	(Milfont & Duckitt, 2010)	(Moussaoui et al., 2016)
5	*Science will not be able to solve our environmental problems.**	(Milfont & Duckitt, 2010)	(Moussaoui et al., 2016)
6	*Whenever possible, I try to save natural resources.*	(Milfont & Duckitt, 2010)	(Moussaoui et al., 2016)
7	*Protecting peoples' jobs is more important than protecting the environment.**	(Milfont & Duckitt, 2010)	(Moussaoui et al., 2016)
8	*I am sure that we, farmers, can reduce CO2 emissions.*	(Jugert et al., 2016), adapted	Researcher-translated
9	*I don't think that we, farmers, have the means to protect the environment.**	(Jugert et al., 2016), adapted	Researcher-translated
10	*I am sure that we, farmers, can reduce the negative consequences of climate change.*	(Jugert et al., 2016), adapted	Researcher-translated
11	*I don't think that we, farmers, can make a difference for the climate in the long run.**	(Jugert et al., 2016), adapted	Researcher-translated
12	*I often try to persuade my entourage that the environment is important.*	(Milfont & Duckitt, 2010)	Researcher-translated
13	*Humans will eventually learn enough about how nature works to be able to control it.**	Dunlap et al, 2000	(Schleyer-Lindenmann et al., 2016)
14	*Despite our special abilities humans are still subject to the laws of nature.*	Dunlap et al, 2000	(Schleyer-Lindenmann et al., 2016)
15	*In my daily life, I do not try to conserve water and/or power.**	(Milfont & Duckitt, 2010)	Researcher-translated
16	*When I seed a new crop, I make sure it is a local strain.*	Researcher-made, based on Graf et al. (2016)	Researcher-translated
17	*I do not clear out the mowing product from the mowed field.**	Researcher-made, based on Graf et al. (2016)	Researcher-translated
18	*As far as possible, I check the presence of animals in the plots that I will mow.*	Researcher-made, based on Graf et al. (2016)	Researcher-translated

19	*I mow the plots from the inside to the outside to allow animals to escape.*	Researcher-made, based on Graf et al. (2016)	Researcher-translated
20	*I know the 6 most common invasive exotic plants on farms.*	Researcher-made, based on Graf et al. (2016)	Researcher-translated
21	*I mechanically fight against invasive exotic plants*	Researcher-made, based on Graf et al. (2016)	Researcher-translated
22	*Global warming is a normal and natural cyclical phenomenon.**	Researcher-made	Researcher-translated
23	*Climate strikes are a good way to change things.*	Researcher-made	Researcher-translated
24	*I actively participate in climate strikes.*	Researcher-made	Researcher-translated
25	*Climate has always changed, there is nothing unusual these days.**	Researcher-made	Researcher-translated

Supplementary material III – Questionnaire

Supplementary III a – Common part for collaborators and non-collaborators

Données vous concernant

Nom :___________________________________ Prénom :________________________________

Tranche d'âge :

☐ Entre 18 et 30 ans
☐ Entre 30 et 45 ans
☐ Entre 46 et 65 ans
☐ Plus de 65 ans
☐ Ne souhaite pas y répondre

Sexe :

☐ Homme
☐ Femme
☐ Ne souhaite pas y répondre

Etat civil :

☐ Célibataire
☐ Marié·e
☐ Divorcé·e
☐ Séparé·e
☐ Veuf·ve
☐ Ne souhaite pas y répondre

Accès à internet

☐ Oui
☐ Non

Email :____
(Si vous souhaitez recevoir des informations sur les Effraies des clochers)

Exploitation agricole

Dans cette exploitation, vous êtes :

☐ Propriétaire
☐ Exploitant
☐ Autre (précisez) :____

Sur quel type d'exploitation travaillez-vous (plusieurs réponses possibles) ?

☐ Grandes cultures
☐ Cultures fourragères
☐ Cultures maraîchères et horticulture
☐ Arboriculture
☐ Viticulture
☐ Lait et bovins
☐ Porcins
☐ Chevaux/Chèvres/Moutons
☐ Volailles et œufs
☐ Autre (précisez) :________________________

Quelle est la surface de l'exploitation ?

☐ Moins de 5 ha
☐ 5-10 ha
☐ 11-20 ha
☐ 21-30 ha
☐ 31-40 ha
☐ Plus de 40 ha

Combien d'autres personnes travaillent dans l'exploitation

☐ Aucune

☐ 1

☐ 2

☐ 3

☐ 4

☐ 5

☐ Plus (précisez) :_________________________

Quels sont vos liens avec ces personnes

☐ Famille

☐ Employé·e

☐ Autre (précisez) :____

Quel type d'agriculture pratiquez-vous ?

☐ Traditionnelle

☐ Biologique

☐ IP-Suisse

☐ Biodynamique

☐ Autre (précisez) :____

Participez-vous à un réseau agro-écologique ?

☐ Oui

☐ Non

Mettez-vous en place, sur votre domaine, des structures de promotion de la biodiversité (plusieurs réponses possibles) ?

☐ Oui

- ☐ Nichoirs à passereaux
- ☐ Tas de branches
- ☐ Tas de pierres
- ☐ Etangs
- ☐ Arbres haute-tige
- ☐ « Hôtel à insectes »
- ☐ Perchoirs à rapaces
- ☐ Autres (précisez) :____

☐ Non

Prévoyez-vous d'en intégrer (d'autres) sur votre exploitation (plusieurs réponses possibles) ?

☐ Oui

- ☐ Nichoirs à passereaux
- ☐ Tas de branches
- ☐ Tas de pierres
- ☐ Etangs
- ☐ Arbres haute-tige
- ☐ « Hôtel à insectes »
- ☐ Perchoirs à rapaces
- ☐ Autres (précisez) :____

☐ Non

Relation avec les scientifiques

Recevez-vous régulièrement des informations concernant la nature ?

☐ Oui

De la part de qui (plusieurs réponses possibles) ?

☐ OFEV ☐ Station ornithologique de Sempach

☐ ProNatura ☐ AgriHebdo

☐ WWF ☐ Terre & Nature

☐ Universités suisses ☐ Autre (précisez) :____________

☐ Non

Ces informations vous sont-elles utiles ?

☐ Oui

☐ Non

Pourquoi ?____

Lisez-vous des articles scientifiques publiés par des chercheur·e·s universitaires concernant la nature ?

☐ Oui

☐ Non

Pourquoi ?____ __________________________

Lisez-vous des articles concernant la nature publiés dans AgriHebdo ?

☐ Oui

☐ Non

Pourquoi ?____

Estimez à quel point vous êtes d'accord avec les points suivants :	Pas du tout d'accord	Pas d'accord	Sans avis	D'accord	Tout à fait d'accord	Je ne souhaite pas répondre
Le travail des chercheur·e·s de l'Université de Lausanne permet de faire des découvertes essentielles.	☐	☐	☐	☐	☐	☐
Les chercheur·e·s ne travaillent pas sur des sujets assez concrets.	☐	☐	☐	☐	☐	☐
Les connaissances des chercheur·e·s sont trop théoriques.	☐	☐	☐	☐	☐	☐
La communication des chercheur·e·s avec le grand public est trop compliquée.	☐	☐	☐	☐	☐	☐
La communication des chercheur·e·s avec le grand public n'est pas assez développée.	☐	☐	☐	☐	☐	☐
Les connaissances produites à l'Université sont dignes de confiance.	☐	☐	☐	☐	☐	☐
Les scientifiques de l'Université sont des expert·e·s dans leur domaine.	☐	☐	☐	☐	☐	☐
Les conseils prodigués par l'Université ne sont pas réalisables.	☐	☐	☐	☐	☐	☐
Les scientifiques sont trop déconnecté·e·s du travail de terrain.	☐	☐	☐	☐	☐	☐

Questionnaire d'opinions

Êtes-vous membre d'une ou plusieurs association·s vouée·s à la protection de l'environnement ?

☐ Oui Si oui, la ou lesquelle·s ? ____
☐ Non

Soutenez-vous une ou plusieurs association·s vouée·s à la protection de l'environnement même sans en être membre ?

☐ Oui Si oui, la ou lesquelle·s ?____
☐ Non

Êtes-vous membre d'une ou de plusieurs association·s paysanne·s ?

☐ Oui Si oui, la ou lesquelle·s ?____
☐ Non

Soutenez-vous une ou plusieurs association·s paysanne·s même sans en être membre ?

☐ Oui Si oui, la ou lesquelle·s ?____
☐ Non

Estimez à quel point vous êtes d'accord avec les points suivants :	Pas du tout d'accord	Pas d'accord	Plutôt pas d'accord	Plutôt d'accord	D'accord	Tout à fait d'accord	Je ne souhaite pas répondre
Les êtres humains ont le droit de modifier l'environnement naturel selon leurs besoins.	☐	☐	☐	☐	☐	☐	☐
L'équilibre de la nature est assez fort pour faire face aux effets des nations industrielles modernes.	☐	☐	☐	☐	☐	☐	☐
La prétendue « crise écologique » qui guette le genre humain a été largement exagérée.	☐	☐	☐	☐	☐	☐	☐
J'aimerais rejoindre un groupe écologiste et y participer activement.	☐	☐	☐	☐	☐	☐	☐
La science ne sera pas capable de résoudre nos problèmes environnementaux.	☐	☐	☐	☐	☐	☐	☐
Autant que possible, j'essaie d'économiser les ressources naturelles.	☐	☐	☐	☐	☐	☐	☐
Protéger l'emploi des gens est plus important que protéger l'environnement.	☐	☐	☐	☐	☐	☐	☐

	Pas du tout d'accord	Pas d'accord	Plutôt pas d'accord	Plutôt d'accord	D'accord	Tout à fait d'accord	Je ne souhaite pas répondre
Je suis sûr·e que nous, agriculteur·trice·s, pouvons réduire les émissions de CO_2.	☐	☐	☐	☐	☐	☐	☐
Je ***ne*** *pense* ***pas*** *que nous, agriculteur·trice·s, avons les moyens de protéger l'environnement.*	☐	☐	☐	☐	☐	☐	☐
Je suis sûr·e que nous, agriculteur·trice·s, pouvons réduire les conséquences négatives du changement climatique.	☐	☐	☐	☐	☐	☐	☐
Je ***ne*** *pense* ***pas*** *que nous, agriculteur·trice·s, pouvons faire une différence pour le climat sur le long terme.*	☐	☐	☐	☐	☐	☐	☐
J'essaie régulièrement de convaincre mon entourage que l'environnement est important.	☐	☐	☐	☐	☐	☐	☐
Les humains finiront par en apprendre suffisamment sur le fonctionnement de la nature pour pouvoir la contrôler[1]	☐	☐	☐	☐	☐	☐	☐
Malgré des aptitudes particulières, les humains sont toujours soumis aux lois de la nature	☐	☐	☐	☐	☐	☐	☐
Dans mon quotidien et dans mon travail, je ***n'****essaie* ***pas*** *d'économiser l'eau et/ou le courant électrique*	☐	☐	☐	☐	☐	☐	☐
Lorsque j'ensemence une nouvelle culture, je veille à ce que ce soit une souche locale.	☐	☐	☐	☐	☐	☐	☐
Je ***n'****évacue* ***pas*** *le produit de la fauche du champ fauché.*	☐	☐	☐	☐	☐	☐	☐
Dans la mesure du possible, je vérifie la présence d'animaux dans les parcelles que je vais faucher.	☐	☐	☐	☐	☐	☐	☐
Je fauche les parcelles de l'intérieur vers l'extérieur pour permettre aux animaux de s'enfuir.	☐	☐	☐	☐	☐	☐	☐

	Pas du tout d'accord	Pas d'accord	Plutôt pas d'accord	Plutôt d'accord	D'accord	Tout à fait d'accord	Je ne souhaite pas répondre
Je connais les 6 plantes exotiques envahissantes les plus fréquentes dans les exploitations agricoles.	☐	☐	☐	☐	☐	☐	☐
Je lutte mécaniquement contre les plantes exotiques envahissantes.	☐	☐	☐	☐	☐	☐	☐
Le réchauffement climatique est un phénomène cyclique normal et naturel.	☐	☐	☐	☐	☐	☐	☐
Les grèves pour le climat sont une bonne façon de changer les choses.	☐	☐	☐	☐	☐	☐	☐
Je participe activement aux grèves pour le climat.	☐	☐	☐	☐	☐	☐	☐
Le climat a toujours changé, il n'y a rien d'anormal ces temps-ci.	☐	☐	☐	☐	☐	☐	☐

De manière générale, pensez-vous que le changement climatique actuel soit dû aux activités humaines ?	☐ 1 Je n'y crois pas	☐ 2	☐ 3	☐ 4	☐ 5 J'en suis persuadé·e
De manière générale, comment pensez-vous être engagé·e écologiquement dans votre vie de tous les jours ?	☐ 1 Pas du tout engagé·e	☐ 2	☐ 3	☐ 4	☐ 5 Très engagé·e

Supplementary material III b – Part for collaborators only

Effraie des clochers (ou Chouette effraie)

Depuis combien de temps avez-vous un nichoir sur votre propriété ?_________________________________

Êtes-vous la personne qui a accepté/demandé la pose du nichoir ?

☐Oui

☐Non Quel est votre lien avec cette personne ?
C'est mon/ma…
☐ Conjoint / Conjointe
☐ Mari / Femme
☐ Père / Mère
☐ Autre (précisez) :____

Pour quelle·s raison·s avez-vous accepté/demandé la pose du nichoir (plusieurs réponses possibles) ?

☐ Intérêt scientifique
☐ Intérêt pour la nature
☐ Intérêt ornithologique
☐ Intérêt pour l'Effraie des clochers
☐ Pour lutter contre les rongeurs
☐ Je connaissais personnellement la personne qui voulait poser ce nichoir
☐ J'ai appris d'une connaissance que poser un nichoir est une bonne chose
☐ Aucune raison particulière
☐ Autre (précisez) :____ __________________

A l'heure actuelle, quelle est l'utilité du nichoir pour vous (plusieurs réponses possibles) ?

☐ Pour acquérir des connaissances scientifiques
☐ Pour protéger la nature
☐ Pour aider les oiseaux
☐ Pour aider l'Effraie des clochers
☐ Pour lutter contre les rongeurs
☐ Pour le plaisir
☐ Aucune utilité particulière
☐ Autre (précisez) :____ ____________________

Avez-vous déjà entendu parler du groupe de recherche d'Alexandre Roulin, autrement que par la mise en place du nichoir ?

☐ Oui Si oui, comment (plusieurs réponses possibles) ?
☐ Non
☐ Dans les médias locaux
☐ Sur les réseaux sociaux
☐ A une conférence
☐ Par bouche à oreille
☐ A la télévision
☐ Autre (précisez) :___________________________________

Si oui, quel projet en particulier ? ____

Si votre nichoir a déjà été occupé, avez-vous déjà vu « vos » chouettes ?

☐ Oui
☐ Non
☐ Il n'y a jamais eu de chouette dans mon nichoir

Sur une échelle de 1 à 10, estimez à quel point vous êtes attaché·e aux chouettes présentes dans votre nichoir

☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
1 Pas du tout attaché·e	2	3	4	5	6	7	8	9	10 Très attaché·e	Il n'y a jamais eu de chouette dans mon nichoir

Avez-vous déjà montré le nichoir et/ou les chouettes à votre entourage (enfants, amis, famille) ?
☐ Oui
☐ Non
Pourquoi ?____

Pour chaque information concernant le groupe de recherche, notez à quel point cela vous intéresserait de l'obtenir :

	Pas du tout	Un peu	Moyennement	Beaucoup
Les sujets de nos recherches.	☐	☐	☐	☐
Les résultats de nos recherches.	☐	☐	☐	☐
Le nombre de couvées qui ont eu lieu dans votre nichoir depuis sa pose.	☐	☐	☐	☐
Le nombre d'œufs pondus à chaque saison.	☐	☐	☐	☐
Le nombre de jeunes ayant atteint l'âge de s'envoler à chaque saison.	☐	☐	☐	☐
Les données récoltées (photos, tracés GPS,…) si elles sont disponibles.	☐	☐	☐	☐
Des informations générales sur les Effraies des clochers.	☐	☐	☐	☐
Des conseils pour aider les chouettes dans leur chasse aux rongeurs.	☐	☐	☐	☐

Quelles autres informations vous intéresseraient ?____

Comment voudriez-vous obtenir ces informations (plusieurs réponses possibles) ?
☐ Grâce à un site internet avec un login personnel
☐ Via une brochure annuelle
☐ Par mail
☐ Par SMS
☐ Autre (précisez :____

A quelle fréquence rencontrez-vous les chercheur·e·s de l'Université de Lausanne ?
☐ Plusieurs fois par année
☐ Une fois par année
☐ Moins d'une fois par année
☐ Jamais

Lorsque les chercheur·e·s de l'Université de Lausanne sont au nichoir, si vous en avez la possibilité, est-ce que vous allez voir ce qu'ils font ?
☐ Oui
☐ Non

Si oui, pourquoi (plusieurs réponses possibles) ?
☐ Par curiosité
☐ Pour surveiller qu'aucun dégât ne soit fait
☐ Par intérêt pour les chouettes
☐ Par intérêt pour la recherche scientifique
☐ Pour leur garantir l'accès au nichoir
☐ Autre (précisez) :____ ______________________

Si non, pourquoi (plusieurs réponses possibles)
☐ Ils sont trop distants
☐ Cela ne m'intéresse pas
☐ Je n'ai pas le temps
☐ Je ne suis pas à proximité quand ils viennent
☐ Je ne suis pas au courant quand ils viennent
☐ Autre (précisez) :____ __________________

Selon vous, les éléments ci-dessous sont-ils dérangeants ?

	Oui	Non
Déjections ou autres salissures	☐	☐
Bruits provoqués par les chouettes	☐	☐
Bruits provoqués par les chercheur·e·s de l'Université de Lausanne	☐	☐

Autre (précisez) :____

Avez-vous déjà eu de mauvaises expériences depuis que le nichoir est en place (avec les chouettes, les personnes de l'Université ou de la station ornithologique, d'autres personnes…) ?
☐ Oui La ou lesquelle·s ?
☐ Non ____

En quelques mots, expliquez-nous votre ressenti par rapport aux Effraies des clochers présentes sur votre terrain :

____

____

____

Remarques générales :

____

____

____

Supplementary material III c – Part for non-collaborators only

Effraie des clochers (ou Chouette effraie)

Avez-vous déjà entendu parler de nichoirs à Effraie des clochers ?

☐ Oui
☐ Non

Comment ?

☐ Via d'autres agriculteurs qui en ont un
☐ Dans les médias locaux
☐ Sur les réseaux sociaux
☐ A une conférence
☐ Par bouche à oreille
☐ A la télévision
☐ Autre (précisez) :_________________________

Seriez-vous intéressé·e par la mise en place d'un nichoir à Effraie des clochers chez vous ?

☐ Oui
☐ Non

Si oui, pour quelles raisons ?

☐ Intérêt scientifique
☐ Intérêt pour la nature
☐ Intérêt ornithologique
☐ Intérêt pour l'Effraie des clochers
☐ Pour lutter contre les rongeurs
☐ Je connais personnellement une personne qui pourrait poser ce nichoir
☐ J'ai appris d'une connaissance que poser un nichoir est une bonne chose
☐ Aucune raison particulière
☐ Autre (précisez) :____

Avez-vous déjà entendu parler du groupe de recherche d'Alexandre Roulin?

☐ Oui
☐ Non

Si oui, comment (plusieurs réponses possibles) ?

☐ Dans les médias locaux
☐ Sur les réseaux sociaux
☐ A une conférence
☐ Par bouche à oreille
☐ A la télévision
☐ Autre (précisez) :____

Si oui, quel projet en particulier ?

____

Remarques générales :

____

Supplementary material IV – MCAR test results

Table S4: Results of fitting Little's test on the missing data per survey.

Survey	*Statistic*	*df*	*p.value*
S1	1340.12	2232	1.00
S2	1300.97	1678	1.00
S3	907.14	2241	1.00

Supplementary material V – Analysis of Equivalence

Table S5: Results of the equivalence analysis between collaborators and non-collaborators. Results of applying a Student t-test to the numerical variable (age) and a Pearson Chi-squared test for the categorical variables (civil state, farm type, farm size, type of agriculture) to compare the distributions between collaborators (N=109) and non-collaborators (N=102). Descriptive values (mean, standard deviation, counts and percentages) are provided for each group as well as the results of the corresponding tests. p.values have been corrected with Bonferroni correction. Significant results are indicated in bold.

Variable	Collaborators (N=109)	Non-Collaborators (N=102)	Test result
Age	Mean = 53.01 (sd=11.02)	Mean = 51.33 (sd=11.47)	*t(145.17)=0.392 p=1.00*
Gender			
Men	**79 (72.48%)**	**91 (89.22%)**	***$\chi^2(1)=7.43$ p=.038***
Women	**15 (13.76%)**	**3 (2.94%)**	
Civil State			
Single	18 (16.51%)	24 (23.53%)	*$\chi^2(4)=3.51$ p=1.00*
Married	68 (62.39%)	59 (57.84%)	
Divorced	8 (7.34%)	9 (8.82%)	
Separated	3 (2.75%)	1 (0.98%)	
Widow·er	0 (0%)	1 (0.98%)	
*Farm type**			
Mix (>2 types)	66 (60.55%)	63 (61.76%)	*$\chi^2(13)=20.66$ p=.48*
Large crops	19 (17.43%)	9 (8.82%)	
Large crops and fodder crops	5 (4.59%)	6 (5.88%)	
Large crops and horses	3 (2.75%)	3 (2.94%)	
Large crops and poultry	3 (2.75%)	4 (3.92%)	
Large crops and cattle	2 (1.83%)	4 (3.92%)	
Large crops and arboriculture	1 (0.92%)	2 (1.96%)	
Arboriculture	1 (0.92%)	0 (0%)	
Large crops and viticulture	1 (0.92%)	3 (2.94%)	
Cattle	3 (2.75%)	0 (0%)	
Fodder crops and cattle	2 (1.83%)	0 (0%)	
Horses/Goats	1 (0.92%)	0 (0%)	
Cattle and Horses	1 (0.92%)	0 (0%)	
Large crops and vegetable crops	0 (0%)	7 (6.86%)	
Farm size			
Small (<20 ha)	19 (17.43%)	8 (7.84%)	*$\chi^2(2)=5.30$ p=.42*
Medium (21-40 ha)	32 (29.36%)	40 (39.22%)	
Large (>40 ha)	50 (45.87%)	49 (48.04%)	
Type of agriculture			
Traditional	32 (29.36%)	23 (22.55%)	*$\chi^2(5)=2.62$ p=1.00*
Traditional and IP-Suisse	32 (29.36%)	31 (30.39%)	
IP-Suisse	26 (23.85%)	29 (28.43%)	
Organic	15 (13.76%)	15 (14.71%)	
Organic and IP-Suisse	2 (1.83%)	3 (2.94%)	
Undefined	1 (0.92%)	0 (0%)	

Given the large number of categories within farm type, initial chi-squared tests did not meet all conditions. To address this, categories were grouped for statistical robustness, which did not alter the results of the analyses ($\chi^2(2)=4.10$, p=.48*), thus confirming the comparability of the datasets. Note that while this categorization approach was adopted for statistical validity, the original, more detailed categorization is retained in this table for comprehensive insight

Supplementary material VI - Measurement reliability and validity

VI-1 Factor analysis – *Attitudes towards science*

Since "attitudes towards science" is highly context-specific in this study, we developed our own scale to measure this construct (Table S2). The exploratory factor analysis (EFA) revealed a two-factor structure (Table S6), which were identified as 'Trust towards science' (Factor 1) and 'Perceived limitations of science' (Factor 2). Item 8 did not consistently group into either factor and was therefore discarded. The two-factor solution yielded a moderate fit (RMSEA = .089, 90% CI = .064-.116; TLI = .894; RMSR = .04). The inter-factor correlations indicate that the factors are well distinct (*r* = -.13), and in an inverse relationship.

Table S6: Exploratory Factor Analysis (EFA) for attitudes towards science: Result of the EFA performed on items relating to farmers' attitudes towards science, which revealed a 2-factor structure - that we named 'Trust towards science' (Factor 1) and 'Perceived limitations of science' (Factor 2). Mean scores (Mean), standard deviations (SD), and factor loadings for each item are presented. Items are grouped into factors based on their highest loading values, highlighted in bold. 'Rd' indicates removed items.

	Items	Mean	SD	Loading	
				Factor 1	Factor 2
6	*The knowledge produced at the University of Lausanne is trustworthy.*	3.53	1.24	**.86**	.06
7	*University scientists are experts in their field.*	3.4	1.18	**.78**	-.05
1	*The work of researchers at the University of Lausanne enables essential discoveries.*	3.54	1.17	**.69**	-.07
9	*Scientists are too disconnected from field work*	3.38	1.21	.02	**.78**
3	*Researchers knowledge is too theoretical.*	3.32	1.18	-.01	**.71**
4	*Communication of researchers with general public is too complicated.*	3.21	1.01	-.06	**.52**
2	*Researchers do not work on concrete enough subjects.*	3.15	1.06	-.22	**.41**
5	*Communication of researchers with general public is not sufficiently developed.*	3.26	1.09	.23	**.39**
8	*Advice provided by the University is not feasible.*			Rd	
Proportion of variance explained by factor				.53	.47
Cumulative proportion of variance explained by factor				.53	1

Cronbach's alpha estimates of internal consistency for each factor was analyzed per survey wave and according to the collaboration status and show an overall good internal consistency as most values are above 0.7, with varying levels within and between groups through survey waves (Table S7).

Table S7: Cronbach's Alpha Values for the two factors related to attitudes towards science: Cronbach's alpha values for 'Trust towards science' and 'Perceived limitation of science' for both collaborators and non-collaborators across three survey waves (S1, S2, S3).

	Collaborators			**Non-Collaborators**		
	S1	**S2**	**S3**	**S1**	**S2**	**S3**
Trust towards science	0.80	0.67	0.72	0.74	0.84	0.75
Perceived limitations of science	0.57	0.73	0.82	0.70	0.76	0.72

VI-2 Factor analysis – *Attitudes and behaviors towards the environment*

For “attitudes and behaviors towards the environment”, we utilized existing scales, notably the New Ecological Paradigm (NEP) scale (Dunlap et al., 2000; Milfont & Duckitt, 2010), supplemented with additional items devised by the present researchers to add specific agricultural pro-environmental behaviors (Graf et al., 2016) (see Table S2 for a complete list of items). The EFA revealed a two-factor structure (Table S8), which were identified as 'pro-environmental attitudes' (Factor 1) and 'self-reported pro-environmental behaviors' (Factor 2). Some items were removed because of their non-conformity with the others (items 4, 5, 14, 23, 24), or because they were context-dependent, varying with the type of farming and field management and did not uniformly reflect the farmers' individual willingness towards pro-environmental behavior (item 17). The factor 'collective efficacy' was also discarded because of its non-consistency (items 8, 9, 10, 11). The two-factor solution yielded a moderate fit (RMSEA = .082, 90% CI = .071-.093; TLI = .84; RMSR = .06). A medium negative inter-factor correlation was observed between the two factors (r = -.4).

Table S8: Exploratory Factor Analysis (EFA) for attitudes and behaviors towards the environment: Result of the EFA performed on items relating to farmers' attitudes and behaviors towards the environment, which revealed a 2-factor structure - that we named 'Pro-environmental attitudes' (Factor 1) and 'Self-reported pro-environmental behaviors' (Factor 2). Mean scores (Mean), standard deviations (SD), and factor loadings for each item are presented. Items are grouped into factors based on their highest loading values, highlighted in bold. 'Rd' indicates removed items.

Items		Mean	SD	Loading	
				Factor 1	Factor 2
22	*Global warming is a normal and natural cyclical phenomenon.*	3.07	1.37	**.73**	.14
25	*Climate has always changed, there is nothing unusual these days.*	2.86	1.36	**.70**	.04
3	*The so-called "ecological crisis" facing humankind has been greatly exaggerated.*	3.1	1.43	**.70**	.00
2	*The balance of nature is strong enough to cope with impacts of modern industrial nations.*	2.84	1.31	**.67**	-.17
7	*Protecting peoples' jobs is more important than protecting the environment.*	2.99	1.11	**.50**	-.14
13	*Humans will eventually learn enough about how nature works to be able to control it.*	2.66	1.32	**.39**	-.28
1	*Humans have the right to modify the natural environment to suit their needs.*	3.2	1.34	**.32**	-.14
18	*As far as possible, I check the presence of animals in the plots that I will mow.*	4.63	1.68	.04	**.78**
19	*I mow the plots from the inside to the outside to allow animals to escape.*	4.32	1.58	.14	**.69**
6	*Whenever possible, I try to save natural resources.*	4.58	1.56	-.10	**.57**
12	*I often try to persuade my entourage that the environment is important.*	4.19	1.49	-.20	**.50**
16	*When I seed a new crop, I make sure it is a local strain.*	3.97	1.56	-.11	**.50**
20	*I know the 6 most common invasive exotic plants on farms.*	3.98	1.56	.02	**.49**
21	*I mechanically fight against invasive exotic plants*	4.11	1.61	-.08	**.47**
15	*In my daily life, I do not try to conserve water and/or power.**	2.63	1.46	.24	**-.46**
4	*I would like to join and actively participate in an environmentalist group.*			Rd	
5	*Science will not be able to solve our environmental problems.*			Rd	
8	*I am sure that we, farmers, can reduce CO2 emissions.*			Rd	
9	*I don't think that we, farmers, have the means to protect the environment.*			Rd	
10	*I am sure that we, farmers, can reduce the negative consequences of climate change.*			Rd	
11	*I don't think that we, farmers, can make a difference for the climate in the long run.*			Rd	
14	*Despite our special abilities humans are still subject to the laws of nature.*			Rd	
17	*I do not clear out the mowing product from the mowed field.*			Rd	
23	*Climate strikes are a good way to change things.*			Rd	
24	*I actively participate in climate strikes.*			Rd	
Proportion of variance explained by factor				.51	.49
Cumulative proportion of variance explained by factor				.51	1.00

*Item is reverse scored; means and standard deviations reflect score before reverse coding.

Cronbach's alpha estimates of internal consistency for the two factors was analyzed per survey wave and per collaboration status and show an overall good internal consistency, with varying levels within and between groups through survey waves (Table S9).

Table S9: Cronbach's Alpha Values for the two factors related to attitudes and behaviors towards the environment: Cronbach's alpha values for 'Pro-environmental attitudes', and 'Self-reported pro-environmental behaviors' for both collaborators and non-collaborators across three survey waves (S1, S2, S3).

	Collaborators			**Non-Collaborators**		
	S1	**S2**	**S3**	**S1**	**S2**	**S3**
Pro-environmental attitudes	0.76	0.78	0.81	0.72	0.76	0.81
Pro-environmental behaviors	0.74	0.72	0.58	0.78	0.79	0.83

Chapter 3

Exploring how scientific and pro-environmental attitudes relate to ecological practices among Swiss farmers

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A.R.: Conceptualization, Funding acquisition, Supervision, Writing – review & editing.
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Abstract

Agriculture plays a central role in biodiversity conservation, with farmers acting as primary managers of the land and key actors in implementing sustainable practices. Their decisions and actions significantly influence ecosystem health, underscoring the importance of understanding the drivers of pro-environmental behaviors within the agricultural community. This study sought to analyze the association between pro-environmental and scientific attitudes on the one hand, and structural measures of pro-environmental behaviors on the other hand, among Swiss farmers. Using surveys from 2020 to 2022, along with direct assessments of Biodiversity Promotion Areas (BPAs), and Credit Point System (CPS), this research aimed to uncover the personal factors that motivate farmers to engage in pro-environmental behaviors. Our results indicated a positive association between pro-environmental attitudes and the proportion of high-quality BPAs. Contrary to initial hypotheses, no significant association was found between self-reported pro-environmental behaviors and assessments of biodiversity promotion areas nor credit point system. In addition, no tested attitudes were significantly associated with BPA richness nor with the number of CPS points, suggesting that external constraints may strongly influence these behaviors. These findings suggest a complex relationship between farmers' attitudes and their pro-environmental actions. This study highlights the need for further research and emphasizes the importance of considering psychosocial variables to develop targeted interventions and policies that support farmers in their critical role in biodiversity conservation and ensure that agricultural practices contribute positively to environmental conservation efforts.

Keywords: agriculture, attitudes towards science, biodiversity promotion areas, pro-environmental attitudes, pro-environmental behaviors, sustainable practices.

1. Introduction

Agriculture, occupying over 30% of the world's land area (Ramankutty et al. 2008; Foley et al. 2011), is one of the main causes of environmental degradation (Foley et al. 2005; Stoate et al. 2009) and a primary driver of biodiversity loss (Maxwell et al. 2016). To mitigate this negative impact, and even to counterbalance it by increasing biodiversity, numerous strategies have been developed (Perfecto and Vandermeer 2010), and the critical role of farmers in biodiversity conservation has been increasingly acknowledged in recent years (Perfecto and Vandermeer 2010; Tscharntke et al. 2012). As a consequence, governments worldwide have been implementing a variety of measures to encourage sustainable agricultural practices among farmers. Many countries have adopted policies that promote wildlife-friendly farming, with specific programs targeting an improvement in farmland biodiversity (OECD 2023). In Europe, under the Common Agricultural Policy 2014-2020 (CAP), farmers received direct payments when they maintained permanent grasslands, undertook crop diversification, and dedicated 5% of their lands to ecological focus areas (Regulation 1307/2013). With the CAP 2023-2027, the ambitions are greater, with the objective to reach 10% of agricultural land under organic farming. To reach this, every farm will have at least 3% of arable land dedicated to biodiversity and non-productive elements, and 25% of the budget for direct payment will be allocated to eco-schemes to encourage environment-friendly farming practices (European Commission, 2024).

In Switzerland, since 1993, farmers are required to allocate at least 7% of their agricultural land as Biodiversity Promotion Areas (BPA) (OFAG, 2024). These areas are integral to Swiss agricultural policy, which provides subsidies to farmers for maintaining and enhancing the ecological quality of their land. Since the Agricultural Policy 2014-2017 (OFAG, PA 14-17), the quality of these BPAs in terms of contribution to biodiversity conservation is rigorously assessed, and higher subsidies are granted for areas meeting higher quality to further incentivize farmers (OFAG-OPD, 2024). Each BPA can be categorized either as quality one, which meets the minimum required standards, or quality two, characterized by outstanding ecological value specific to each type of biodiversity promotion area. This system not only encourages the creation of diverse habitats, such as hedgerows, wildflower strips, and extensively used meadows or pastures, but also promotes the maintenance of these areas at a high ecological standard. Each habitat type serves unique ecological functions, contributing to a rich biodiversity (Aviron et al. 2009; Schütz et al. 2022). By 2025, it is planned to increase the biodiversity promotion areas that are the most impactful for biodiversity, with farmers being asked to allocate at least 3.5% in arable land. Biodiversity promotion areas in arable land are highly important as they provide wildlife and native crop flowers with habitats that are undisturbed over a longer period than other biodiversity promotion areas. Included in arable lands are wildflower strips, which are particularly interesting for biodiversity as they are left to grow naturally, with minimal human intervention. They provide many ecosystem services (Schütz et al. 2022), boost small mammal populations (Arlettaz, Krähenbühl, et al. 2010), providing food abundance for raptor species (Aschwanden et al. 2005), increase insect pollination potential (Sutter et al. 2018), and increase farmland bird population (Zingg et al. 2019). Additionally, Swiss farmers are encouraged to implement targeted measures like small structures to enhance biodiversity (e.g., wood stacks or rock piles), raptor perches, or bird nest boxes, further supporting specific species.

Given the central role that farmers play in enhancing biodiversity through these various conservation practices, it is essential to investigate the drivers behind their engagement. Understanding these motivations can provide insights into how agricultural policies and programs can be more effectively designed and implemented to support and expand these sustainable practices. Previous research has primarily focused on evaluating the direct outcomes of biodiversity promotion areas on biodiversity (Batáry et al. 2011; Batáry et al. 2015; Gabel et al. 2018) or on results-based approaches to conservation (Herzon et al. 2018). However, farmers' decisions and behaviors are often influenced by underlying psychological constructs, which are frequently ignored. This gap limits our understanding of the underlying attitudes that significantly influence farmers’ engagement in conservation efforts. Although the relationship between attitudes and behaviors is well-documented, particularly through Ajzen’s theory of planned behaviors (Ajzen 1991) and has been extensively studied in the current literature (examples of studies on farmers’ attitudes and pro-environmental behaviors, see Borges et al. 2014; Price and Leviston 2014; Senger et al. 2017), there is little research on how attitudes translate into tangible impacts on structural and territorial measures, such as implementing biodiversity promotion areas. Most studies assess farmers’ behavior with self-reported data, as evidenced by several literature reviews (Burton 2014; Bartkowski and Bartke 2018; Milliet et al. 2023). These self-reported data are typically gathered via surveys, due to their ease of collection and ability to rapidly yield vast amounts of information (Lange and Dewitte 2019). In contrast, direct measures of pro-environmental behaviors are more challenging to implement due to logistical and resource constraints (Lange and Dewitte 2019) and are thus much less evaluated in the current literature.

In addressing these gaps, our study aims to analyze the relationship between attitudes and structural measures of farmers indicating pro-environmental behaviors. We used three indicators: the proportion of high-quality biodiversity promotion areas, the richness of biodiversity promotion areas, and the number of CPS points. The latter is a tool developed by the Swiss Ornithological Institute in collaboration with IP-Suisse which measures farmers' overall pro-environmental behaviors, taking into account various potential confounding factors (Jenny et al. 2013). The data presented in this study focuses on attitudes towards science, pro-environmental attitudes, and self-reported pro-environmental behaviors, and were drawn from surveys conducted between 2020 and 2022. Based on existing literature that suggests a link between positive attitudes towards science and pro-environmental behaviors (Cologna and Siegrist 2020), we hypothesize a positive relationship between attitudes towards science and the structural on-farm measures of pro-environmental behaviors. Based on the theory of planned behaviors (Ajzen 1991), which states that attitudes precede and predict behaviors, we expect a positive correlation between pro-environmental attitudes and the structural on-farm measures of pro-environmental behaviors. Finally, we aim to critically assess the validity of self-reported pro-environmental behaviors, which is currently a subject of debate (Kormos and Gifford 2014). This will provide insights into the accuracy and reliability of self-assessment in reflecting actual pro-environmental actions among our study population.

This study aims to explore how individual beliefs and perceptions contribute to broader environmental conservation efforts. It aims to bridge the gap between psychological constructs and quantifiable environmental actions and advancing the understanding of sustainable agricultural practices.

2. Methods

This study investigates the predictive power of attitudes towards science, pro-environmental attitudes, and self-reported pro-environmental behaviors on structural on-farm measures of pro-environmental behaviors, using survey data and on-farm data provided by both the DGAV (Direction générale de l'agriculture, de la viticulture et des affaires vétérinaires) and IP-Suisse.

2.1 Sampling and data

A total of 257 farmers were invited to participate in this study by responding to a self-administrated questionnaire designed to collect sociodemographic and psychosocial variables. The questionnaires were sent annually over three years (2020, 2021, and 2022). Participants for this study were selected from three main sources. Initially, some participants were collaborators in a project to protect barn owls carried out by our research group and were selected from the research group's address book. Additionally, other participants who were not involved in the conservation project were randomly selected from a list of farmers from the state of Vaud in the same region as the first group. These individuals completed all three survey waves. The third group, also not engaged in the conservation project and selected from the same list, only contributed to the final survey wave in 2022. Although the analysis initially considered the distinction between these groups, no significant differences were found. Therefore, this predictor was then removed from the final analysis.

2.2 Sociodemographic and psychosocial variables

For this study, data were collected using self-administrated questionnaires to gather the attitudes data as well as some sociodemographic control variables. Participants reported their demographic details such as age, gender, production system, and farm size. To assess attitudes towards science, respondents rated their agreement with nine statements on a 5-point Likert scale (*1=Strongly Disagree, 5=Strongly Agree*). Using Exploratory Factor Analysis, we clustered these responses into two distinct variables: "trust towards science" (M=3.55, SD=0.96, α=0.79) and "perceived limitations of science" (M=3.34, SD=0.78, α=0.72).

Similarly, attitudes towards the environment and self-reported pro-environmental behaviors were evaluated through responses to 25 statements, on a 6-point Likert scale (*1=Strongly Disagree, 6=Strongly Agree*). Exploratory Factor Analysis was used to extract two key variables: "pro-environmental attitudes" (M=4.02, SD=0.84, α=0.8) and "self-reported pro-environmental behaviors" (M=4.35, SD=1.01, α=0.81).

For a comprehensive explanation of the methodological framework, including the questionnaire design and factor analysis procedures, please refer to Milliet et al. (submitted).

2.3 Structural on-farm measures of pro-environmental behaviors

All potential participants were initially contacted by phone to explain the goal of the study and to obtain their agreement for data collection on their structural on-farm measures of pro-environmental behaviors provided by both the DGAV (Direction générale de l'agriculture, de la viticulture et des affaires vétérinaires) and IP-Suisse. Structural on-farm measures were categorized into three different variables, each reflecting different aspects of farmers' commitment to ecological conservation. These variables were the proportion of high-quality biodiversity promotion areas, the richness of biodiversity promotion areas, and the number of CPS points. Out of the contacted farmers, 181 agreed to participate, including 50 collaborators, 77 non-collaborators since 2020 (NC-Group 1) and 54 non-collaborators since 2022 (NC-Group 2). Data on biodiversity promotion areas provided by the DGAV were obtained for 171 farmers (47 collaborators, 72 NC-Group 1, and 52 NC-Group 2) and CPS data were obtained for 56 farmers (12 collaborators, 24 NC-Group 1, 20 NC-Group 2).

2.3.1 Biodiversity Promotion Areas

Biodiversity promotion areas (BPA) are key components of Swiss Agricultural Policy, designed to enhance and preserve biodiversity within agricultural landscapes. There are several types of BPAs, such as extensively used meadows and pastures, hedges and rows of trees, flower strips and field margins, or high-stem orchards. Farmers who allocate parts of their land as BPAs receive financial compensation from the government and engage in long term contracts (at least 8 years). Every BPA is classified based on its quality as defined by the Swiss government. Quality one (QI) biodiversity promotion areas meet the minimum required standards, while quality two (QII) are characterized by outstanding ecological value. These areas garner higher subsidies than quality one due to their enhanced contribution to biodiversity promotion.

In this study, we used data provided by the DGAV to determine the total area of biodiversity promotion areas for each farmer (N=171), providing insight into their engagement in pro-environmental behaviors through two main measures: the proportion of high-quality BPAs and BPAs richness.

2.3.1.1 Proportion of high-quality BPAs

Quality two biodiversity promotion areas (QII) are recognized for their superior ecological values, making the proportion of these areas a robust indicator of farmers' commitment to enhancing the ecological quality of their land. In light of this, we calculated for each participant (N=171) the proportion of high-quality biodiversity promotion areas (QII) in comparison to their total biodiversity promotion areas (QI + QII).

2.3.1.2 BPAs richness

In addition to quality, the richness of biodiversity promotion areas plays an essential role in promoting biodiversity by offering a broader array of ecological habitats (Herzog et al. 2017). This diversity not only reflects the scope of ecological engagement among farmers but also underscores their commitment to pro-environmental behaviors, highlighting their intrinsic motivation against practical constraints. To capture this dimension, we calculated the richness of biodiversity promotion areas (BPAs) for each farmer (N=171). This richness index is calculated as the ratio of the number of distinct BPA types present to the total number of BPAs managed by the farmer.

2.3.2 CPS points

To quantitatively assess the intensity and efficacy of broader pro-environmental practices beyond mere biodiversity promotion areas, this study incorporated data from the Credit Point System (CPS), provided by IP-Suisse. The CPS, developed by Jenny et al. (2013), serves as a pragmatic approach for farmers to quantify their contributions to biodiversity. It encompasses a catalog of 32 options that farmers can implement to positively impact farm biodiversity, ranging from participating in the Swiss agri-environment scheme's Biodiversity Promotion Areas to adopting specific agricultural practices such as the non-use of herbicides and staggered mowing. Importantly, CPS is designed to account for farm size, as it assigns points based on the proportion of each measure implemented relative to the overall farm area, and they are weighted according to their benefit for biodiversity. Farmers are required to score at least 15 points to get the IP-Suisse label, but they can score more points by applying these various measures on their farm, highlighting their concrete motivation for biodiversity. Given that CPS points are updated annually based on farmers' contributions, we collected these data for each IP-Suisse affiliated farmer (N=56) for the years 2019, 2020, 2021, 2022, and 2023.

2.4 Transparency and openness

Statistical analyses in this study were carried out using R version 4.2.1 (R Core Team, based in Vienna, Austria), with the RStudio interface (RStudio Team, 2022). We fitted models and examined them for predictor collinearity, and model assumptions were verified via the *performance* package (Lüdecke et al., 2021) and by visual inspection of the residual diagnostic plots. Effects were considered significant when p-values were smaller than .05.

The design, hypotheses, and analyses of this research were not pre-registered. Participant inclusion was primarily guided by the number of farmers taking part in the conservation project. This initial group was expanded to include non-collaborators who participated in the survey, as described in Milliet et al. (submitted), and further refined by obtaining consent from farmers to use their data. The data and log files used in the analyses are available on the project's page on the Open Science Framework (OSF).

For the sake of disclosure, it should be noted that other variables were measured in this study beyond the scope of this paper. The association between the collaboration in the conservation project status and psychosocial variables and their association over time were analyzed in a previous study (Milliet et al., submitted).

3. Results

3.1 Descriptive results

Regarding farm characteristics, our analysis indicated a prevalence of large farms, with over half of the respondents owning farms larger than 40 hectares. The farm types within our sample were diverse, predominantly farms engaging in a mix of agricultural activities, such as combined cattle farming and cropping, followed by large crop farms. As for the production system, the majority of respondents employed either conventional farming methods (22%) or adhered to the IP-Suisse label (33%), or a combination of both (31%). A smaller group of farmers (12%) reported using organic farming practices.

It is important to highlight that our data set was skewed towards men participants (11 women and 159 men). To account for this, we conducted analyses on both the full sample and on a subset containing only men. Given that the results were consistent across both analyses, we opted to include the entire sample in our findings.

3.1.1 Biodiversity Promotion Areas

Overall, farmers had 8.08% of high-quality biodiversity promotion areas on their farm (*SD=8.2%, max=41.43%, min=0.20%,* Fig. 1A), and a richness of 0.37 (*SD=0.11, max=0.8, min=0.17*, Fig. 1B).

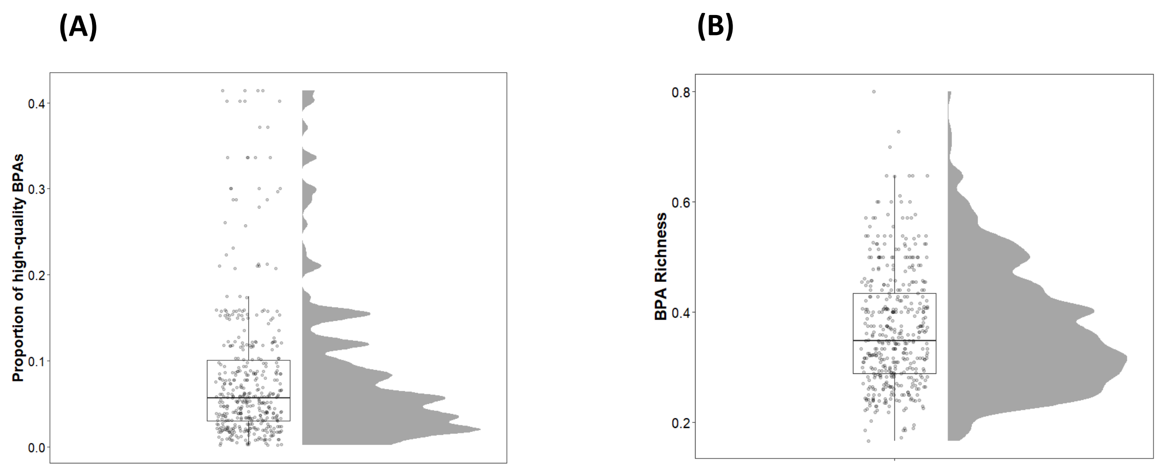

Figure 1: Representation of the various biodiversity promotion areas metrics*: Graphical representation of the distribution of the proportion of high-quality biodiversity promotion area (BPA) (A), and the BPAs richness (B).*

3.1.2 CPS points

IP-Suisse farmers (N=56) had on average 21.6 CPS points (*SD=4.41, max=31.7, min=4*), which varied slightly over the years (*2019: mean=21.66, SD=3.93; 2020: mean = 21.69, SD=3.98; 2021: mean=21.98, SD=3.90; 2022: mean=21.67, SD=4.93; 2023: mean=21.11, SD=4.76*, Fig. 2)

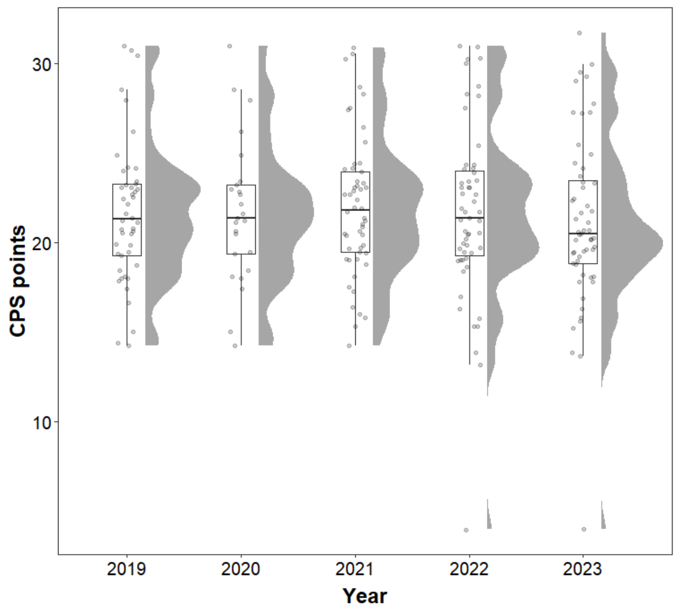

Figure 2: Representation of the CPS points over the years: *Graphical representation of the distribution of the CPS points for the years 2019 to 2023.*

3.1.3 Correlation between the various structural on-farm measures

Analysis revealed a non-significant negative correlation between the proportion of high-quality biodiversity promotion areas (BPAs) and their richness (*r(169) = -.18, p=.86*), a slight positive correlation between the proportion of high-quality BPAs and the number of CPS points (*r(42) = .26, p=.09*), and a non-significant negative correlation between the BPA richness and the number of CPS points (*r(42) = -.15, p=.31*). These weak correlations suggest that the three variables capture different dimensions of farmers' pro-environmental behaviors, each offering a unique perspective on their environmental engagement.

3.2 The relationship between attitudes and self-reported pro-environmental behaviors with structural on-farm measures of pro-environmental behaviors

The main objective of this study is to estimate the relationship between attitudes towards science, pro-environmental attitudes, and self-reported pro-environmental behaviors, on the one hand, and structural on-farm measures of pro-environmental behaviors, on the other hand. This was done through three sets of analyses, each focusing on a specific measure of pro-environmental behavior. The first analysis was on the proportion of high-quality biodiversity promotion areas (BPAs), the second on the richness of BPAs, and the last on the number of CPS points.

3.2.1 Biodiversity Promotion Areas

Farmers commit to BPAs for 8 years, resulting in BPAs data exhibiting stability over time. Consequently, we used data from the third wave of the survey only for the attitude's variables, being the wave with most respondents.

3.2.1.1 Proportion of high-quality BPAs

We first explored the proportion of high-quality BPAs (QII) on farms, bounded between 0 and 1. We used generalized linear models (GLM) with a binomial distribution from the function *glmer* from the package *lme4* (Bates et al., 2015). In this model, attitudes towards science (i.e. trust towards science, perceived limitations of science), pro-environmental attitudes, and self-reported pro-environmental behaviors were added as fixed factors. Moreover, to account for sociodemographic variables, we added farmers' age, and farm size as control fixed factors. The type of agriculture (Conventional, IP-Suisse, Organic, or a mix of several) was added as a random intercept.

The analysis revealed that pro-environmental attitudes were positively correlated with the proportion of high-quality BPA. This relationship suggests that farmers with greater perception of ecological matters have higher high-quality BPA on their land. We found no evidence of an effect of the other variables tested, namely trust towards science, perceived limitations of science, self-reported pro-environmental behaviors, farm size, and farmers' age (Table 1).

Table 1: Analyses for the proportion of high-quality BPAs: Results of fitting generalized linear mixed models to the proportion of high-quality biodiversity promotion areas (BPAs) bounded between 0 and 1. The type of agriculture (Conventional, IP-Suisse, Organic, Conventional and IP-Suisse, Organic and IP-Suisse) was added as random intercepts. Significant terms (p<0.05) are written in bold.

Variable	Estimates (SE)	t	p
(Intercept)	0.02 (0.21)	-5.31	<0.01
Trust towards science	0.91 (0.08)	-1.02	0.308
Perceived limitations of science	0.93 (0.08)	-0.93	0.354
Pro-environmental attitudes	1.49 (0.12)	5.08	**<0.001**
Self-reported pro-environmental behaviors	1.03 (0.09)	0.29	0.772
Age	1.01 (0.01)	1.64	0.101
Farm size – Large	0.93 (0.21)	-0.32	0.747
Farm size – Medium	0.68 (0.17)	-1.57	0.115
Random Effects		$\tau_{00\ \text{type of agriculture}}$ (SD)	0.04 (0.21)
		Nb groups	5
Model fit		Observations	112
		Marginal R^2	0.041
		Conditional R^2	0.053

3.2.1.2 BPAs richness

The analysis of the second measured pro-environmental behaviors focused on the richness of biodiversity promotion areas (BPAs). Again, a generalized linear model (GLM) with a beta distribution from the function *glmer* from the package *lme4* (Bates et al., 2015) was used, and the same predictors as previously (trust towards science, perceived limitations of science, pro-environmental attitudes, and self-reported pro-environmental behaviors), as well as the same control variables (farmers' age, farm size). The type of agriculture (Conventional, IP-Suisse, Organic, or a mix of several) was also added as a random intercept.

Unlike the first analysis, the model found no significant association between pro-environmental attitudes and the BPAs richness, nor with attitudes towards science and self-reported pro-environmental behaviors. However, the analysis revealed a significant negative association between farmers' age and BPAs richness. This finding indicates that older farmers tend to have lower richness of biodiversity promotion areas on their farms compared to their younger counterparts. Furthermore, farmers operating on smaller farms tend to maintain higher BPAs richness compared to larger farms (Table 2).

Table 2: Analyses for BPAs richness: Results of fitting generalized linear mixed models to the richness of biodiversity promotion areas (BPAs). The type of agriculture (Conventional, IP-Suisse, Organic, or a mix) was added as random intercepts. Significant terms ($p<0.05$) are written in bold.

Variable	Estimates (SE)	t	p
(Intercept)	0.79 (0.11)	-1.71	0.087
Trust towards science	0.96 (0.04)	-1.16	0.247
Perceived limitations of science	1.03 (0.04)	0.72	0.470
Pro-environmental attitudes	1.04 (0.04)	1.05	0.292
Self-reported PEB	1.03 (0.04)	0.73	0.468
Age	0.92 (0.03)	-2.30	**0.022**
Farm size - Large	0.60 (0.08)	-3.84	**<0.001**
Farm size - Medium	0.79 (0.11)	-1.75	0.081
Random Effects		τ_{00} type of agriculture (SD)	0.01 (0.10)
		Nb groups	5
Model fit		Observations	112
		Marginal R^2	0.014
		Conditional R^2	0.017

3.2.2 CPS points

In our final analysis, we explored the number of CPS points, a measure specific to farmers affiliated with the IP-Suisse label. We thus used a subset of farmers in this analysis (N=56). Our analysis incorporated data from all survey periods alongside CPS points specifically for the corresponding years of the surveys (2020, 2021, and 2022) as CPS points are evaluated annually. We constructed a linear mixed model from the function *lmer* from the package *lme4* (Bates et al., 2015). Attitudes towards science (i.e. trust towards science and perceived limitations of science), pro-environmental attitudes, and self-reported pro-environmental behaviors were added as fixed factors, together with control fixed factors (age, and farm size), and year. To account for repeated measures, the farmer identity was added as a random intercept.

Our analysis revealed that none of the variables tested showed a statistically significant effect on the number of CPS points. Farm size suggested potential influence, with medium-sized farms having fewer CPS points compared to small farms. However, this effect was not visible between large and small farms (Table 3).

Table 3: Analyses for CPS points: Results of fitting linear mixed models to the number of CPS points per farmer per year. Farmer identity (FarmerID) was added as random intercepts. Significant terms ($p<0.05$) are written in bold.

Variable	Estimates (SE)	t	p
(Intercept)	17.02 (4.71)	3.61	**0.001**
Trust towards science	0.34 (0.32)	1.07	0.288
Perceived limitations of science	0.19 (0.53)	0.36	0.721
Pro-environmental attitudes	-0.15 (0.51)	-0.30	0.766
Self-reported PEB	0.15 (0.32)	0.49	0.629
Age	0.07 (0.06)	1.18	0.242
Farm size - Large	-3.52 (2.63)	-1.34	0.186
Farm size – Medium	-5.66 (2.69)	-2.10	**0.039**
Year	0.43 (0.32)	1.33	0.189
Random Effects		$\tau_{00\ farmerID}$ (SD)	11.12 (3.3)
		Nb groups	42
Model fit		Observations	75
		Marginal R^2	0.154
		Conditional R^2	0.855

4. Discussion

The primary objective of this research was to estimate the predictive power of attitudes towards science and the environment on farmers' structural measures of pro-environmental behaviors. Given agriculture's significant impact on the environment (Foley et al. 2005; Stoate et al. 2009), understanding the personal motivators that drive farmers towards more pro-environmental practices is essential. To the best of our knowledge, this research represents the first quantitative assessment of pro-environmental behaviors among Swiss farmers and their correlation with attitudes towards science and the environment. Previous studies in this field have mainly relied on result-based approaches to evaluate the effectiveness of pro-environmental actions on environmental outcomes (Herzon et al. 2018) or on demographic factors explaining farmers' commitment (Knowler and Bradshaw 2007; Burton 2014). The present study differs from this trend by aiming to identify the intrinsic factors that motivate farmers to adopt pro-environmental behaviors and to quantitatively measure these behaviors. Our investigation concentrated on three main measured on-farm pro-environmental behaviors, namely the proportion of high-quality biodiversity promotion areas (BPAs), the BPA richness, and the number of CPS points. Each of these metrics serves as an indicator reflecting different levels of farmers' commitment to ecology.

4.1 Biodiversity promotion areas

In Switzerland, high-quality biodiversity promotion areas (BPA) are essential to increase on-farm biodiversity, as they have higher ecological standards. Farmers receive higher subsidies for this type of areas, but they are more constraining regarding management compared to lower-quality BPAs. They thus represent a good proxy for farmers' engagement towards biodiversity conservation. In addition to high quality, the richness of biodiversity promotion area is also essential, providing various ecological habitats (Herzog et al. 2017) and is a good indicator of farmers' commitment to pro-environmental actions.

The observed relation between pro-environmental attitudes and the proportion of high-quality BPAs suggests that farmers who are more skeptical towards ecological matter are less engaged in biodiversity conservation. This finding is in line with our expectations and suggests that personal beliefs are related to environmental practices in farming. This study highlights the potential for farmers' personal beliefs to drive environmental change by translating pro-environmental attitudes into actionable conservation practices. Addressing this skepticism is not simply a matter of changing minds but of transforming agricultural practices. Efforts to mitigate skepticism could play an essential role in promoting biodiversity conservation on farms, and educational and conservation programs that aim to shift perceptions about the importance of ecological matters could have far-reaching effects on conservation efforts. By enhancing understanding and appreciation of ecological values among farmers, such initiatives could promote a more conducive environment for the adoption of biodiversity promotion areas. This approach emphasizes the importance of addressing ecological skepticism, not only as a way to change attitudes but also as a strategy to achieve tangible improvement in biodiversity conservation on agricultural lands.

However, the study found no significant association between farmers' attitudes towards the environment and the richness of biodiversity promotion areas (BPA). The decision to enhance BPA richness could be more influenced by practical constraints and opportunities, such as financial resources, availability of support, and land management priorities, rather than solely by farmers’ pro-environmental attitudes compared to high-quality BPAs. This distinction highlights the intricate and indirect influence pro-environmental attitudes might have on farmers' pro-environmental actions. Due to this complexity, additional research is required to further explore the interplay between personal beliefs, practical constraints, and conservation outcomes, and to disentangle the various factors that contribute to farmers' choices regarding biodiversity conservation.

Our analysis revealed that self-reported pro-environmental behaviors showed no significant relation with measured pro-environmental behaviors. This result was not expected and highlights a discrepancy between how pro-environmental behaviors are reported and how they are empirically observed. This divergence suggests that farmers’ perceptions or self-assessments of their pro-environmental actions may not accurately reflect their actual practices on the ground. Several factors may contribute to this discrepancy. First, self-reported behaviors are subject to biases such as social desirability bias, where respondents may over-report behaviors they believe are viewed favorably by society or, in this case, the research community (Kormos and Gifford 2014). Second, there may be a lack of awareness among farmers about what constitutes effective pro-environmental behaviors, as noted in previous studies (Knook et al. 2020). Finally, self-reported pro-environmental behaviors in this study were general on-farm practices, with a particular focus on mowing methods and invasive species management. To better understand the consistency between self-reported and measured pro-environmental behaviors, future research should aim to directly compare self-reported and measured pro-environmental behaviors, ensuring that both sets of data refer to identical activities. Overall, our results underscore the critical importance of accurately measuring farmers' pro-environmental behaviors to reliably identify the underlying drivers of these practices.

The lack of a significant relation between attitudes towards science and structural measures of pro-environmental behaviors provides a nuanced understanding of the complex dynamics that govern farmers' environmental actions. This finding suggests that although farmers may acknowledge and appreciate scientific knowledge, this recognition does not necessarily translate into their conservation practices. Several factors could contribute to this disparity. Farmers may prioritize short-term viability over longer-term, science-informed environmental strategies due to pragmatic constraints such as economic pressures, available resources, or management challenges. There could be a differentiation between theoretical appreciation of science and its practical applicability in farming contexts. While farmers may understand and agree with scientific findings on ecological matters, they may find it challenging to integrate these insights into actionable practices due to a lack of clear guidance, support, or resources that translate science into practice, as summarized by Farwig et al. (2017). Additionally, it is possible that the aspects of science valued by farmers may not be directly linked to the pro-environmental practices measured in this study. Bridging the gap between scientific knowledge and practical farming operations is crucial in achieving this goal. Efforts to enhance the impact of scientific attitudes on environmental practices could benefit from focused extension services and specific on-farm advice that translate scientific findings into concrete, feasible actions. Additionally, promoting dialogue between the scientific community and farmers can help identify and address specific barriers to the use of science to promote sustainable agriculture, as evidenced by Arlettaz, Schaub, et al. (2010) and proposed by many others (Braunisch et al. 2012; Laurance et al. 2012; Young et al. 2014; Farwig et al. 2017).

Regarding sociodemographic factors, our analysis showed that farm size is negatively associated with biodiversity promotion areas' richness. Overall, our results suggest that smaller farms may be more engaged towards biodiversity conservation, in terms of BPA richness. This contradicts the previous overall agreement that larger farms typically associate with greater ecological engagement (Lastra-Bravo et al. 2015). Differences could be due to the definition of farm size, as they differ quite a lot among European countries (Wigier and Kowalski 2017), but also to the sample size bias, particularly the underrepresentation of farms smaller than 20 hectares in our study. To address these issues and offer more definitive insights, future research should aim to expand the sample to include a broader range of farm sizes, enabling a more comprehensive understanding of the link between farm size and engagement in biodiversity conservation. Our analysis also revealed a negative relation between farmers' age and the richness of biodiversity promotion areas (BPAs). This result is consistent with previous findings, which report that younger farmers are more engaged in pro-environmental practices (Burton 2014). However, no effect was found for the quality of BPAs. This may indicate that while older farmers may focus on maintaining or enhancing the quality of these areas, younger farmers appear to simultaneously strive for both quality and diversity. The distinction between focusing on quality versus diversity highlights the nuanced approaches that different age groups may adopt in their environmental management practices, reflecting a balance between ecological goals and operational practicability.

4.2 CPS points

Our analysis revealed no significant association between any of the variables tested and the number of CPS points among IP-Suisse farmers. Previous studies have primarily focused on assessing the effectiveness of CPS in actually measuring on-farm biodiversity (Jenny et al. 2013; Birrer et al. 2014; Zellweger-Fischer et al. 2015; Stoeckli et al. 2017; Gabel et al. 2018). Our findings emphasize the need for further research into farmers' personal variables that may predict CPS points, with an increased sample size to facilitate more in-depth analysis that was not possible in the current study. This metric is of great interest because it takes into account various confounding factors. The variation observed among our study participants suggests a remarkable level of commitment, with the majority exceeding the baseline requirement of 15 points. However, it also points to the complexity of factors that motivate and influence the achievement of CPS points, which we were not able to capture in the present study.

5. Conclusion

Farmers' pro-environmental behaviors are essential for promoting sustainable agricultural practices and conserving biodiversity. This study highlights the nuanced relationships between farmers' pro-environmental attitudes and their pro-environmental behaviors, underscoring the complexity of translating personal beliefs into tangible conservation efforts. Furthermore, our research has revealed a significant gap between self-reported and measured pro-environmental behaviors, highlighting a critical need for further research. These findings demonstrate the necessity for future research to use objective methodologies when evaluating pro-environmental behaviors. Research is crucial for understanding the drivers behind sustainable farming practices, enabling the development of effective policies and interventions to promote pro-environmental engagement within the farming community. Enhancing our understanding of these dynamics will be key to supporting farmers in their role as land managers and ensuring the longevity of agricultural ecosystems.

Material access

Open Science Framework link:
https://osf.io/52c83/?view_only=fd5e108155054b5a8b1eee10d19b1ba6

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Supplementary material

Supplementary material I – Analysis of Equivalence

Table S1: Results of the equivalence analysis between collaborators, non-collaborators Group 1, and non-collaborators Group 2. Results of applying a Kruskal-Wallis test to the numerical variable (age) and a Pearson Chi-squared test for the categorical variables (civil state, farm type, farm size, type of agriculture) to compare the distributions between collaborators (N=50), non-collaborators Group 1 (N=77), and non-collaborators Group 2 (N=54). Descriptive values (mean, standard deviation, counts and percentages) are provided for each group as well as the results of the corresponding tests. P.values have been corrected with Bonferroni correction. Significant results are indicated in bold.

Variable	**Collaborators (N=50)**	**Non-Collaborators Group 1 (N=77)**	**Non-Collaborators Group 2 (N=54)**	**Test result**
Age	Mean = 51.012 (sd=10.99)	Mean = 51.94 (sd=10.30)	Mean = 48.76 (sd=9.66)	H(2) = 3.45 p= 1.00
Gender				
Men	**35 (70%)**	**73 (94.81%)**	**51 (94.44%)**	**$\chi^2(2)$=9.645 p=.048**
Women	**7 (14%)**	**2 (2.59%)**	**2 (3.70%)**	
Civil State				
Single	8 (16%)	18 (23.38%)	12 (22.22%)	$\chi^2(8)$= 5.55 p=1.00
Married	30 (60%)	48 (62.34%)	33 (61.11%)	
Divorced	4 (8%)	7 (9.09%)	7 (12.96%)	
Separated	2 (4%)	0 (0%)	2 (3.70%)	
Widow·er	0 (0%)	1 (1.30%)	0 (0%)	
Farm type*				
Mix (>2 types)	34 (68%)	49 (63.63%)	37 (68.52%)	$\chi^2(20)$= 22.48 p=1.00
Large crops	10 (20%)	6 (7.79%)	7 (12.96%)	
Large crops and poultry	2 (4%)	4 (5.19%)	2 (3.70%)	
large crops and cattle	1 (2%)	4 (5.19%)	3 (5.55%)	
large crops and horses	1 (2%)	3 (3.89%)	0 (0%)	
large crops and viticulture	1 (2%)	1 (1.30%)	2 (3.70%)	
Cattle	1 (2%)	0 (0%)	0 (0%)	
Large crops and fodder crops	0 (0%)	6 (7.79%)	2 (3.70%)	
Large crops and arboriculture	0 (0%)	1 (1.30%)	0 (0%)	
Fodder crops and cattle	0 (0%)	0 (0%)	1 (1.85%)	
Large crops and vegetable crops	0 (0%)	3 (3.89%)	0 (0%)	
Farm size				
Small (<20 ha)	5 (10%)	6 (7.79%)	6 (11.11%)	$\chi^2(4)$ = 4.79 p=1.00
Medium (21-40 ha)	12 (24%)	30 (38.96%)	25 (46.29%)	
Large (>40 ha)	28 (56%)	39 (50.65%)	23 (42.59%)	
Type of agriculture				
Traditional	7 (14%)	15 (19.48%)	19 (35.19%)	$\chi^2(8)$ = 11.72 p=.99
Traditional and IP-Suisse	20 (40%)	26 (33.77%)	10 (18.52%)	
IP-Suisse	15 (30%)	25 (32.47%)	19 (35.19%)	
Organic	7 (14%)	9 (11.69%)	6 (11.11%)	
Organic and IP-Suisse	1 (2%)	2 (2.60%)	0 (0%)	

Given the large number of categories within farm type, initial chi-squared tests did not meet all conditions. To address this, categories were grouped for statistical robustness, which did not alter the results of the analyses ($\chi^2(4)$=7.89, p=.99*), thus confirming the comparability of the datasets. Note that while this categorization approach was adopted for statistical validity, the original, more detailed categorization is retained in this table for comprehensive insight.

Chapter 4

The effects of land use changes on site occupancy and breeding success of the barn owl (*Tyto alba*) from 1993 to 2020

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The effects of land use changes on site occupancy and breeding success of the barn owl (*Tyto alba*) from 1993 to 2020

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ABSTRACT

Land use changes, driven by human activities such as agricultural intensification and urban expansion, have drastic effects on biodiversity. As these changes are anticipated to continue, understanding species' adaptations to their evolving habitats is essential to find solutions for effective conservation efforts and sustainable management. In this study, we investigated how long-term changes in the agricultural landscape influence the breeding performance of a population of barn owls (*Tyto alba*) residing in nest boxes using data collected from 1993 until 2020. Specifically, we assessed how agricultural intensification, urbanization, and site availability affected barn owls' site occupancy and breeding success. Our results reveal that nest boxes surrounded by more agricultural fields are more likely to be occupied and have higher fledging success. Additionally, nest boxes installed higher on the barn were more likely to be occupied. Owls laid more eggs in nest boxes facing North than South or East. Clutches laid in nest boxes installed at higher altitudes were smaller. Finally, nest boxes with a higher density of surrounding nest boxes were less likely to be occupied and had smaller clutches. These insights show barn owls high reliance on the agricultural landscape surrounding their nesting sites, but also the importance of nest box characteristics to optimize their breeding success.

1. Introduction

Over the past decades, the environment has undergone profound transformations, shaped by the ever-increasing human population and the various strategies and decisions that societies have implemented in response to this growth. Landscapes, once characterized by the ecological richness of wildlife species, are now altered by anthropogenic activities. Among these, agricultural landscapes are perhaps the most affected (Stoate et al., 2009), undergoing a shift towards more intensive farming practices, a prevalence of monocultures with larger field sizes, and a substitution of natural surfaces by cultivated areas. Unfortunately, this intensification comes at a considerable environmental cost, notably with the decrease of biodiversity in agricultural landscapes (Robinson and Sutherland, 2002; Benton et al., 2003; Herzog et al., 2012; Wilson et al., 2016; Sirami et al., 2019). Among the most affected species are farmland birds, which have experienced a dramatic decline worldwide in the past few years (Bowler et al., 2021, Antoniazza et al., 2018). Nearly three

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years after a study published in the journal Science revealing that North America had lost 3 billion breeding birds since 1970 (Rosenberg et al., 2019), the 2022 State of the Birds Report for the United States (North American Bird Conservation Initiative, 2022) found that bird declines are continuing in almost every habitat, except wetlands. Grassland birds are experiencing the most severe declines among all habitats, a trend closely associated with intensified agricultural practices (Donald et al., 2006; Newton, 2004). The situation is similar in Europe, where land-use change tends to be a strong driver of bird population decline (Bowler et al., 2021; Silva et al., 2024). Therefore, it is essential to find solutions that not only meet the increasing demand for agricultural production but also actively preserve agricultural biodiversity.

Together with agricultural intensification, urban areas also keep growing, both in size and density, leading to habitat fragmentation and resource depletion. While some species have demonstrated a remarkable capacity to adapt to urban environments, described as urban exploiters by Blair (1996), the majority of species are restricted to increasingly small and isolated natural habitats. Many studies analyzed how bird species thrive in urban environments. Møller (2009) found that bird species better adapted to urban environments have specific characteristics (e.g. large breeding ranges, high propensity for dispersal, high rates of feeding innovation, and short flight distance when approached by a human), while Sol et al. (2014) found a phylogenetic signal for urbanization tolerance, implying that some families are more tolerant than others, such as *Sturnidae, Corvidae* or *Columbidae*. To develop efficient conservation strategies in such constantly changing environments, it is essential to understand how species respond to these changes.

Among the many species coping with the challenges posed by land use changes, the barn owl (*Tyto alba*) emerges as an exemplary study species. This nocturnal raptor lives in agricultural landscapes (Perrins and Snow, 1998), preying on small mammals, and nesting in barns and buildings (Roulin, 2020, Perrins and Snow, 1998). This dual reliance on both agricultural lands and urban areas makes the barn owl an ideal model for investigating how they are impacted by agricultural and urban changes. Furthermore, this species can contribute to natural pest control in agricultural fields (Meyrom et al., 2009; Donázar et al., 2016; Luna et al., 2020; Montoya et al., 2021), limiting small mammal populations that could otherwise cause significant crop damage (Peleg et al., 2018). In fact, during the breeding season alone, a breeding pair can consume up to 1000 prey items to feed their nestlings (George and Johnson, 2021, Schalcher et al., 2023). Therefore, understanding the adaptation of this bird to land use changes is essential. Previous studies have already explored this. Frey et al. (2011) studied a Swiss barn owl population from 1987 to 2009, estimating the influence of landscape features comprising urban areas and agricultural fields on barn owl breeding performances. Yet they did not account for environmental change, considering it as stable during the studied period, limiting insights into its impact on barn owls breeding success. Hindmarch et al. (2012) investigated the effect of landscape features, focusing on grasslands, urban areas, and roads, on a Canadian barn owl population. However, their study was constrained by limited data, having only two observation years, in 1990 and 2007.

The core objective of the present study is to evaluate the impact of land use change, specifically focusing on the agricultural intensification, urban areas expansion, and nest box density, on barn owl site occupancy and breeding success since the 1990s. On one hand, site occupancy provides insights into barn owl habitat preferences, helping to identify key habitat features influencing nest site selection. On the other hand, analyses on breeding success provide reliable measurements of the influence of habitat characteristics on barn owl reproductive success. By examining both variables together, we aim to assess which land uses correspond to high-quality habitats for the barn owl, focusing as much on the selection of breeding sites as on breeding performances, as advised by Johnson (2007).

We used data collected through a research project initiated in the early 1990s in Switzerland: On the Swiss Plateau, nearly 400 nest boxes have been gradually installed on farms since 1993 by scientists from the University of Lausanne in collaboration with the Swiss Ornithological Institute, with farmers' agreement. In the present study, we analyzed data accumulated since the start of this project to present days, encompassing variables such as agricultural land use change, urban area development, nest box density, and nest box characteristics. Through a multifaceted approach, we seek to gain a comprehensive understanding of how land use changes have influenced barn owl breeding success, to provide the best conservation strategies targeting this species. We expect landscape homogenization to adversely affect the breeding success of barn owls. Indeed, landscape heterogeneity enhances prey density and accessibility (Arlettaz et al., 2010; Gentili et al., 2014; Serafini et al., 2019; Sirami et al., 2019), suggesting that habitats with more diverse structures are likely to support better breeding outcomes. Regarding urban expansion, given barn owls' adaptation to human settlements, we expect a limited impact from the intensification of urban areas. However, this aspect has not been thoroughly investigated previously over the long term, and it is crucial to determine whether there is a threshold beyond which urbanization begins to negatively affect this species. Finally, our study aims at examining the influence of nest box characteristics and site density on barn owl breeding parameters. Research in other regions has explored similar dynamics, such as in the Hula Valley in Israel, where the location of nest boxes has been found to influence occupancy, nest boxes placed on trees showing higher occupancy, followed by nest boxes on poles in the shade and finally nest boxes on poles in the sun (Charter and Rozman, 2022). Similarly, in the Napa Valley in the USA, nest boxes constructed of wood and placed higher off the ground were more likely to be occupied (Wendt and Johnson, 2017). Despite these insights, the nest boxes and environmental conditions in our study differ from these examples. As such, we do not have specific predictions, but rather aim to elucidate the overall impact of nest box characteristics and site density on barn owl populations within our study context.

2. Material and methods

2.1. Study area and data collection

The present study focuses on a wild population of barn owls residing in nest boxes in Western Switzerland (Fig. 1 A-B). The study area of approximately 1'000 km^2 is mainly dominated by agricultural fields and urban areas comprising predominantly villages, the preferred habitat of the barn owl (Bunn et al., 1982).

Nest boxes are installed on barn walls, either inside with the flying hole facing the outside, or outside the barn (Fig. 1C). There can be up to two nest boxes installed in the same barn. Each barn with nest boxes, either one or two, is considered as a breeding site in this present paper. Nest boxes are usually installed between 4 and 10 m above the ground. They have been installed progressively since the 1990 s, reaching a total of 379 nest boxes at 310 different breeding sites nowadays.

For each nest box, we extracted five characteristics that can possibly impact barn owls' site occupancy and breeding success: (1) the orientation, referring to the direction in which the nest box entrance faces, specifically categorized as North, East, South, or West; (2) the height above the ground in meters where the nest box is installed in or on the barn; (3) the altitude above sea level where the nest box is located; (4) the number of nest boxes present at the breeding site (either one or two); (5) whether the nest box was occupied by a barn owl pair the preceding year or not.For the current study, only nest boxes installed before 1993 and that remained in place until 2021 were selected, ensuring a consistent temporal framework for the analyses (n=89). Among those nest boxes, the majority were facing East (n=54), followed by North (n=18), and South (n=13), and only four were facing West. Due to this bias in the dataset, we decided to remove the four nest boxes facing West from the analyses. Moreover, the vast majority are placed inside barns (n=74). It was thus decided to remove the 15 nest boxes placed outside barns for the same reasons. Consequently, the final analyses were conducted on 48 distinct breeding sites, encompassing a total of 72 nest boxes, as some nest boxes are placed at the same site (Fig. 1 A).

Every year, each nest box was monitored every month between March and August to assess if it was occupied or not, i.e. if a clutch

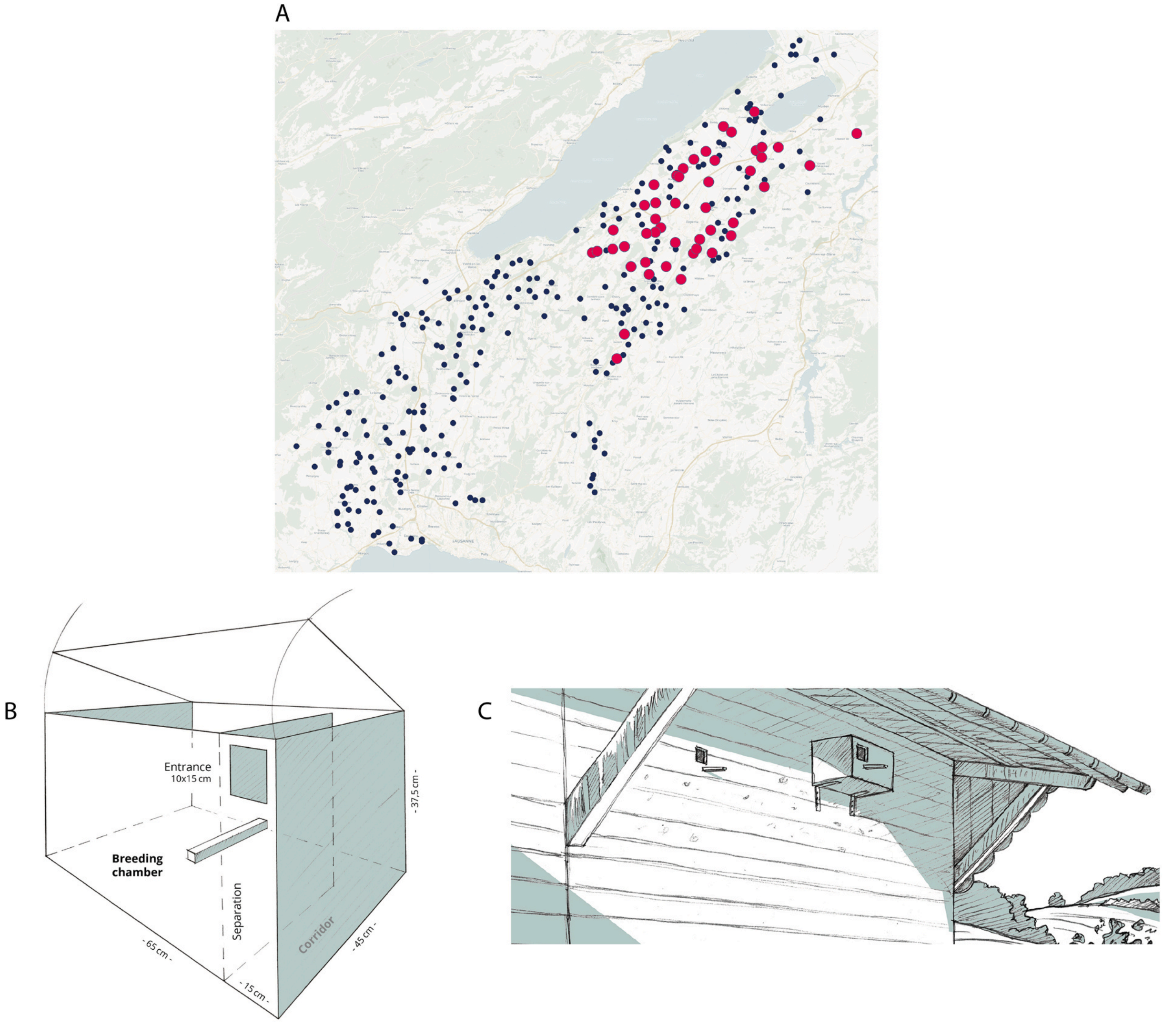

Fig. 1. Study area and nest box characteristics: (A) Map of the study area, with all nest boxes represented in black dots, and nest boxes selected for the present study in pink. (B) Scheme of a nest box, with internal dimensions. (C) Representation of the installation of two nest boxes, one inside the barn with the flying hole facing the outside (on the left) and one installed outside the barn (on the right). ©Laurent Willenegger for the artwork from Roulin (2020).

was present. Then, following Frey and colleagues' protocol (2011), breeding parameters were collected, including the clutch size, and the number of fledglings that survived until they were able to fly (over 55 days of age). Barn owls can produce several clutches per year. The first clutch represents the actual selection made by barn owl pairs throughout the winter. If this clutch fails or is abandoned, they can produce a replacement clutch. Finally, they can produce a second clutch after successfully completing the first one. For each clutch, the male and female identity was recorded, as well as the laying date, which is defined as the date when the first egg was laid, calculated according to the first-hatched nestling wing length, assuming a period of 32 days for incubation (Béziers and Roulin, 2016).

2.2. Surrounding environment

To estimate the impact of the surrounding environment on barn owl breeding parameters, we extracted three variables, namely the intensification of urban areas and agricultural fields and the density of surrounding breeding sites. Those three variables were extracted within a 1.5 km radius around each breeding site, corresponding to the rounded average home range size of barn owls (Almasi et al., 2013; Séchaud et al., 2021).

2.2.1. Urban areas

To determine the intensification of urban areas, we extracted the proportion of urban areas around each breeding site. We obtained aerial photos (50 cm resolution) of our study area from the Swiss Federal Office of Topography for the years 1993, 1998, 2007, and 2020. Using QGIS software 3.12.0 (QGIS Development Team, 2009), urban areas were manually delimited on the aerial photos. Any isolated building, city, or village was considered as urban area. The proportion of urban area in the 1.5 km radius was then extracted for each breeding site for the 4 years using the package *sf* in R (Pebesma, 2018). We then applied a linear interpolation between each year to estimate values for every year from 1993 to 2020 using the *approx* function in R.

2.2.2. Agricultural fields

The agricultural intensity level was determined by the number of fields surrounding each breeding site. A higher number of fields was supposed to be associated with increased field margins, which typically indicates less intensive agricultural use. Conversely, fewer fields suggest larger, more consolidated farming areas that are often more intensively cultivated. To extract the average number of fields around each breeding site, an algorithm able to detect field boundaries based on pixel greyscale values from the same aerial photos as urban areas was developed (Fig. S1). To do this, the pixel values of each photo were normalized to range from 0 to 255. A Gaussian blur with a sigma of 2 was applied to enhance between-fields contrast while minimizing within-fields variance (Canny, 1986; Wells, 1986). Forests, that were provided by the Swiss TLM3D catalogue (Swiss Topographic Landscape Model, n.d.) and urban areas, obtained as described in the above paragraph, were then assigned greyscale values of 0 to account only for agricultural fields. The number of fields was determined by analyzing the variance of greyscale values within a moving pane of 5 pixels on 6 transects of 1.5 km around the breeding site, at angles of 0°, 60°, 120°, 180°, 240°, and 300°, to capture a comprehensive and representative sample of the agricultural landscape surrounding each breeding site. To obtain an average number of fields around each breeding site, the mean of the 6 transects was extracted. This process was done for the years 1993, 1998, 2007, and 2020. Similar to urban area calculation, we then performed a linear interpolation using the *approx* function in R to estimate the mean number of fields for every year from 1993 to 2020.

2.2.3. Surrounding breeding sites density

To estimate whether the number of breeding sites surrounding each nest box could have an impact on barn owl breeding success and site occupancy, we extracted for each selected site the density of surrounding breeding sites in a radius of 1.5 km. As nest boxes were installed progressively since the 1990 s, we extracted this density every year, accounting for all available breeding sites, not only the ones selected in this study. This density metric was determined by summing the reciprocals of the distances to surrounding breeding sites, calculated as follows: $Density = \sum_{i=1}^{n} \frac{1}{d_i}$; where n is the number of surrounding breeding sites, and d_i represents the distance from the focal site to each breeding site. In our analysis, we differentiated the density measurements into two distinct categories for a more nuanced understanding. Firstly, we calculated the overall density of available breeding sites, encompassing all surrounding breeding sites, regardless of their occupancy status. This provided a broad view of the breeding site environment. Secondly, we focused specifically on barn owl breeding density, by calculating the density of only those breeding sites that were occupied, either before the laying date or simultaneously depending on the analysis.

2.2.4. Climatic data

Finally, as the analysis focuses on a 30-year period, it is essential to account for climatic variables. We thus extracted both daily temperature (minimal, maximal, mean) and average daily sum of precipitation data for every selected breeding site each year (MeteoSuisse, 2023).

2.3. Statistical analyses

The goal of this study is to understand what environmental factors impact barn owl site occupancy and breeding success. This was done through three sets of analyses, each one of them focusing on a specific response variable.

We first determined the factors influencing barn owl breeding parameters by focusing only on the first clutches of each breeding pair of the season. The reasons for this choice are threefold: second clutches typically occur near the first one or based on nest box availability rather than their specific characteristics, since many nest boxes are already occupied by pairs completing their first breeding attempt. Furthermore, the breeding success of second clutches is impacted by many confounding factors, such as the laying date of the first clutch or the size of the first clutch, and thus depends less on the environment (Béziers and Roulin, 2016). Finally, the probability of doing a second clutch depends on the parents' experience (Béziers and Roulin, 2016). For each first clutch, we extracted two breeding success variables: (1) the clutch size, defined as the number of eggs laid, and (2) the fledging success, corresponding to the proportion of eggs that hatched and survived until they were able to fly (over 55 days). For the clutch size, a linear mixed model (LMM) from the function *lmer* from package *lme4* (Bates et al., 2015) was used. Fledging success was modeled with a weighted generalized linear mixed model (GLMM) with a binomial family using the function *glmer* from the package *lme4* (Bates et al., 2015), with clutch size as weights. To disentangle between success and failure, we also run the model accounting only for successful clutches, i.e. clutches with at least one fledgling.

For the two global models, the predictors remained constant. The fixed factors included the surrounding environment (i.e. the number of fields interpolated, the proportion of urban areas interpolated, and the density of surrounding breeding sites), and nest box characteristics (i.e. the orientation, the height, the altitude, the number of nest boxes present at the site (one or two), whether the nest box was occupied the year before or not), as well as control variables, including climatic data (for the clutch size: average minimal daily temperatures and average daily sum of precipitations since 01st October the year preceding the laying date to the laying date; for the fledging success: number of extreme days (days above the average maximal temperature of the period) and average daily sum of precipitations from hatching date to 100 days after laying date), and laying date. We included the female ID, male ID, nest box ID, and year as random intercepts in the models to account for the non-independency of data and repeated measures. To understand the distinct impacts of the two variables of density of surrounding breeding sites, namely the density of available breeding sites and the density of breeding barn owls, we conducted our analysis in two separate runs. Each run included one of these variables, allowing us to isolate and compare their respective effects on the response variables.

We then determined the factors influencing site occupancy. A breeding site was defined as occupied in a given year if at least one barn owl's egg was found at the site, regardless of whether it was a first, replacement, or second clutch, and not occupied otherwise. In cases with double nest boxes at the same breeding site, occupancy was mutually exclusive; if one box was occupied in a given year, the other was not. To ensure analytical robustness and to avoid potential bias introduced by the mutual exclusion, we calculated occupancy based on the following criteria: if one of the nest boxes was occupied, that record was retained; if neither of the nest boxes was occupied, one record was randomly selected. This random selection was important to maintain the unbiased nature of the data. It is important to note that there were 12 instances where both nest boxes at the same site were simultaneously occupied within the same year, representing 0.8% of the data. In these rare cases, both records were retained to accurately reflect the site occupancy dynamics.

A GLMM with a binomial family was used using the function *glmer* from the package *lme4* (Bates et al., 2015). The predictors used were kept constant and aligned with those used in the first clutch level analyses (namely surrounding environment and nest box characteristics), except for the climatic data which were annual means (annual average minimal temperatures, annual average maximal temperatures, annual average precipitations). As the orientation and the height can vary between nest boxes at the same site, the nest box ID nested in the site ID was used as random intercepts in the models, in addition to the year for repeated measures. Again, we ran twice the model, once with the density of available breeding sites and once with the density of barn owl breeding.

All statistical analyses were conducted with R 4.2.1 (R Core Team, 2022), with RStudio (R. Team, 2022) as the graphic user interface. Models were fitted, checked for collinearity between predictors, and assumptions were verified using the *performance* package (Lüdecke et al., 2021) and by visually inspecting the residual diagnostic plots. The effects were considered significant when

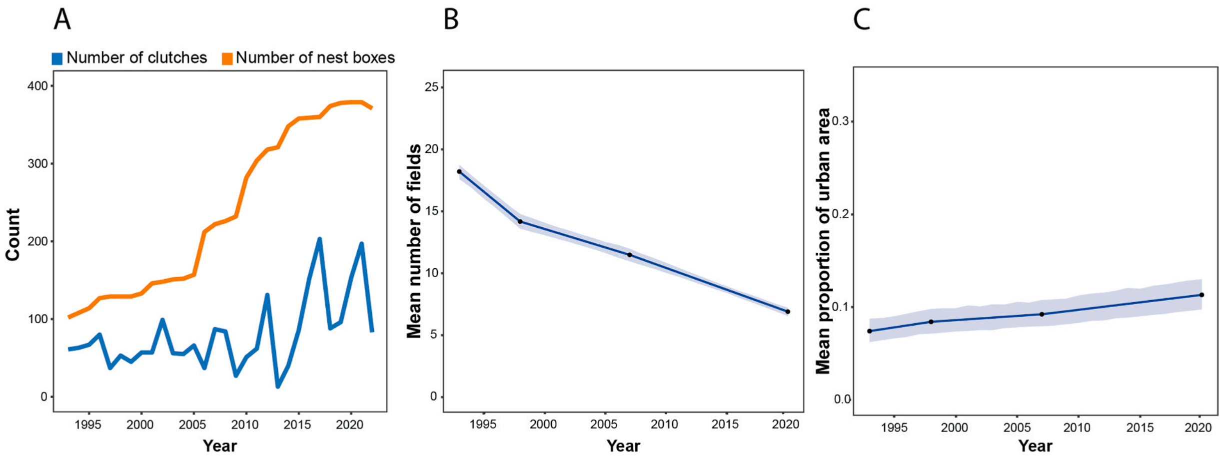

Fig. 2. Evolution of the number of nest boxes, clutches, agricultural fields, and proportion of urban areas over time: (A) Number of clutches (in blue) and number of nest boxes (in orange) from 1993 to 2020; (B) number of agricultural fields and (C) proportion of urban area within a radius of 1.5 km around the breeding sites from 1993 to 2020, with blue shaded area representing the 95% confidence interval of the estimated means (solid blue line), while the black dots represent the mean for the 4 years extracted.

their p-values were smaller than 0.05. Non-significant variables were removed step by step from the global model, making sure the Akaike information criterion (AIC) decreased when removed, to obtain the final model. If the AIC increased when a variable was removed, it was kept in the final model, even if not significant. In all models, linear predictors were z-scores standardized, involving a centering around a mean of zero and scaling to units of one standard deviation. This procedure allows direct comparison across variables. Spatial autocorrelation was assessed for each model by plotting residuals against spatial coordinates, and no evidence of spatial autocorrelation was detected across all models.

3. Results

Since 1993, a growing number of nest boxes have been installed, starting with 129 nest boxes in 1993 and ending up to 379 nest boxes in 2020 (Fig. 2A). As previously explained, for the present study, only nest boxes installed before 1993 and remained in place until 2021 were selected. The following analyses are then conducted on 72 nest boxes at 48 distinct breeding sites.

The habitat around the breeding sites changed substantially between 1993 and 2020. The number of agricultural fields decreased from 18 fields (*SD=2*) on average in 1993–6 fields (*SD=1*) in 2020, thus showing a 66.6% decrease (Fig. 2B). The proportion of urban areas, on the other hand, increased from 7.4% (*SD=5.3%*) in 1993–11.3% (*SD=7.3%*) in 2020, thus showing a 52.7% increase (Fig. 2C).

3.1. Breeding parameters

3.1.1. Clutch size

Regarding the clutch size, barn owls laid on average 5.8 eggs (*SD = 1.6*). The density of surrounding breeding sites tended to negatively impact the clutch size, with clutches decreasing by approximately 0.15 eggs per unit increase in density (Table 1, Fig. 3A). However, this was not the case when accounting for the density of occupied breeding sites (*scaled breeding barn owl density: Est=-0.01, SE=0.14, t=-0.08)*. Moreover, clutch size was impacted by nest box characteristics: Clutches were larger by roughly one egg in nest box facing North compared to South or East (*North: mean=6.57, CI: 6.02–7.11; East: mean=5.74, CI: 5.46–6.03; South: mean=5.75, CI: 5.31–6.20;* Table 1, Fig. 3B). No significant difference was observed between East and South orientations. Altitude is also essential, with an estimated decrease of 0.25 eggs for every 100-meter increase in altitude (Table 1, Fig. 3C). Finally, each 10-day delay in laying date led to an increase in clutch size by around 0.07 eggs (Table 1). We found no evidence of an effect of the other variables tested, namely the proportion of urban area, the number of agricultural fields, the height of the nest box, the number of nest boxes at the site, whether the nest box was occupied the previous year or not, and the climatic data on the clutch size (Table 1).

3.1.2. Fledging success

The second model focused on the fledging success (Table 2). On average, 69% of eggs hatched and reached fledging (*SD=30%*). An

Table 1
Analyses for clutch size: Results of fitting linear mixed models to the clutch size, before and after step-selection. Nest box ID, year, female ID, and male ID were added as random intercepts. Significant terms (p<0.05) are written in bold. The model is based on 406 broods in 64 different nest boxes at 47 distinct sites between 1993 and 2020.

Parameter	Global model			Final model		
Variable	Estimates (SE)	t	p	Estimates (SE)	t	p
Clutch size						
(Intercept)	6.58 (0.33)	19.78	<0.001	6.57 (0.27)	24.56	<0.001
Scaled proportion of urban areas	-0.09 (0.10)	-0.84	0.404	Rd		
Scaled number of agri. fields	-0.09 (0.11)	-0.84	0.402	Rd		
Scaled density of surr. breeding sites	-0.15 (0.08)	-1.85	0.065	-0.15 (0.08)	-1.89	0.059
East orientation	-0.84 (0.27)	-3.15	0.002	-0.82 (0.26)	-3.16	0.002
South orientation	-0.79 (0.34)	-2.36	0.019	-0.81 (0.31)	-2.62	0.009
Scaled heigth [m]	-0.09 (0.09)	-1.00	0.317	Rd		
Scaled altitude	-0.19 (0.09)	-2.01	0.045	-0.16 (0.08)	-1.99	0.047
Nb of nest boxes at the site	0.07 (0.20)	0.33	0.744	Rd		
Occupied previous year	-0.10 (0.16)	-0.64	0.523	Rd		
Scaled minimum T° previous winter	0.02 (0.16)	0.11	0.912	Rd		
Scaled mean precip. previous winter	-0.08 (0.15)	-0.53	0.597	Rd		
Scaled laying date	0.20 (0.12)	1.64	0.102	0.21 (0.08)	2.72	0.007
Random Effects						
	σ^2		1.52	σ^2		1.54
	$\tau_{00\ F\_ring}$		0.54	$\tau_{00\ F\_ring}$		0.51
	$\tau_{00\ M\_ring}$		0.06	$\tau_{00\ M\_ring}$		0.05
	$\tau_{00\ nestid}$		0.01	$\tau_{00\ nestid}$		0.00
	$\tau_{00\ year}$		0.29	$\tau_{00\ year}$		0.28
Model fit						
	Observations		406	Observations		406
	Marginal R^2		0.065	Marginal R^2		0.088
	AIC		1529.1	AIC		1502.2

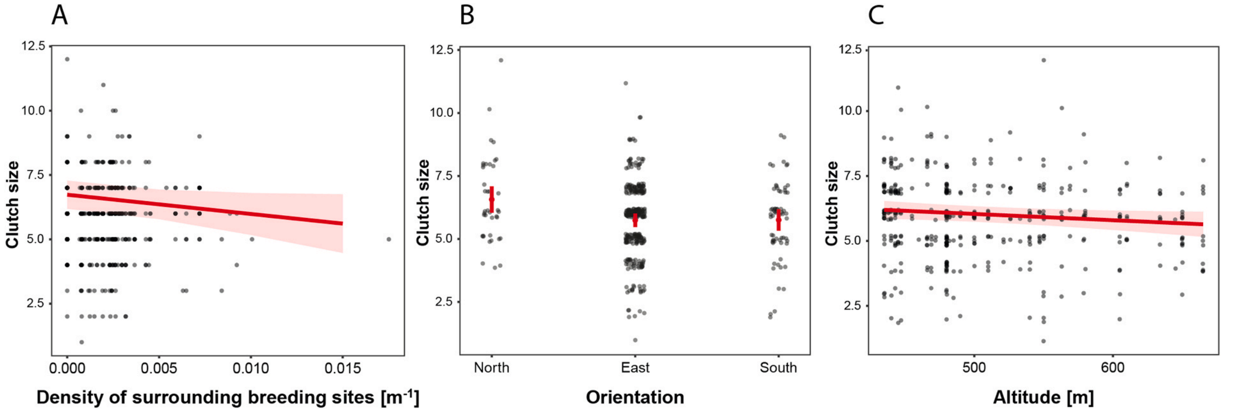

Fig. 3. Factors influencing clutch size: (A) the association between the density of surrounding breeding sites and clutch size, with the red shaded area representing the 95% confidence interval around the estimated means in solid red line, while the data are shown in black; (B) clutch size categorized by orientation, the data being shown in black, the red dots representing the predicted mean and the bars the 95% confidence intervals; (C) the correlation between altitude and clutch size, with the red shaded area representing the 95% confidence interval around the estimated means in solid red line, while the data are shown in black. The graphs present unscaled relationships for interpretative clarity, despite models utilizing scaled predictors.

increase in the proportion of urban areas was positively associated with fledging success, with fledging success exceeding 75% in nest boxes surrounded by at least 20% of urban area (Fig. 4A). This result was consistent when accounting only for successful clutches (*scaled proportion of urban areas: Est=1.14, SE=0.07, t=2.04, p=0.042)*. The number of agricultural fields was also positively associated with fledging success, as fledging success was higher in nest boxes surrounded by more agricultural fields (Fig. 4B). However, this result was not consistent when accounting only for successful clutches (*scaled number of fields: Est=1.06, SE=0.09, t=0.66, p=0.51*). Nest boxes occupied the previous year tended to have 6% lower fledging success than non-occupied nest boxes, and this was consistent when accounting only for successful clutches (*occupied previous year: Est=0.77, SE=0.1, t=-1.98, p=0.047*). Mean precipitations during the fledgling period decreased fledging success, which dropped below 75% when precipitation exceeded 3 mm per day on average (Fig. 4*C)*. This result was consistent when accounting only for successful clutches (*scaled mean precipitations: Est=0.84, SE=0.06, t=-2.3, p=0.021*). Finally, successful clutches laid later in the season had decreased success odds, falling below 75% of success for clutches

Table 2
Analyses for fledging success: Results of fitting weighted generalized mixed model with binomial family to the fledging success, before and after step-selection. Nest box ID, year, female ID, and male ID were added as random intercepts. Significant terms (p<0.05) are written in bold. The model is based on 406 broods in 64 different nest boxes at 47 distinct sites between 1993 and 2020.

Parameter	Global model			Final model		
Variable	Estimates (SE)	t	p	Estimates (SE)	t	p
Odds ratio of fledging success						
(Intercept)	5.06 (1.65)	4.98	<0.001	3.09 (0.43)	8.10	<0.001
Scaled proportion of urban areas	1.27 (0.14)	2.23	0.026	1.21 (0.10)	2.21	0.027
Scaled number of agri. fields	1.27 (0.13)	2.37	0.018	1.27 (0.12)	2.45	0.014
Scaled density of surr. breeding sites	1.12 (0.10)	1.29	0.196	Rd		
East orientation	0.69 (0.19)	-1.36	0.175	Rd		
South orientation	0.68 (0.23)	-1.13	0.259	Rd		
Scaled heigth [m]	1.07 (0.10)	0.76	0.449	Rd		
Scaled altitude	1.10 (0.12)	0.92	0.358	Rd		
Nb of nest boxes at the site	0.79 (0.17)	-1.13	0.258	Rd		
Occupied previous year	0.75 (0.12)	-1.82	0.069	0.74 (0.12)	-1.92	0.054
Scaled number of extreme days	0.98 (0.08)	-0.23	0.822	Rd		
Scaled mean precipitations	0.82 (0.07)	-2.23	0.026	0.82 (0.07)	-2.29	0.022
Scaled laying date	0.86 (0.07)	-1.94	0.053	0.90 (0.06)	-1.53	0.127
Random Effects						
	σ^2		3.29	σ^2		3.29
	$\tau_{00\ F\_ring}$		1.03	$\tau_{00\ F\_ring}$		1.05
	$\tau_{00\ M\_ring}$		0.30	$\tau_{00\ M\_ring}$		0.34
	$\tau_{00\ nestid}$		0.00	$\tau_{00\ nestid}$		0.00
	$\tau_{00\ year}$		0.09	$\tau_{00\ year}$		0.08
Model fit						
	Observations		406	Observations		406
	Marginal R^2		0.031	Marginal R^2		0.024
	AIC		1432.6	AIC		1424.0

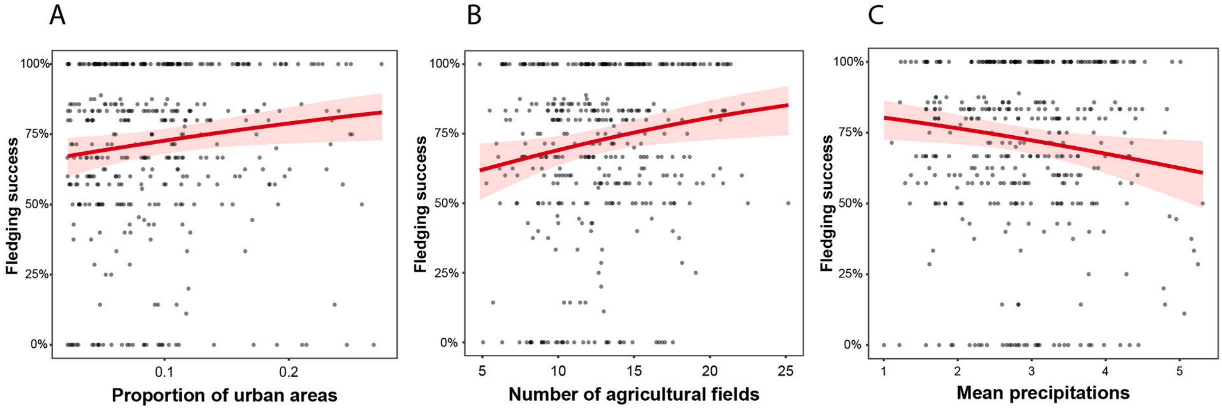

Fig. 4. Factors influencing fledging success: the correlation between fledging success and (A) the proportion of urban areas; (B) the number of agricultural fields; and (C) the mean precipitations. The red shaded area represents the 95% confidence interval around the estimated means in solid red line, while the data are shown in black. The graphs present unscaled relationships for interpretative clarity, despite models utilizing scaled predictors.

laid after late April (*scaled laying date: Est=0.83, SE=0.05, t=-3.04, p=0.002)*. This result was not significant when accounting for all clutches, failed one included (Table 2). We found no evidence of an effect of the other variables tested, namely the density of surrounding breeding sites, the nest box characteristics, and the temperature on fledging success.

3.2. Annual breeding site occupancy

On average, the annual breeding site occupancy was 25% (*SD=43%*). Our GLMM reveals that the proportion of urban areas is essential, exceeding 50% of occupancy in sites surrounded by more than 20% of urban area (Fig. 5A). Moreover, the number of agricultural fields tended to positively impact the annual occupancy, with breeding sites surrounded by 20 fields on average being occupied more than 50% of the years (Fig. 5B). Conversely, an increase in the density of surrounding breeding sites was associated with a 28% decrease in the odds of occupancy (Fig. 5C). This was not the case when accounting for the density of occupied breeding sites (*scaled breeding barn owl density: Est=-0.21, SE=0.15, t=-1.35*). Nest box height above ground was positively associated with occupancy, with a 21% increase in odds of occupancy per meter increase in height. Finally, sites occupied the previous year showed nearly four times the likelihood of being occupied again compared to sites not occupied the previous year. We did not find any evidence for an effect of other variables tested, namely the orientation, the altitude, and the climatic data (Table 3).

4. Discussion

By analyzing more than 30 years of barn owl population monitoring data, we assessed how changes in land use through 30 years

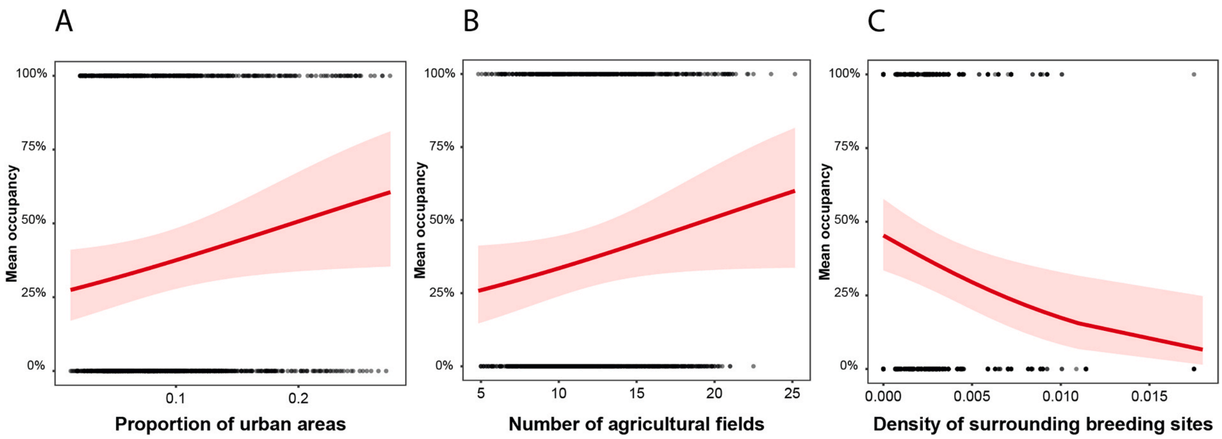

Fig. 5. Factors influencing the annual site occupancy: the correlations between annual site occupancy and (A) the proportion of urban area, (B) the number of agricultural fields, and (C) the density of surrounding breeding sites. Red shaded area represents the 95% confidence interval around the estimated means in solid red line, while the data are shown in black. The graphs present unscaled relationships for interpretative clarity, despite models utilizing scaled predictors.

influenced barn owl site occupancy and reproductive success. Overall, our findings highlight the important role of agricultural landscapes in supporting barn owls' reproductive success, emphasizing the need to maintain the complexity and diversity of agricultural fields. Moreover, various nest box characteristics as well as the density of surrounding breeding sites appear as important and should be considered when installing new nest boxes.

In particular, the number of agricultural fields surrounding barn owl nest boxes appears to influence both fledging success and, to a smaller extent, annual site occupancy. This increase in breeding success with increasing number of agricultural fields could be attributed to more diverse and heterogeneous landscapes, with a lot of field margin structures, where prey availability was found to be high (Bühler et al., 2023). Enhanced breeding success in such environments not only benefits the barn owl population but also might help limit small mammal populations in these agricultural areas, as barn owls are a tool in biological pest control (Labuschagne et al., 2016, George and Johnson, 2021). This highlights the importance of habitat diversity within barn owl home ranges. This was shown in our population in a previous study where we looked at a shorter period (5 years) (Almasi et al., 2015) and found that breeding performances were higher in structurally more diverse landscapes. These results thus should encourage farmers to consider practices that promote landscape heterogeneity, such as maintaining or increasing the number of smaller fields, to help the conservation of barn owl populations. It is important to acknowledge that the measure of field numbers as a proxy for agricultural intensity assumes that the total area under cultivation remains relatively stable. However, this may not always be the case. An increase in the number of fields could also result from urban expansion or the subdivision of larger fields, which might have differing ecological impacts. It should be noted that our study did not measure the total agricultural area within the observed landscapes for methodological constraints. This represents a limitation in interpreting the effects of agricultural field number changes on barn owl habitat quality and use. Future research could benefit from incorporating detailed land cover data to assess not only the number but also the total area of agricultural fields. This would allow for a more precise assessment of how changes in agricultural practices influence barn owl populations and other aspects of biodiversity.

The influence of urban areas on barn owl breeding success and nest box occupancy appears to be negligible in our study area, and even positive for the fledging success and the mean occupancy. Given barn owls' ability to adapt to and exploit human settlement for nesting, those results are not surprising and are in line with those from Frey et al. (2011), who reported no significant influence of environmental features on barn owl's breeding parameters from 1987 to 2009. However, Frey and colleagues assumed that the habitat did not change throughout those years. Our analysis shows that, even when accounting for the change, the results are consistent. Hindmarch et al. (2012) also found no significant impact of urban cover on nest box occupancy in Canada, though their study did not explore how urban cover might affect breeding success. However, the negligible effects of urban areas on barn owl breeding success observed in the present study should not be interpreted as an endorsement for the expansion of urban areas. Almasi et al. (2015) demonstrated that nestlings raised in intensively cultivated areas or frequently disturbed areas have higher baseline corticosterone levels, leading to a negative effect on nestling fitness. This suggests that while urban areas may correlate positively with fledging success and site occupancy, anthropogenic effects overall may not be beneficial to barn owl populations in the long-term. Additionally, the characteristics of urban areas must be considered. Larger cities with limited green areas likely exert more negative effects, whereas

Table 3
Analyses for annual site occupancy: Results of fitting generalized linear models with binomial family to the mean site occupancy. Nest box ID nested in the site ID, and year were added as random intercepts. Significant terms ($p<0.05$) are written in bold. The model is based on 1406 occupancy data in 72 different nest boxes at 48 distinct sites between 1993 and 2020.

Parameter	Global model			Final model		
Variable	Estimates (SE)	t	p	Estimates (SE)	t	p
Odds ratio of mean occupancy						
(Intercept)	0.17 (0.09)	-3.31	0.001	0.28 (0.06)	-5.60	<0.001
Scaled proportion of urban areas	1.28 (0.20)	1.55	0.122	1.34 (0.18)	2.09	0.036
Scaled number of agri. fields	1.28 (0.19)	1.61	0.106	1.28 (0.18)	1.76	0.079
Scaled density of surr. breeding sites	0.72 (0.08)	-2.81	0.005	0.72 (0.09)	-2.78	0.005
East orientation	1.28 (0.60)	0.52	0.603	Rd		
South orientation	1.23 (0.72)	0.36	0.722	Rd		
Scaled heigth [m]	1.31 (0.21)	1.71	0.088	1.43 (0.22)	2.36	0.018
Scaled altitude	0.98 (0.16)	-0.13	0.895	Rd		
Number of nest boxes at the site	1.59 (0.51)	1.43	0.154	Rd		
Occupied year before	4.45 (0.76)	8.74	<0.001	4.37 (0.74)	8.67	<0.001
Scaled mean minimal T°	0.62 (0.24)	-1.26	0.208	Rd		
Scaled mean maximal T°	1.51 (0.54)	1.16	0.247	Rd		
Scaled mean precipitations	1.59 (0.45)	1.62	0.106	Rd		
Random Effects						
	σ^2		3.29	σ^2		3.29
	$\tau_{00\ nest\_letter:siteid}$		0.15	$\tau_{00\ nest\_letter:siteid}$		0.16
	$\tau_{00\ siteid}$		0.60	$\tau_{00\ siteid}$		0.66
	$\tau_{00\ year}$		0.69	$\tau_{00\ year}$		0.78
Model fit						
	Observations		1406	Observations		1406
	Marginal R^2		0.178	Marginal R^2		0.156
	AIC		1473.8	AIC		1464.6

smaller villages rich in green areas may have positive effects, such as increasing prey availability. In our study, the maximum urban area proportion did not exceed 30%, comprising predominantly villages with many farms and houses with gardens, indicating that barn owls still rely on natural or semi-natural environments for their survival.

The influence of the density of surrounding breeding sites emerges as an important factor, having a negative effect on clutch size and site occupancy. Notably, an increase in the density of surrounding breeding sites goes with a decrease in site occupancy. As this is not linked to whether the surrounding nest boxes are themselves occupied, this could be simply due to a higher number of nesting possibilities, thus decreasing the likelihood of sites to be occupied, and not being linked to territoriality or competition for nesting sites. However, the effect of competition is more evident later within the breeding cycle, at egg laying, as nest boxes with higher density of surrounding sites produced fewer eggs. Barn owls may adjust their breeding strategies to resource constraints due to higher population densities. Furthermore, it could also reflect selective behavior by breeding individuals: high-quality individuals, who are more experienced and better at securing optimal resources, might select the best nest sites with lower density of surrounding sites. Consequently, less experienced individuals are left with poorer-quality breeding sites in denser areas, resulting in smaller clutches, as described in the density limiting hypothesis from Fretwell and Lucas (1969).

We also conducted a comprehensive analysis of various nest box characteristics. The orientation had an effect on the clutch size, with larger clutches being laid in nest boxes facing North. This goes in line with the study of Goodenough and Stallwood (2012), who showed that orientation has an impact on the microbial community, which led to differences in Great Tits (*Parus major*) offspring quality, with nest boxes facing North and North-East having lower fungal loads than those facing South and South-West. However, it goes in contradiction to the findings of Butler et al. (2009), who found that, despite significant differences in temperatures and humidity among orientations, the breeding success of American kestrels (*Falco sparverius*) was not impacted. In our case, the sample may exhibit a bias due to the majority of nest boxes being placed in tobacco barns, which are mainly orientated towards the northeast. For installation purposes, the majority of nest boxes follow this orientation, thus possibly explaining the influence of this specific orientation. The height at which the nest box is placed in the barn also impacted the mean site occupancy, with nest boxes placed higher being more likely to be occupied. This could be explained either by easier access for owls in flight, fewer disturbances from humans, or lower predation risk inside the nest box. It is important to note that the main predator in this context is the beech marten (*Martes foina*), which is known to inhabit barns (Roulin, 2020). Although higher placements of nest boxes are generally recommended to deter such predators, we have not empirically tested the correlation between nest box height and predation risk by beech martens, which is anyway relatively rare in our population (personal observation). Therefore, any assumptions regarding the effectiveness of elevated nest boxes in reducing predation risks remain speculative and warrant further investigation. Additionally, the altitude above sea level at which the nest box is placed had a negative effect on clutch size. This result goes in line with barn owls' preference to avoid high altitudes driven by their vulnerability to cold temperatures (Massemin and Handrich, 1997; Thouzeau et al., 1999; Altwegg et al., 2006). However, as the majority of our nest boxes are placed below 600 m above sea level, there is a potential bias in the dataset that should be kept in mind.

Finally, intrinsic clutches factors appear as important predictors of breeding success. The laying date positively impacted clutch size, with late-season clutches being larger, but with lower fledging success for successful clutches, which was already found in previous studies (Roulin, 2002, Chausson et al., 2014). The observed decline in fledging success may be due to lower prey availability later in the season, deteriorating weather conditions, or higher intra-specific competition as more pairs are simultaneously breeding. It is important to note that the data analyzed focused only first clutches, with the breeding season ending by the end of July for the latest. Whether sites were occupied the year before positively impacts site occupancy, as sites that were occupied in the preceding year exhibit a four times higher likelihood of being occupied again. This effect could suggest either site fidelity by adult barn owls, who will prefer to return to the same site, especially if the same pair stayed together as shown by Dreiss and Roulin (2014), or social cues among adult barn owls, who might perceive previously occupied sites as favorable. However, fledging success was observed to be lower in previously occupied nest boxes. As part of our study protocol, the research team does not intervene or clean the nest boxes between breeding seasons. This may lead to the accumulation of organic debris such as pellets and prey remains, creating suitable conditions for the proliferation of ectoparasites, as well as potentially harmful bacteria and viruses. Studies have shown that nests can serve as major source of microorganisms (Goodenough et al., 2017; van Veelen et al., 2017), which could adversely impact fledglings' microbiota, potentially explaining the observed decrease in fledging success.

Interestingly, we could not find any correlation between temperature data and breeding success. This outcome could be particularly encouraging in the context of global climatic changes and rising temperatures. However, a more thorough investigation specifically focusing on climate change is necessary to accurately determine its impact on barn owl breeding success. Given the species' large geographic distribution range (Roulin, 2020), barn owls may possess a high flexibility to a wide range of temperatures and precipitations. Nevertheless, we found a negative correlation between mean precipitations and fledging success. This goes in line with the results of Chausson et al. (2014), who observed a negative effect of precipitation on fledglings' body mass. Increased precipitations can negatively affect prey activity, potentially diminishing barn owl hunting efficiency (Roulin, 2020; Taylor, 1994), leading to lower feeding rates and consequently reduced fledging success.

The overall findings of this study suggest that barn owls can adapt to a changing environment but are still influenced by the agricultural landscape surrounding their nest boxes, as well as the characteristics of the nest box and densities of surrounding breeding sites. This adaptability suggests that the species possesses remarkable flexibility and resilience, which might explain how *Tytonidae* has become one of the most widespread and cosmopolitan families among birds in the world (Roulin, 2020). The barn owl's ability to thrive in diverse environments contributes to its global distribution and success. However, it is important to highlight that, on the whole, the statistical models exhibited notably low R-squared values despite a good fit to the data, indicating that the predictors selected explain a minimal amount of variance. This observation could highlight some highly influential factors that were disregarded in our selection of predictors. Regarding agricultural landscapes, even though field size is known to be negatively linked to biodiversity (Herzog et al., 2012; Fahrig et al., 2015; Sirami et al., 2019), other factors such as the type of agricultural crops were not included in our analysis but should be considered. It might be possible that the type of fields plays a more significant role in influencing barn owls' hunting behaviors (Séchaud et al., 2021; Bühler et al., 2023) and, consequently, their fitness. It would thus be interesting to investigate the evolution of the types of crops and their impact on barn owl breeding success and nest box occupancy, to estimate their efficiency. Such an analysis was not feasible with the greyscale aerial photography used in this study, but incorporating this dimension would deeply enhance our understanding of environmental influences on barn owl breeding success.

5. Conclusion

In conclusion, our study highlights the important role of agricultural fields in the reproductive success of barn owls in the long term. Moreover, it emphasizes the importance of proper installation of nest boxes, a critical tool in supporting barn owl populations. Finally, this research highlights the adaptive capacity of barn owls, offering a positive perspective on their resilience. By understanding the factors that influence barn owl site occupancy and breeding success, especially in agricultural landscapes, our study makes an important contribution to conservation efforts. This is essential, considering the potential role raptors can play in stabilizing ecological balance in agricultural landscapes, as they act as biological pest control agents, a concept reviewed by Sergio et al. (2008).

CRediT authorship contribution statement

Estelle Milliet: Writing – review & editing, Writing – original draft, Visualization, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Kim Schalcher:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Anna Grangier-Bijou:** Writing – review & editing, Data curation, Conceptualization. **Bettina Almasi:** Writing – review & editing, Resources. **Fabrizio Butera:** Writing – review & editing, Supervision, Conceptualization. **Alexandre Roulin:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecco.2024.e02988.

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Supplementary material

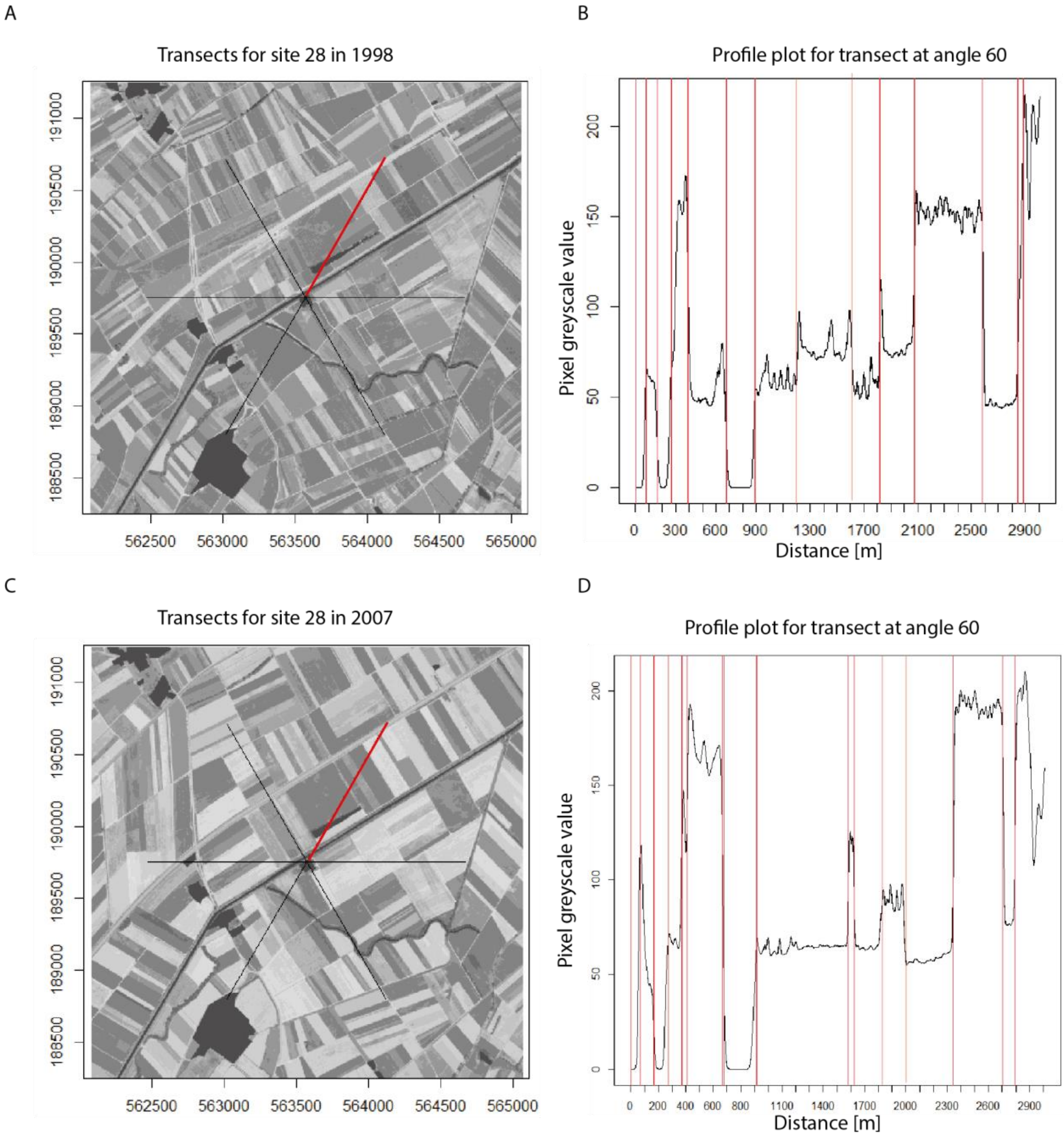

Figure S1: Field boundary detection algorithm using aerial maps: This figure demonstrates how the algorithm identifies field boundaries by analyzing pixel greyscale values in aerial photographs from the years 1998 (panels A and B) and 2007 (panels C and D). The algorithm uses the aerial map (panels A and C), wherein transects are established (black lines). It then extracts the greyscale values along each transect (the red line illustrated), using variations in these values to delimitate field boundaries (panels B and D).

Chapter 5

Understanding the association between biodiversity promotion areas, urban areas, and nest box characteristics, and barn owl site occupancy and breeding success

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K.S.: Conceptualization, Methodology, Writing – review & editing.
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Abstract

Agricultural landscapes have a high potential to contribute positively to biodiversity, given their prevalence across the majority of environments. Recognizing this, numerous governments are incentivizing farmers through direct payments to adopt sustainable practices. These include managing extensive pastures and meadows, or planting wildflowers or hedgerows, among others. Yet, the efficiency of such practices on vertebrate species is not well addressed. In this study, we investigated the factors associated with site occupancy and breeding success of a Swiss population of barn owls (*Tyto alba*) from 2018 to 2020, with a specific focus on extensive agriculture and urban areas surrounding nest boxes. To give specific recommendations, we also estimated the association with nest box characteristics. Our findings reveal that hedgerows surrounding the nest boxes is associated with a more frequent occupancy. However, extensively used pastures had a dual link, decreasing site occupancy but increasing clutch size. The proportion of urban areas were found to negatively relate to both site occupancy and clutch size. Regarding nest box characteristics, we found that the altitude at which they were fixed was negatively correlated with their occupancy, the number of nest boxes placed at the same site (either one or two) was positively correlated with site occupancy. Moreover, clutch size, but not fledging success, was larger in nest boxes placed outside barns than in nest boxes placed inside barns. Based on these findings, specific recommendations are given on optimal nest box placement. Understanding the nuanced relationships between nest box characteristics, environmental factors, and breeding success provides valuable insights for optimizing artificial nesting sites and enhancing the overall reproductive success of barn owls.

Keywords: Artificial nesting site, barn owl fitness, Biodiversity Promotion Areas, nest box installation, *Tyto alba*, urbanization

1. Introduction

Agricultural fields dominate the vast majority of landscapes throughout the world (Tilman et al. 2001). While intensive agricultural practices cause several adverse effects on the environment, including increased agrochemical use, and soil degradation leading to a strong decline in biodiversity (Stoate et al. 2009), extensive agricultural fields also offer notable positive contributions and ecosystem services. Extensively managed fields can enhance soil fertility, regulate water, or increase carbon sequestration (Swinton et al. 2007; Wittwer et al. 2021), having high potential for conservation measures (Tscharntke et al. 2005). Farmers thus play an essential role as practitioners and key actors in biodiversity conservation when adopting sustainable agriculture techniques. In addition to financial incentives to implement such measures due to the subsidies they receive, farmers have an intrinsic motivation, which is grounded in their reliance on natural resources and climatic conditions for agricultural production. This makes them uniquely situated to appreciate the benefits of biodiversity conservation and willing to invest in long-term sustainable practices. As we confront the pressing challenges of climate change and biodiversity loss, the role of farmers in safeguarding our ecosystems becomes increasingly vital.

To fight the apparent loss of biodiversity linked to intensive farming practices, several solutions have been put in place. Some techniques are highly efficient, such as agroforestry, crop rotation, cover cropping, and integrated pest management (Altieri 1999; Tscharntke et al. 2011; Elhakeem et al. 2019; Martin et al. 2020). In Europe, agri-environmental schemes were implemented in 1985 (European Union [EU] Regulation 797/85), consisting of paying subsidies to farmers committed to environmentally friendly practices. These practices include planting wildflowers, hedgerows, extensively managing meadows and pastures for example. Their effectiveness on the populations of plants, insects and small mammals is well documented (Kleijn et al. 2006; Knop et al. 2006; Zingg et al. 2019), with increased biodiversity for such taxa in those areas. However, their impact on larger vertebrates is still understudied, despite these taxa also having a strong impact on biodiversity, serving as keystone, umbrella, sentinel, flagship, or indicator species, as reviewed in Sergio et al. (2008). Understanding the efficacy of such measures is essential for informing farmers about the practices that best support wildlife conservation in agricultural landscapes.

In addition to these practices, farmers can also implement targeted conservation measures. The loss of structural resources for nesting due to agriculture intensification being one of the main causes of the decrease in farmland bird populations (Newton 2004), nest boxes are a great targeted measure, helping specific bird species such as owls (Marti et al. 1979; Meyrom et al. 2009; Gottschalk et al. 2011), kestrels (Hamerstrom et al. 1973), or hoopoe (*Upupa epops*) (Arlettaz, Schaub, et al. 2010). Nest boxes are especially essential for raptors (Gehlbach 1994; Johnson 1994; Eschenbauch et al. 2009; Arlettaz, Krähenbühl, et al. 2010; Gottschalk et al. 2011) that hunt small mammals in the fields (Roulin 2020, Perrins & Snow, 1998). Raptors thus help maintain biodiversity in agroecosystems, as they serve as biological pest-control agents (Meyrom et al. 2009; Donázar et al. 2016; Paz Luna et al. 2020; Montoya et al. 2021). However, nest boxes should be placed with care, as they differ from natural nesting sites in several ways. The surrounding landscape, such as roads (Mulholland et al. 2018) and buildings (Partecke et al. 2006; Almasi et al. 2015), can impact species survival and reproduction rates. Nest box density can also increase inter- and intra-specific competition (Serrano-Davies et al. 2017). Finally, nest box placement (i.e. location, height, and orientation) is essential, as it can affect site occupancy frequency (Goodenough et al. 2008; Wendt and Johnson 2017). It is therefore important to evaluate the factors that could potentially influence the nest box selection process and occupancy, and the subsequent breeding performances of birds to optimize their installation in the best habitat meeting the birds' requirements.

For raptors in farmland areas, farms are often the most adequate locations for nest box installation, due to their proximity to suitable hunting grounds. The barn owl (*Tyto alba*) is a perfect case study, breeding on farmland where natural nesting cavities are usually scarce, and nesting in artificial nest boxes without problems. Being very efficient predators (Schalcher et al., 2023), hunting small mammals in open and semi-open areas (Perrins & Snow, 1998), they can influence small mammal populations, making them a valuable tool for biological pest control. On the Swiss Plateau, more than 300 nest boxes have been installed since the 1990s on local farms by scientists, with the agreement and collaboration of farmers. This scientific project has helped to stabilize the local population of this species (Antoniazza et al., 2018), a notable achievement given its classification as nearly threatened in overall Switzerland according to the Swiss Red List (Knaus et al. 2021).

In a previous study (Milliet et al., 2024), we explored the breeding success and site occupancy of barn owls for three decades, from 1993 to 2020, focusing on the number of agricultural fields and the proportion of urban areas surrounding the nest boxes. While this long-term analysis provided valuable insights into general trends and patterns, it highlighted the need for a more nuanced examination of the environmental factors influencing barn owl breeding success. Consequently, the present study aims to deepen this analysis by utilizing more precise and detailed environmental data. Building on our foundational work, we now specifically focus on factors which farmers can consider when installing a nest box, which are categorized into three main domains: (1) the surrounding agricultural and urban environment; (2) the nest box characteristics; and (3) the surrounding breeding site density. We expect barn owls to select nest boxes with a higher proportion of extensive areas in the surroundings, as such areas are known to provide higher prey densities (Arlettaz, Krähenbühl, et al. 2010). Regarding urban areas, effects in the literature do not reach a clear consensus. Frey et al. (2011) reported no association between barn owl breeding success and urban areas, while Almasi et al. (2015) observed a negative effect on nestlings' physiology and body condition but a positive effect on the number of fledglings. Given barn owls high adaptability to live with humans (Hindmarch and Elliott 2015), we do not have clear expectations about the effect of urban areas on barn owl breeding success. Instead, our aim is to further investigate these relationships. Finally, regarding surrounding breeding site density, we expect barn owls to select nest boxes with fewer and/or further breeding sites in their surroundings, as found by Meyrom et al. (2009). As this is, to the best of our knowledge, the first analysis of nest box characteristics in this study area, we do not have predefined expectations, but our objective is to explore their influence comprehensively. This refined approach allows us for a more precise understanding of how the environment directly associates with barn owl breeding success and site occupancy over three years (2018-2020). By comparing and contrasting these findings with our earlier long-term observations (Milliet et al., 2024), we aim to provide a more comprehensive and accurate picture of the importance of extensive agricultural structures for barn owl breeding success. Moreover, it will then be possible to give specific recommendations on the optimal conditions for barn owl nest box installation to any interested practitioners and organizations, promoting the conservation of this species and their habitat. This represents a unique opportunity to raise awareness about a usually unknown bird species, as well as promote biological pest control among local farmers.

2. Material & Methods

2.1 Study area

The present study was carried out from 2018 to 2020 and focused on a wild population of barn owls residing in nest boxes on the Swiss Plateau. This region is characterized by agricultural fields and urban areas corresponding to the preferred habitat of the barn owl (Bunn et al., 1982, Séchaud et al. 2021).

A total of 379 nest boxes have been installed since the 1990s and are regularly monitored between March and August every year. When discovering a clutch, a standardized protocol of nest visits was systematically executed to record various breeding parameters (Frey et al. 2011), in particular the laying date, the clutch size, and the number of fledglings, as well as the female and male identity. Barn owls can produce several clutches per breeding season. During the winter, barn owl pairs select their nest box for their first clutch. In case of failure or abandonment of this first clutch, a replacement clutch may be produced. Following the completion of the first clutch, barn owl pairs can produce a second clutch.

Nest boxes are placed on barn walls, either inside with the entrance hole facing the outside or directly on the outside walls. Depending on the barn, they can be placed in different orientations, at different heights and sometimes two nest boxes are placed in the same barn. Each barn with one or two nest boxes is considered as a breeding site in the present study. To account for these differences, we extracted the characteristics of each nest box, specifically the orientation (direction in which the nest box entrance faced, specifically categorized as North, East, South, West), the height above the ground in meters, the location (whether nest boxes are installed inside or outside barns), the altitude above sea level where the nest box is located, the number of nest boxes present in the same barn (either one or two), and the nest box age in years.

2.2 Habitat characteristics

The goal of this study is to estimate the influence of the surrounding environment on barn owl breeding success and site occupancy. Therefore, we focused on three main habitat types, namely urban areas, agricultural landscapes, and surrounding breeding site density, within barn owls home range (Almasi et al. 2015; Séchaud et al. 2021). All variables were thus extracted within a 1.5 km radius around each breeding sites (7 km^2) for each year between 2018 and 2020.

2.2.1 Urban areas

To characterize the urban areas, we used the TLM3D catalog of the Swiss Federal Office of Topography (Swiss Topographic Landscape Model). For each site, we extracted three variables: the proportion of roads, the proportion of urban areas, and the density of the urban areas. To quantify the proportion of roads around each site, we extracted all roads in the 1.5 km radius. To account for different road types, we applied type-specific buffers to each road segment (Supp. material I). The resulting area of roads was then calculated and divided by the total area of the 1.5 km radius to get the total proportion of roads. For the proportion of urban areas, we extracted each building within the 1.5 km radius around each site. A buffer of 50 meters was then applied around each building, and these areas were then merged to form a full urban area. The total area of this merged urban area was then calculated and used to calculate the proportion of the total urban area within 1.5 km radius around the breeding site. Finally, to estimate the density of the urban area, we summed the area of each building without the 50 m buffer and divided it by the total urban area. This calculation yielded the density of urbanized space, providing a metric to understand the concentration of built structures within the defined urban areas surrounding each breeding site.

2.2.2 Agricultural fields

For agricultural landscapes, we used data provided by the “Direction Générale de l’Agriculture, de la Viticulture et des Affaires Vétérinaires” of the states of Vaud and Fribourg, which provided the field type of each parcel owned by a farmer. We focused particularly on extensive areas, which were defined as agricultural fields providing direct payments for biodiversity promotion areas from the Swiss Confederation (AGRIDEA 2018). For each breeding site, we extracted the total area of all agricultural fields around each breeding site in the 1.5 km radius, including both cultivated fields and permanent fields. Then, based on this total area, we calculated the proportion of biodiversity promotion areas according to four categories: extensively used pastures and meadows; wildflowers areas; and hedgerows (Supp. material II for a detailed list of fields per category).

2.2.3 Surrounding breeding site density

To assess the relationship between surrounding breeding sites and barn owl breeding success, a density metric was calculated for each focal site. The surrounding site density was determined by summing the reciprocals of the distances to surrounding sites. The formula used for calculation is as follows:

$$Density = \sum_{i=1}^{n} \frac{1}{d_i}$$

Where *n* is the number of surrounding sites, and d_i represents the straight distance from the focal site to each surrounding site. This metric was utilized to assess the potential competition for resources and the overall quality of the breeding environment.

Our analysis differentiated among four specific categories of site density to provide a nuanced understanding of the different environmental and competitive pressures: (1) barn owl breeding site density: the overall density of barn owl breeding sites surrounding each focal site, without regard to their occupancy status. This measurement provides insight into the availability of potential breeding sites for barn owl; (2) Occupied barn owl breeding site density: the density of barn owl breeding sites that were occupied, either before the laying date or simultaneously depending on the analysis. This measure focuses on the direct competition barn owls face for nest sites with conspecifics. Moreover, as common kestrel (*Falco tinnunculus*) are potential competitors, we extracted the same densities for kestrel breeding sites to helps to assess the level of potential inter-specific competition. These measures were (3) kestrel breeding site density: the overall density of kestrel breeding site, irrespective of occupancy; and (4) density of occupied kestrel sites: the density of breeding sites occupied by kestrels, either before the laying date or simultaneously depending on the analysis. As kestrels can use both types of nest boxes, the ones designed for barn owls and the ones designed for kestrels (those boxes are never occupied by barn owls), both types were included in the kestrel sites densities.

By calculating densities based on both the overall availability and actual occupancy of breeding sites, we aimed to distinguish between the effects of potential versus direct competition and the broader environmental breeding sites characteristics influencing barn owl breeding success.

2.3 Statistical analyses

The present study aims to estimate the factors associated with barn owl's site occupancy and reproductive success. This was done through three different models, each focusing on a specific response variable, namely the annual site occupancy, the clutch size, and the fledging success.

First, we focused on the annual breeding site occupancy, with a breeding site considered as occupied if at least one egg was laid in a specific year, including first, replacement and second clutches. A generalized linear mixed model (GLMM) with a binomial family was fitted on the annual site occupancy using the function *glmer* from the package *lme4* (Bates et al., 2015). The nest box characteristics (i.e. orientation (categorized as North, East, South, West), height in meters, location (whether inside or outside the barn), altitude above sea level in meters, number of nest boxes at the site (either one or two) and nest box age in years), the surrounding breeding site densities (i.e. surrounding barn owl and kestrel site densities) and the surrounding environment (i.e. the proportion of roads, the proportion of urban areas, the density of urban areas, the total area of agricultural fields, the proportion of extensive pastures, the proportion of wildflower areas, the proportion of extensive meadows, the proportion of hedgerows) were used as predictors. The year and the site ID were used as random intercepts in the models. In cases when two nest boxes are installed at the same site, we kept only one nest box record per site per year, as their occupancy was mutually exclusive. This means that if one nest box was occupied in a given year, the other was not. We calculated occupancy as follows: if one of the nest box was occupied, that record was kept; if neither of the nest boxes was occupied, one record was randomly selected.

Then, to estimate the factors related to clutch size and fledging success, we focused on the first annual clutch of each breeding pair. We chose only first clutches because the breeding parameters of second clutches depend on many confounding factors, such as the success of the first clutch or the parents' conditions (Béziers and Roulin 2016). We modelled the clutch size with a linear mixed model (LMM) using the function *lmer* from the package *lme4* (Bates et al., 2015), and fledging success (i.e. the number of fledglings over the clutch size) with a weighted GLMM with binomial family, with clutch size as weights, using the function *glmer* of the package *lme4* (Bates et al., 2015). To differentiate between successful and failed clutches, we also ran the model accounting only for successful clutches (clutches with at least one fledgling). Covariates were used as for the annual site occupancy model, i.e. the nest box characteristics, the surrounding breeding site densities and the surrounding environment, adding control predictors specific to the clutch, namely the laying date and the barn owl pair identity (classified into four categories, namely the same pair as the previous year, the same female but a different male as the previous year, the same male but a different female as the previous year, or different pair). For the surrounding breeding site densities, two separate runs were conducted to differentiate between the density of available breeding sites and the density of occupied breeding sites. Each run included one of these variables for both barn owls and kestrels, allowing us to isolate and compare their respective effects on the response variables. We included the female ID, male ID, nest box ID nested in site ID, and year as random intercepts in the models.

Statistical analyses were performed using R 4.2.1, with RStudio as a graphic user interface (R Core Team, Vienna, Austria; RStudio Team, 2022). Collinearity among predictors was checked for each model, and assumptions were verified with the *performance* package (Lüdecke et al., 2021). Additionally, residual diagnostic plots were visually inspected. The effects were considered significant when their p-values were below 0.05. The global model was constructed with predictors having biological importance. To refine the global model, non-significant variables were systematically removed, ensuring a reduction in the Akaike Information Criterion (AIC). Variables that, when removed, led to an AIC increase were retained in the final model. In every model, linear predictors were z-scaled, which allows direct comparison of effect sizes across variables of different units. Spatial autocorrelation was checked for all models by plotting residuals against spatial the coordinates, and we found no evidence of spatial autocorrelation.

3. Results

In total, 300 nest boxes at 232 different sites were analyzed. The nest boxes were on average 19 years old (*SD=10 years; min=3 years, max=40 years*), placed at an average altitude of 539 m (*SD=81m, min=375m, max=797m*), at a height of 6.4 m (*SD=1.98m, min=2.34m, max=12.52*). The majority were placed inside barns (*N=254*), orientated towards East (*N=172*) or North (*N=92*), and alone in the barns (*N=162*).

On average, nest boxes were surrounded by 6.2% of roads (*SD=2.2%, min=2.9%, max=19.3),* and 17.7% of urban areas (*SD=9.7%, min=4%, max=72%*). Regarding extensive areas, they were surrounded by 7.2% of extensive pastures (*SD=4.4%, min=0%, max=20.1%*), 0.8% of wildflower areas (*SD=0.7%, min=0%, max=4.4%*), 18.8% of extensive meadows (*SD=7.4%, min=0%, max=42.7%*) and 0.7% of hedgerows (*SD=0.4%, min=0.02%, max=2.7%*).

3.1 Breeding site occupancy

For the three years considered, 23% of breeding sites were occupied in 2018, 26% in 2019 and 36% in 2020, leading to an overall occupancy of 28%.

The analysis of site occupancy, conducted using a GLMM, revealed significant effects from a variety of predictors (Table 1). The model demonstrated a negative correlation between altitude and site occupancy: occupancy diminished sharply with increasing altitude, falling to below 12% of occupancy at altitudes above 700 meters (*Fig. 1A*). Additionally, nest boxes placed alone in barns tended to be 36% less likely to be occupied compared to pairs of nest boxes (*mean occupancy of single nest boxes=0.31; mean occupancy of pairs of nest boxes=0.48*). We did not find any evidence that the orientation, height, location, and age of the nest box explained annual occupancy rates. The proportion of surrounding extensive areas showed a mixed association. While the presence of hedgerows around nest boxes positively influenced occupancy, increasing the odds of occupancy by 47% (*Fig. 1D)*, extensive pastures had the opposite effect, with odds of occupancy dropping by 50% (*Fig. 1C*). Finally, the model indicated that urban density was negatively related to site occupancy (*Fig. 1B*).

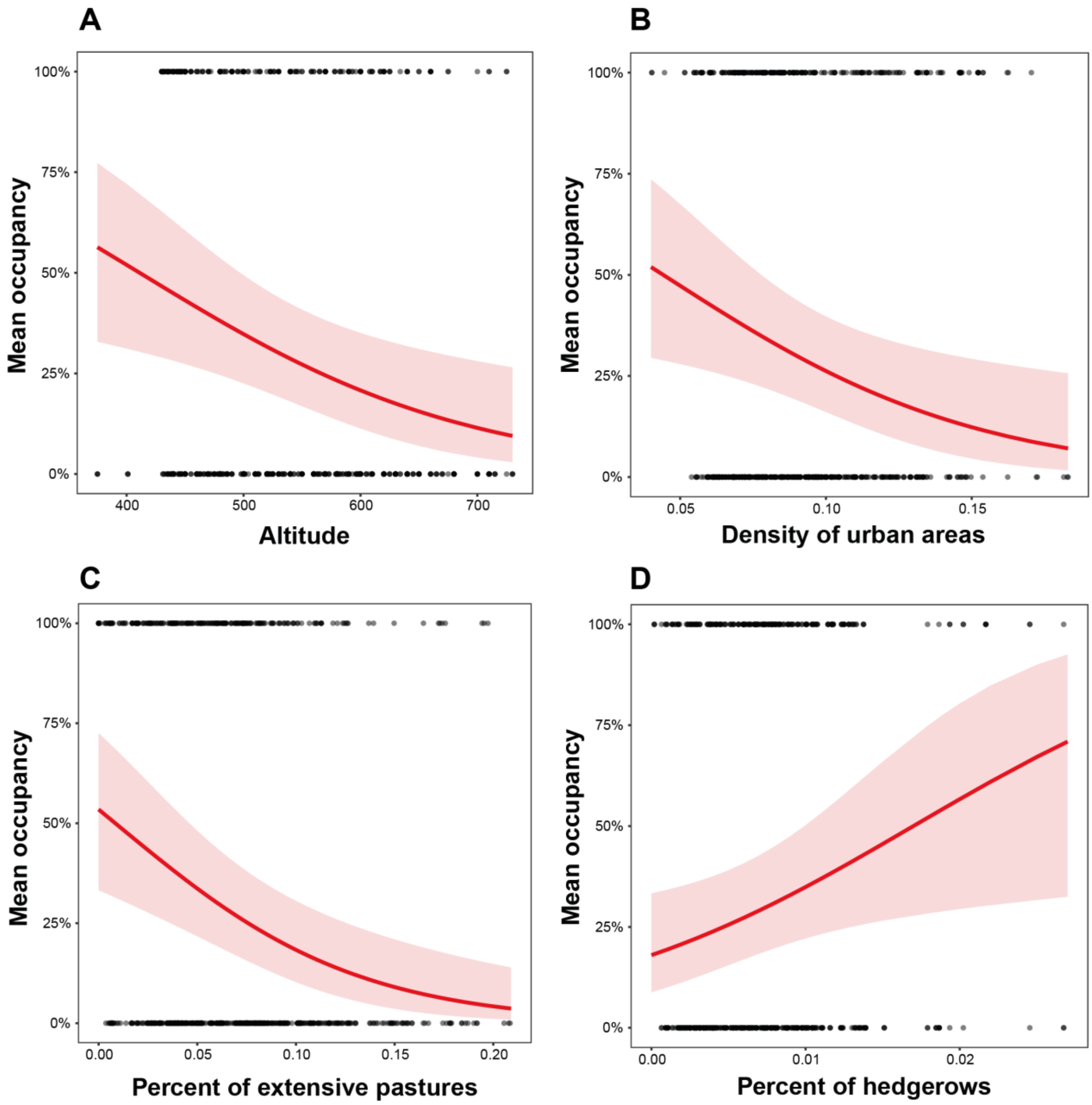

Figure 1: Influence of environmental factors and nest box characteristics on mean site occupancy: the association between mean site occupancy and (A) the altitude, (B) the density of urban areas surrounding the nest box, (C) the proportion of extensive pastures (D) the proportion of hedgerows. The red shaded area represents the 95% confidence interval around the estimated means in solid red line, while the data are shown in black. The graphs present unscaled relationships for interpretative clarity, despite models utilizing scaled predictors.

Table 1: Analyses for annual site occupancy: Results of fitting generalized linear models with binomial family to the mean site occupancy. The global model was constructed with all predictors having a biological significance. The final model was selected with backward step-selection, ensuring an increase in AIC. The predictors removed from the global to the final model are indicated with the sign "Rd". Nest box ID nested in the SiteID and year were added as random factors. Significant terms ($p<0.05$) are written in bold. The model is based on 232 sites between 2018 and 2020.

Parameter Variable	Global model			Final model		
	Estimates (SE)	t	p	Estimates (SE)	t	p
Mean occupancy						
(Intercept)	0.28 (0.13)	-2.76	0.006	0.30 (0.10)	-3.71	<0.001
Scaled altitude	0.53 (0.12)	-2.77	**0.006**	**0.57 (0.12)**	**-2.66**	**0.008**
East orientation	1.02 (0.41)	0.05	0.963	Rd		
South orientation	0.71 (0.39)	-0.62	0.535	Rd		
West orientation	0.97 (0.59)	-0.05	0.959	Rd		
Located outside	1.48 (0.68)	0.86	0.389	Rd		
Scaled heigth [m]	1.38 (0.30)	1.49	0.135	Rd		
Scaled nest box age	0.78 (0.14)	-1.41	0.159	Rd		
Number of nest boxes at the site	1.90 (0.72)	1.68	0.092	1.96 (0.70)	1.88	0.060
Scaled proportion of roads around	1.06 (0.32)	0.19	0.848	Rd		
Scaled density of urban areas	0.56 (0.16)	-2.01	**0.045**	**0.62 (0.12)**	**-2.45**	**0.014**
Scaled proportion of urban areas	1.15 (0.35)	0.46	0.649	Rd		
Scaled area of fields	1.28 (0.30)	1.04	0.300	Rd		
Scaled proportion of extensive pastures	0.51 (0.11)	-3.02	**0.003**	**0.50 (0.10)**	**-3.49**	**<0.001**
Scaled proportion of wildflowers	1.18 (0.19)	1.04	0.298	Rd		
Scaled proportion of extensive meadows	0.99 (0.19)	-0.07	0.947	Rd		
Scaled proportion of hedgerows	1.37 (0.25)	1.68	0.093	**1.47 (0.25)**	**2.28**	**0.023**
Scaled surrounding barn owl site density	0.74 (0.13)	-1.74	0.081	Rd		
Scaled surrounding kestrel site density	0.92 (0.15)	-0.52	0.606	Rd		
Random Effects						
	σ^2		3.29	σ^2		3.29
	$\tau_{00\ site\ ID}$		2.96	$\tau_{00\ site\ ID}$		3.05
	$\tau_{00\ year}$		0.18	$\tau_{00\ year}$		0.18
Model fit	Observations		708	Observations		708
	Marginal R^2		0.182	Marginal R^2		0.153
	AIC		815.8	AIC		798.8

3.2 Breeding parameters

3.2.1 Clutch size

The model focusing on the clutch size (Table 2) showed that, on average, 5.44 eggs were laid per clutch (*SD=1.5 eggs, min=1 egg, max=9 eggs*). The location of the nest box was found to be important, as clutches were larger by approximately 0.56 eggs in nest boxes placed outside the barns (*mean inside=5.24 eggs; mean outside=5.89 eggs*). We did not find any evidence that the orientation of the nest box, the altitude, the height, the nest box age and the number of nest boxes present at the site, explained any variation in clutch size. Regarding the surrounding environment, the proportion of extensive pastures tended to correlate positively with the clutch size, with larger clutches in nest boxes surrounded by increased proportion of extensive pastures. Finally, urban areas have dual relationships, as clutches were larger in nest boxes surrounded by denser urban areas (Fig. 2A) but smaller when surrounded by a higher proportion of urban areas (Fig. 2B).

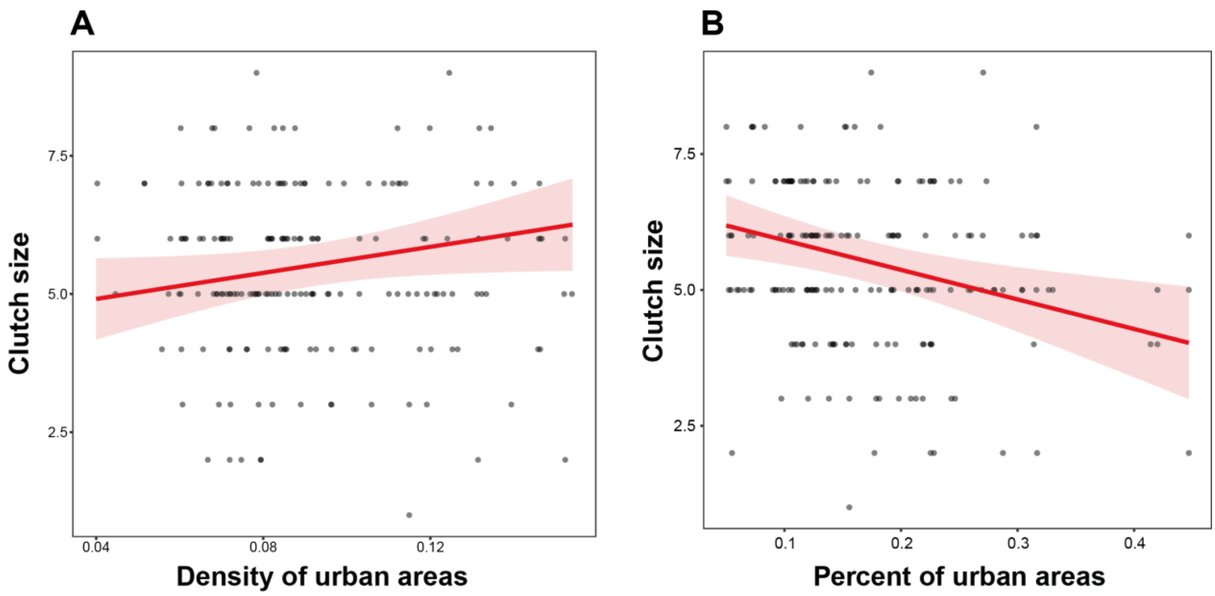

Figure 2: Influence of urban areas on clutch size: the association between clutch size and (A) the density of urban areas and (B) the proportion of urban areas, with the red shaded area representing the 95% confidence interval around the estimated means in solid red line, while the data are shown in black. The graphs present unscaled relationships for interpretative clarity, despite models utilizing scaled predictors.

Table 2: Analyses for clutch size: Results of linear models to the clutch size. The global model was constructed with all predictors having a biological significance. The final model was selected with backward step-selection, ensuring an increase in AIC. The predictors removed from the global to the final model are indicated with the sign "Rd". Nest box ID nested in site ID, year, female ID and male ID were added as random factors. Significant terms ($p<0.05$) are written in bold. The model is based on 188 broods in 118 different nest boxes between 2018 and 2020.

Parameter	Variable	Global model			Final model		
		Estimates (SE)	t	p	Estimates (SE)	t	p
Clutch size							
	(Intercept)	5.76 (0.81)	7.13	<0.01	5.24 (0.20)	25.97	<0.01
	Scaled altitude	0.03 (0.17)	0.19	0.852	Rd		
	East orientation	0.27 (0.31)	0.86	0.393	Rd		
	South orientation	0.14 (0.49)	0.29	0.771	Rd		
	West orientation	-0.42 (0.49)	-0.86	0.393	Rd		
	Located outside	0.77 (0.34)	2.22	**0.028**	**0.56 (0.25)**	**2.24**	**0.027**
	Scaled heigth [m]	-0.05 (0.17)	-0.30	0.763	Rd		
	Same female before	-0.87 (0.97)	-0.90	0.371	Rd		
	Same male before	-0.67 (0.77)	-0.88	0.380	Rd		
	Different pair	-0.73 (0.73)	-1.00	0.319	Rd		
	Scaled nest box age	0.02 (0.13)	0.12	0.906	Rd		
	Nb of nest boxes at the site	-0.00 (0.29)	-0.01	0.992	Rd		
	Scaled proportion of roads around	0.01 (0.23)	0.04	0.967	Rd		
	Scaled density of urban areas	0.33 (0.23)	1.42	0.158	0.30 (0.16)	1.92	0.056
	Scaled proportion of urban areas	-0.46 (0.22)	-2.12	**0.036**	**-0.46 (0.15)**	**-3.09**	**0.002**
	Scaled area of fields	-0.05 (0.19)	-0.28	0.776	Rd		
	Scaled proportion of extensive pastures	0.26 (0.18)	1.48	0.142	0.24 (0.13)	1.84	0.067
	Scaled proportion of wildflowers	0.02 (0.14)	0.13	0.893	Rd		
	Scaled proportion of extensive meadows	0.05 (0.15)	0.32	0.752	Rd		
	Scaled proportion of hedgerows	-0.11 (0.16)	-0.68	0.498	Rd		
	Scaled surrounding barn owl site density	-0.13 (0.14)	-0.92	0.358	Rd		
	Scaled surrounding kestrel site density	0.12 (0.13)	0.96	0.337	Rd		
	Laying date	0.12 (0.13)	0.92	0.359	Rd		
Random Effects							
		σ^2		1.51	σ^2		1.53
		$\tau_{00\ Female\ ID}$		0.43	$\tau_{00\ Female\ ID}$		0.35
		$\tau_{00\ Male\ ID}$		0.00	$\tau_{00\ Male\ ID}$		0.00
		$\tau_{00\ nest\ ID\ :\ site\ ID}$		0.29	$\tau_{00\ nest\ ID\ :\ site\ ID}$		0.22
		$\tau_{00\ site\ ID}$		0.00	$\tau_{00\ site\ ID}$		0.00
		$\tau_{00\ year}$		0.08	$\tau_{00\ year}$		0.07
Model fit		Observations		188	Observations		188
		Marginal R^2		0.176	Marginal R^2		0.124
		AIC		751.0	AIC		700.7

3.2.2 Fledging success

The last model focused on the fledging success (Table 3). On average, 63.3% of eggs hatched and survived until fledging (*SD=31.7%*). The density of surrounding barn owl breeding sites appears as the only significant predictor, fledging success being higher in nest boxes with higher densities of surrounding barn owl sites (*Fig. 3)*. This trend was also found when accounting for surrounding sites simultaneously occupied (*scaled surrounding occupied barn owl site density: Est=1.21, SE=0.13, t=1.83, p.value=0.068*).

The result of the density was consistent when accounting only for successful clutches (*scaled density of surrounding barn owl sites: Est=1.26, SE=0.11, t=2.57, p.value=0.010*).

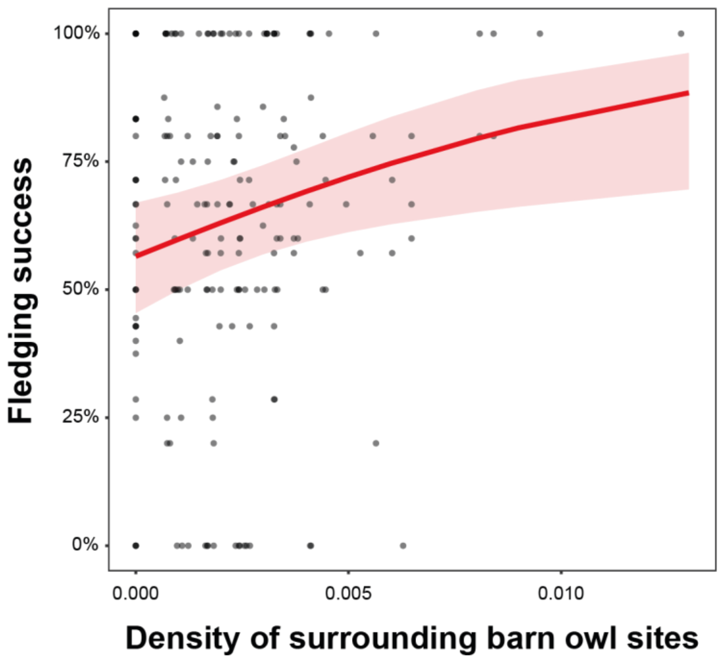

Figure 3: Influence of surrounding barn owl site density on fledging success: the association between the density of surrounding barn owl breeding sites and fledging success, with the red shaded area representing the 95% confidence interval around the estimated means in solid red line, while the data are shown in black. The graphs present unscaled relationships for interpretative clarity, despite models utilizing scaled predictors.

Table 3: Analyses for fledging success: Results of the weighted generalized mixed model with binomial family to the fledging success with clutch size as weight. The global model was constructed with all predictors having a biological significance. The final model was selected with backward step-selection, ensuring an increase in AIC. The predictors removed from the global to the final model are indicated with the sign "Rd". Nest box ID nested in site ID, year, female ID, and male ID were added as random factors. Significant terms (p<0.05) are written in bold. The model is based on 188 broods in 118 different nest boxes between 2018 and 2020.

Parameter Variable	Global model			Final model		
	Estimates (SE)	t	p	Estimates (SE)	t	p
Fledging success						
(Intercept)	3.34 (2.29)	1.76	0.078	1.78 (0.35)	2.95	0.003
Scaled altitude	1.03 (0.15)	0.19	0.850	Rd		
East orientation	0.64 (0.17)	-1.63	0.102	Rd		
South orientation	0.99 (0.42)	-0.02	0.981	Rd		
West orientation	0.63 (0.26)	-1.10	0.271	Rd		
Located outside	0.63 (0.19)	-1.56	0.118	Rd		
Scaled heigth [m]	0.90 (0.13)	-0.68	0.495	Rd		
Same female before	0.65 (0.55)	-0.50	0.616	Rd		
Same male before	1.06 (0.67)	0.09	0.926	Rd		
Different pair	0.75 (0.46)	-0.47	0.640	Rd		
Scaled nest box age	1.11 (0.13)	0.86	0.392	1.17 (0.12)	1.51	0.131
Nb of nest boxes at the site	1.11 (0.28)	0.42	0.671	Rd		
Scaled proportion of roads around	1.12 (0.22)	0.55	0.583	Rd		
Scaled density of urban areas	0.74 (0.14)	-1.53	0.125	Rd		
Scaled proportion of urban areas	1.23 (0.24)	1.07	0.286	Rd		
Scaled area of fields	1.20 (0.20)	1.12	0.261	Rd		
Scaled proportion of extensive pastures	0.84 (0.13)	-1.09	0.278	Rd		
Scaled proportion of wildflowers	0.87 (0.11)	-1.12	0.264	Rd		
Scaled proportion of extensive meadows	0.96 (0.12)	-0.28	0.778	Rd		
Scaled proportion of hedgerows	0.91 (0.13)	-0.69	0.488	Rd		
Scaled surrounding barn owl site density	1.34 (0.16)	2.42	**0.015**	**1.32 (0.15)**	**2.53**	**0.011**
Scaled surrounding kestrel site density	0.98 (0.11)	-0.21	0.832	Rd		
Laying date	0.95 (0.10)	-0.49	0.627	Rd		
Random Effects						
	σ^2		3.29	σ^2		3.29
	$\tau_{00\ \text{Female ID}}$		0.25	$\tau_{00\ \text{Female ID}}$		0.40
	$\tau_{00\ \text{Male ID}}$		0.47	$\tau_{00\ \text{Male ID}}$		0.44
	$\tau_{00\ \text{nest ID : site ID}}$		0.00	$\tau_{00\ \text{nest ID : site ID}}$		0.00
	$\tau_{00\ \text{site ID}}$		0.00	$\tau_{00\ \text{site ID}}$		0.00
	$\tau_{00\ \text{year}}$		0.07	$\tau_{00\ \text{year}}$		0.08
Model fit	Observations		188	Observations		188
	Marginal R^2		0.056	Marginal R^2		0.023
	AIC		682.6	AIC		656.1

4. Discussion

Agricultural lands, which dominate our landscapes (Tilman et al. 2001), play a crucial role in influencing the environment. This is particularly true for species that rely heavily on these areas, such as barn owls. This species depends on agricultural fields to hunt small mammals (Perrins & Snow, 1998), and use artificial nest boxes fixed on barns for nesting. Understanding the influence of agriculture on their breeding parameters is essential for improving conservation strategies for this species and providing information to farmers interested in sustainable practices. Moreover, barn owls are highly efficient predators, consuming up to 800 prey items per breeding attempt during the short 62-day chick-rearing period (St. George and Johnson 2021; Schalcher et al. 2023), thus helping to control small mammal populations (Labuschagne et al. 2016; Montoya et al. 2021). They are essential for farmers who would like to replace pesticides with biological pest control agents. By monitoring more than 200 breeding sites over three years, we evaluated the relationships between fine-scale landscape structures and site occupancy and barn owl breeding success. We found that some agricultural practices positively relate to barn owls' breeding parameters, especially biodiversity promotion areas such as extensively used pastures or hedgerows.

More specifically, a high proportion of hedgerows in the surroundings was associated with a higher likelihood of occupancy. These areas are especially important for barn owls, as they can use them for hunting from a perch (Schalcher et al. 2023). This result shows the importance of such structures for nest box occupancy and encourage their implementation by farmers. However, we did not find any evidence of a relation between the proportion of wildflower areas and barn owl breeding success nor site occupancy. This goes in line with the results found in a previous study (Arlettaz, Krähenbühl, et al. 2010) showing that wildflower areas increase small mammal densities but that barn owls do not forage specifically into such areas. However, this goes in contradiction to a recent study by Séchaud et al. (2021), who showed that barn owls preferred wildflower areas for hunting. One potential explanation for the lack of results in the present study could be the homogeneity of the study area and the very low proportion of wildflower areas overall. It would be interesting to perform such analysis in a more varying environment with a higher proportion of wildflower areas to deeply understand their impact.

Another unexpected result is the dual effect of the proportion of extensively used pastures. While extensive pastures are positively correlated with larger clutch sizes, an intriguing negative relation with site occupancy was also observed. Given that pastures are known for high small mammal densities (French et al. 1976; Aschwanden et al. 2007) and are selected hunting grounds especially during the non-breeding season, providing ample food resources for barn owls (Bühler et al. 2023), it is reasonable to assume that barn owls in pasture-rich areas are in better condition and can thus increase their clutch size. However, the negative correlation with site occupancy warrants further investigation. One plausible explanation could be that the proportion of pastures correlates with untested variables that adversely affects barn owl site occupancy. These unidentified factors might be environmental, ecological, or anthropogenic. Given this possibility, it would be highly beneficial to replicate this analysis over multiple years and in other species. Such studies could help determine the consistency of this pattern and potentially uncover the hidden variables influencing barn owl site occupancy in pasture-rich environments.

The urban areas surrounding the nest boxes also appear as an important factor associated with barn owls' breeding success. Barn owls are highly adapted to human settlements, having used them as nesting grounds over the years (Roulin 2020). In the present study, we found no evidence of a relationship between the proportion of urban areas and site occupancy, highlighting barn owl adaptability to human settlements. However, the density of urban areas was found to negatively relate with site occupancy, showing that even if barn owls exhibit this adaptability, they must still secure suitable hunting grounds nearby, which is possible in sparser urban areas. This is supported by the fact that a high proportion of urban areas was found to negatively relate with clutch size. However, the density of urban areas was found to positively correlate with clutch size. This suggests that barn owls may benefit from environments where smaller, but denser urban areas are interspersed with agricultural fields. It is important to note that the proportion of urban area surrounding the breeding sites in this study was on average low and consists mainly of villages with numerous farms and houses with gardens. Interestingly, we did not detect any association between roads and barn owl breeding success, contradicting previous research (Frey et al. 2011; Charter et al. 2012; Hindmarch et al. 2012). This suggests a dual role of roads: while they are a major cause of mortality for barn owls (Boves and Belthoff 2012; De Jong et al. 3029), they can also provide perches for hunting, as noted by Schalcher et al. (2023).

Regarding the nest box characteristics, several factors stand out as having a significant association with site occupancy and breeding success. Altitude was found to be important, as nest boxes at higher altitudes were less likely to be occupied. This is probably due to barn owls' avoidance of high locations driven by their difficulties to cope with harsh winters (Altwegg et al. 2006). Moreover, nest boxes placed in pairs within the same barn tended to be more likely to be occupied. This could be explained by the increased nest box availability when two nest boxes are placed together, decreasing the inter-specific competition, especially with common kestrels. In addition to this, barn owls can use the second nest box as roosting site during the day, as found by Séchaud et al. (2021), or for second annual clutch (Béziers and Roulin 2016).

Location on the barn also appears to be important, with barn owls producing larger clutches in nest boxes placed outside barns. This may be attributed to the environmental conditions prevalent outside the barns, such as enhanced ventilation or cooler temperatures, which potentially offer more optimal conditions for the females incubating eggs. Alternatively, outside conditions might be more challenging, prompting an increase in clutch size as a compensatory response to anticipated higher offspring mortality. An in-depth investigation into the microclimate within the nest boxes, comparing those situated inside versus outside, would help understand whether and how the environmental conditions inside the nest box differ and impact barn owl breeding strategies. However, our findings did not reveal any notable correlation between nest box location and fledging success, implying that the variations in clutch size do not translate to differences in offspring survival to fledging. This lack of correlation suggests that while external placement may favor larger initial clutch sizes, it does not necessarily affect the overall breeding success.

The orientation was not observed to associate with barn owls' breeding parameters in the present study. This finding diverges from the results presented by Butler et al. (2009), who reported a significant effect of nest box orientation on internal temperature and humidity levels in kestrel nest boxes. Specifically, they found that boxes facing west had significantly cooler average temperature and lower humidity levels than those facing South or East, leading to variations in breeding successes. The difference between these findings may be attributed to differences in nest box design. Kestrel nest boxes typically feature a large opening and are placed externally, making them more susceptible to environmental conditions. Conversely, the barn owl nest boxes examined in our study are designed with only a small entry hole and are more enclosed, offering greater protection from external temperature and humidity fluctuations. Additionally, the distribution of nest box orientations in our study was predominantly towards the north and east, primarily due to installation constraints. This uneven distribution could further contribute to the absence of observable effects related to orientation in our findings.

The density of surrounding barn owl breeding site was found to influence only the fledging success. We observed an increase in fledging success in environments with a higher density of surrounding barn owl sites. This finding could indicate that such environments are of higher quality, attracting numerous pairs to breed in the most favorable areas. However, we did not detect any effect of the density of surrounding kestrel sites. This suggests that despite kestrels being competitors for nesting sites and, to a lesser extent, for hunting resources (Charter et al. 2010; Montoya et al. 2021), both species are capable of coexisting within the same environment.

The comparison between the long-term study (Milliet et al., 2024) and the current short-term study reveals intriguing patterns in barn owl breeding behavior and habitat preferences. In the long-term study, we focused on the same response variables as in the present study, and examined how the proportion of urban area and the number of agricultural fields surrounding each breeding sites influenced them. Additionally, we explored the association with the density of surrounding barn owl breeding site, using the same calculation method as applied in the present study. We also examined the relation with nest box characteristics, using the same as in the present study. While some predictors consistently associate with barn owl breeding success across both studies, others are highlighted only in one. Concerning nest box characteristics, both studies highlight their significance, though with different focuses. A consistent predictor in both studies is the altitude above sea level, which was negatively associated with occupancy in the short term and with clutch size in the long-term. Notably, while the long-term data suggested positive relation between urban areas and barn owl fledging success and site occupancy, the present study reveals dual effects of both the density and proportion of urban areas. This finding suggests that more precise urban data can reveal trends that were previously unnoticed. Regarding agricultural landscapes, both studies demonstrate an overall positive association, emphasizing the importance of biodiversity promotion areas for barn owl breeding success. As for the density of surrounding nest boxes, contradictory trends are observed, with negative association found with the clutch size and site occupancy in the long-term, but positive association with fledging success in the short-term. This discrepancy might suggest that the three years analyzed in the current study had good conditions, leading to a decrease in intra-specific competition.

5. Conclusion

In summary, this study analyzed the extent to which the interplay between various environmental landscapes and nest box characteristics associates with barn owl breeding success. Overall, urbanization seems to pose some challenges to the barn owl, especially on site occupancy and clutch size, while biodiversity promotion areas provide favorable conditions. These findings offer valuable insights for people interested in installing barn owl nest boxes. To the best of our knowledge, this study is the first in which nest box characteristics have been analyzed in relation to the breeding parameters of the barn owl, highlighting the pivotal role of nest box installation. Consequently, our study is well suited to set up specific recommendations for the optimal placement of barn owl nest boxes. Overall, the following key recommendations emerge from our analysis:

- Nest box installation: Avoid installing the nest box at high altitude, preferring location below 700 meters. Install a pair of nest boxes in the same barn.
- Agricultural fields: Encourage the incorporation of biodiversity promotion areas within the agricultural landscape to increase barn owl presence and breeding success. Their advantages go beyond barn owls, as these structures are proven to be highly efficient in promoting biodiversity (Aschwanden et al. 2005; Kleijn et al. 2006; Zingg et al. 2019).
- Urban areas: Avoid placing nest boxes in dense urban areas, but opt for rural zones, favoring the proximity to agricultural landscapes and a lower urban density.

This study not only provides practical advice for those interested in helping barn owl populations but also contributes to the broader understanding of the factors associated with barn owls breeding success. These recommendations have the potential to increase barn owl presence, the implementation of which might further contribute to the promotion of biodiversity within agricultural landscapes.

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Supplementary material

Supplementary material I

Road segments and their corresponding buffer size

Road type	Buffer size
Place	20
Freeway	25
Highway	15
Highway exit and entrance	8
Rest area	16
Access road	16
Service driveway	16
10m roads	10.2
8m roads	9.2
6m roads	7.2
4m roads	6.2
3m roads	4.2
2m way	2.8
1m way	1.8
Narrow way	5

Supplementary material II

Agricultural fields categories

Landuse Category	Category used in the analysis
616 Paturages attenants	Extensively used pastures
617 Paturages extensifs	Extensively used pastures
556 Jacheres florales	Wildflower
557 Jacheres tournantes	Wildflower
601 Prairies temporaires	Extensively used meadow
611 Prairies extensives	Extensively used meadow
612 Prairies peu intensives	Extensively used meadow
852 Haies bosq + bande herb.	Hedgerows
857 Haies bosq sans b herb. n	Hedgerows

General Discussion

The interdependence of agriculture and environmental conservation places farmers in a central role as key decision-makers in conservation efforts. Therefore, exploring and promoting sustainable agricultural practices that support biodiversity conservation is essential. To achieve this, it is necessary to assess the role of social aspects and to understand what are the drivers motivating farmers to adopt pro-environmental behaviors. Collaboration between farmers and scientists is emerging as a critical tool, acting as a bridge between the agricultural community and conservation goals. Such partnerships facilitate the sharing of knowledge and resources, while also promoting a sense of shared responsibility for the environment.

Throughout this thesis, we aimed at exploring the importance of agriculture in biodiversity conservation. We first explored farmers' pro-environmental behaviors and their association with participation in a collaborative project through a multifaceted approach. First, in Chapter 1, a systematic review of existing literature revealed a generally positive influence of collaboration on farmers' pro-environmental behaviors, though it also underscored the scarcity of research in this area. Then, in Chapter 2, we examined a specific collaboration between our research group and local farmers and its association with farmers' self-reported pro-environmental behaviors as well as other psychosocial variables such as attitudes towards science and the environment. While collaboration positively correlated with farmers' attitudes towards science, it did not directly influence their self-reported pro-environmental attitudes or behaviors. In the third chapter, we turned to the predictive power of attitudes towards science and the environment on structural on-farm measures of pro-environmental behaviors, and we highlighted the key role pro-environmental attitudes play in predicting such behaviors. In the final two chapters, we shifted focus to the shared interest of the research group and farmers: the barn owl. In these chapters, we aimed to evaluate the relationship between agricultural practices and barn owl breeding success and nest box occupancy, providing insights into optimal practices for supporting this species.

Agriculture's role in biodiversity conservation

The impact of agriculture on biodiversity loss and climate change is often put forward, with practices such as pesticide use and intensive farming being singled out for their visible environmental effects (Stoate et al. 2009; Maxwell et al. 2016; IPCC 2023). However, this thesis presents a more nuanced perspective, recognizing agriculture's significant potential for environmental conservation. With agricultural land covering over 30% of the Earth's non-water surface (Tilman et al. 2001; Ramankutty et al. 2008; Foley et al. 2011), agricultural practices are uniquely positioned to positively influence biodiversity when managed extensively (Tscharntke et al. 2005; Swinton et al. 2007; Wittwer et al. 2021). In Chapter 4, we analyzed the long-term effects of agricultural intensification, and highlighted the importance of landscape heterogeneity for barn owl breeding success and site occupancy. In Chapter 5, we focused on the short-term with more detailed environmental data, and showed that specific agricultural practices such as biodiversity promotion areas positively contribute to barn owl breeding success and site occupancy. These findings underline the potential of agriculture to support biodiversity, offering practical recommendations for conservation-oriented farming practices and barn owl nest box installation.

These chapters also revealed the remarkable resilience of barn owls, showing that urban and agricultural intensification have weak impact on its breeding success and site occupancy. This resilience is not only a sign of the barn owl's adaptability, but also serves as a source of encouragement for farmers. It illustrates that even minimal conservation measures, such as the installation of nest boxes, are beneficial, especially when combined with the implementation of biodiversity promotion areas. This sends a powerful and positive message to farmers, reinforcing the idea that their actions, however small, can make meaningful contribution to conservation efforts. The use of positive reinforcement is known to be an effective motivator for behavioral change, especially in climate change related behaviors (Spence and Pidgeon 2010; Hurlstone et al. 2014). This suggests that framing conservation practices in a positive light can encourage more significant action to conserve biodiversity, and the barn owl is the perfect flagship species to achieve this.

Farmer’s pro-environmental behaviors

The focus on the negative impacts of agricultural practices often overlooks the considerable contributions many farmers make to environmental conservation. Their dependence on ecosystem health for their livelihood should naturally drive them to protect biodiversity, which, in turn supports their productivity and financial stability. Because of their central role in land management, farmers are directly confronted with the consequences of climate change, which affect them both personally and professionally. Thus, farmers are an integral part of biodiversity conservation, and understanding the motivations behind their pro-environmental behaviors is essential.

However, the current literature examining farmers’ pro-environmental behaviors usually focus on their engagement in various agri-environmental schemes and on the sociodemographic variables explaining it (Knowler and Bradshaw 2007; Riley 2011; Burton 2014; Lastra-Bravo et al. 2015; Knook et al. 2018). But analyzes on the psychosocial drivers behind their commitment to pro-environmental practices is often lacking. Integrating social sciences in the study of pro-environmental behaviors is essential, because conservation efforts are inextricably linked to human behaviors and decision-making processes (Mascia et al. 2003; Ehrlich and Kennedy 2005; Schultz 2011). Understanding the psychosocial factors that motivate farmers to engage in pro-environmental behaviors is critical to designing effective conservation policies and to increase sustainable farming practices.

In chapter 3, we highlighted a positive association between pro-environmental attitudes and structural on-farm measures of pro-environmental behaviors, demonstrating that farmers’ personal belief do indeed play a role in predicting their ecological commitment. This finding underscores the importance of aligning conservation strategies with farmers’ values and perspectives, and highlights the potential of psychosocial insights to inform more targeted and effective environmental conservation initiatives.

However, we found no association between self-reported pro-environmental behaviors and their actual implementation (Chapter 3), indicating a gap between perceived and real environmental practices among farmers. This difference highlights the possibility of inaccuracies in farmers' self-assessments of their conservation actions, suggesting that farmers' beliefs or reports about their environmental efforts do not always match their observable practices. This may be due to social desirability bias, which may cause farmers to overstate behaviors they believe are socially or academically favorable (Kormos and Gifford 2014). Additionally, there was a contrast between the self-reported pro-environmental behaviors tested, which were general on-farm practices, such as mowing methods and invasive species management, and the structural measures of pro-environmental behaviors, which were specific implementation asked by the Swiss Government. This makes the latter highly dependent on prevailing agricultural policies. This difference between self-reported and observed behaviors highlights the need for further research to evaluate and clarify the relationship between these two forms of environmental engagement among farmers, ensuring to compare identical activities between self-reported and measured pro-environmental behaviors.

This difference also highlights the critical need for refined methodologies that effectively bridge the gap between perceived actions and actual practices to evaluate and promote pro-environmental behaviors in the agricultural sector. Chapter 1 also emphasizes this necessity, highlighting the absence of a standardized methodology in this research domain. The literature presents various methods for evaluating farmers' pro-environmental behaviors, along with different statistical analyses. Therefore, we emphasize the need for the development of clear methodological guidelines to improve comparability between studies and ensure that research outcomes are directly applicable to environmental practices.

Moreover, the challenges farmers face in implementing practices promoting biodiversity on their land highlight a significant barrier to achieving real conservation outcomes. Difficulties in translating pro-environmental intentions into concrete actions often arise from inadequate resources, time constraints, or economic or policy limitations. States and governments should urgently implement feasible financial compensation measures, adapting laws and regulations to better support farmers committed to pro-environmental actions.

The importance of collaboration

One effective strategy to influence farmers' attitudes towards the environment and, in turn, their pro-environmental behaviors is through collaboration with ecologists. We found in chapter 1 that overall collaboration between ecologists and farmers can promote farmers' pro-environmental behaviors. However, we also highlighted that this field is still emerging, with few papers in the current literature focusing on this, and even more striking the lack of collaboration between farmers and scientists. In light of this, the current thesis is of great interest, especially Chapter 2 which concentrates on a specific case study involving a long-term collaboration between farmers and scientists.

Since 1990, Prof. Alexandre Roulin's research group has studied a population of free-living barn owls. This has been possible thanks to the collaboration of farmers, who agreed to install nest boxes on their farms. This partnership has predominantly benefited scientific research, providing insights into this raptor species and contributing to one of the most extensive databases on a single bird population. However, the social aspect of this project has never been analyzed. This thesis represents an initial exploration into how collaboration with scientists can influence farmers, focusing on their pro-environmental behaviors and attitudes towards science and the environment. As such, it marks the first project within this research group to consider the implications of its work for the farmers involved, setting a foundation for future research on the reciprocal benefits of collaboration in agricultural contexts.

Overall, our research identified a positive correlation between collaboration with the research group and farmers' attitudes towards science. This is highly encouraging, as attitudes towards science have been previously associated with the promotion of pro-environmental behaviors (Lyons and Breakwell 1994; Farwig et al. 2017). In recent times, public trust in science is very variable. This has been particularly highlighted during the COVID-19 pandemic (Kennedy et al. 2022; Caplan 2023; Intemann 2023). This period was marked by an overload of information from various sources, including those not specialized in relevant fields, leading to widespread misinformation, anxiety and doubt. This skepticism is not limited to pandemics, but extends to other critical issues such as climate change (Drummond and Fischhoff 2017). Despite decades of scientific warnings about climate change (Union of Concerned Scientists, 1992), the global response has been inadequate. This lack of trust underscores the urgent need to rebuild faith in scientific expertise and findings. This thesis contributes to the understanding of how collaborative initiatives can serve as a bridge to renew trust in science. By involving farmers directly in scientific research, we can improve their attitudes towards science, which could in turn enhance their commitment to environmental conservation. Such collaboration represents an essential step in mitigating skepticism and promoting a more informed and proactive approach to addressing global challenges such as climate change.

Yet, establishing a direct link between attitudes towards science and actual pro-environmental behaviors among farmers presents complexities. Our findings in chapter 2 indicate no discernible relationship between farmers' self-reported pro-environmental behaviors and their attitudes towards science. Similarly, chapter 3's examination of tangible environmental practices did not reveal any correlation with attitudes towards science either. However, these observations should not be interpreted as diminishing the value of collaboration. Chapter 1 highlights how collaboration can positively influence other significant variables, such as farmer's environmental knowledge and awareness, and how pro-active engagement of farmers is essential. This indicates the profound and potentially long-lasting influence that collaboration can have in promoting pro-environmental practices. In addition, results from Chapter 2 revealed an increase in pro-environmental behaviors and attitudes over time for both collaborators and non-collaborators. This suggests that the onset of collaboration through this thesis may have initiated these positive changes, illustrating the broader influence of collaborative projects on environmental commitment. These results underscore the need for more extensive and focused projects that aim to promote specific pro-environmental behaviors. Initiating collaborative efforts is often more straightforward and immediately actionable than modifying external factors, such as subsidies or laws, which pose significant challenges due to political and socio-economic issues. Future research should prioritize examining concrete conservation projects that actively engage farmers. This approach would enable a more precise evaluation of the relationship between collaboration, attitudes towards science, and pro-environmental behaviors.

Chapter 1 highlighted the crucial role of establishing a straightforward connection between collaboration and pro-environmental behaviors to promote them. The self-reported pro-environmental behaviors assessed in Chapter 2 may have been overly broad and insufficiently aligned with the specific activities of our research group, potentially explaining the lack of correlation between pro-environmental behaviors and collaboration. Indeed, within our research group, we have the opportunity to pilot targeted conservation measures that benefit the barn owl, such as installing raptor perches, promoting the creation of wildflower strips or reducing the use of rodenticides. Actively involving farmers in these initiatives has the potential to positively influence their environmental actions and strengthen their connection to scientific research. Such participatory approaches could serve as a model for enhancing both the adoption of sustainable practices and the broader perception of science among the agricultural community, and should be tested in a future research.

Conclusion

In conclusion, this thesis highlights the critical role of agriculture in biodiversity conservation and the importance of farmers as key actors. Combining empirical research and theoretical discussion, we have explored the potential of collaboration as a driver to promote pro-environmental behaviors among Swiss farmers. Our investigation revealed that the success of such collaborations depends heavily on the proactive and engaged participation of farmers themselves. This work provides an initial exploration of the partnership between our research group and the farming community, aiming to understand its dynamics and outcomes. It highlights the potential for more robust and meaningful collaborations in the future. This thesis emphasizes the importance of enhancing communication between the scientific community and the general public, as achieving substantial progress in conservation efforts and sustainable practices requires a collective approach. It is my hope that this message will be heard by many, especially in the academic community, encouraging a future where collaborative efforts are not just aspirational but a fundamental principle of how we approach environmental protection.

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