

Innovative farmers current and intended use of digital agroforestry tools

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Abstract

CONTEXT: Agroforestry systems provide numerous advantages over monocropping systems, but recent uptake by farmers has been limited, among other reasons, because long-term planning is required. Digital tools can support decision-making processes and could help to increase the implementation of agroforestry. However, empirical evidence on farmers' current use of such tools, as well as the level of willingness to use them, remains unclear.

OBJECTIVE: The study aims to assess i) farmers' current usage of digital agroforestry tools, ii) farmers' intentions to use them in the near future (within the next five years), and iii) factors influencing farmers' digital usage, both currently and in the future.

METHODS: The study was conducted as an online survey among agroforestry pioneers in eight European countries. Descriptive and comparative analyses were used to examine farmers' levels of knowledge, attitudes toward digital agriculture, current use of digital agroforestry tools, future adoption intentions (within the next five years), and associated influencing factors.

RESULTS AND CONCLUSIONS: Of the 119 respondents, the majority show a positive attitude towards digital agriculture, with only 4% opposed to it. In terms of their existing knowledge, there are defined clusters: one-third have no knowledge of digital agriculture or have only heard of it, one-third are in the "awareness" or "interest" phase, and the remaining third are already in the "testing and implementation" phase. The latter is characterized by farmers in a better financial situation. Regarding the introduction of digital agroforestry technologies in the near future, the majority are either positive (37%) or neutral (30%), with only a minority rejecting (12%) or fully rejecting (7%) the idea. While only one-third of farmers currently use digital agroforestry tools, about half intend to do so in the near future, indicating a clear trend towards increased usage.

Two factors are crucial for using digital agroforestry tools: knowledge of agroforestry and a positive attitude towards digital technologies. Regarding potential implementation or use in the near future, "attitude" remains the only decisive factor. These findings indicate that attitudinal factors play a decisive role in both current and prospective digital tool adoption.

SIGNIFICANCE: The study provides empirical insights into the adoption dynamics of digital agroforestry tools among European agroforestry pioneers. By highlighting the central role of farmers' attitudes towards digital transformation, our findings suggest that policy and advisory efforts should go beyond providing technical training and actively promote positive attitudes toward digital transformation. However, to overcome farmers' hurdles, they should also actively encourage a positive attitude towards digital transformation in agriculture and agroforestry.

1. Introduction

Farmers face the challenge of profitably producing food and fibre in volatile markets whilst addressing climate change and environmental deficits (Khatri et al. 2023, Nair, P.K.R. 1985). The practice of agroforestry, i.e. the combination of trees and shrubs with livestock and/or crop production, is one way of increasing the resilience of farming systems to climate change and changing markets (Kay et al. 2019; Raihan 2023). Agroforestry has a long tradition in Europe, with *Dehesas* and *Montados* in the Mediterranean regions, *Streuobst* and orchards in the continental regions and wind breaks and buffer strips in the Atlantic areas (Herzog 1998; Eichhorn et al. 2006; Plieninger et al. 2015). However, for any location, there are multiple suitable combinations possible depending on the system objectives, regarding the combination of trees, arable crops, and/or livestock (Giannitsopoulos et al. 2025). The diversity of possible tree species, spatial configurations, and products (e.g. food, fodder, timber, energy) can result in difficult decisions for people considering agroforestry to be foreseen. In addition, the long-term nature of these systems also requires farmers to consider the implications for the next 30, 60 or even 100 years. In this context, there is a potential role for the use of digital tools (Finger 2023). Tools "how crops and trees interact over time", or "how ecosystem services develop over time" or "how farm profitability will develop over time".

There is a plethora of digital tools to guide farmers, foresters and advisors (Ramil Brick et al. 2022). For example, in arable farming, there are "digital agriculture" tools typically operating on a single year which model crop yield (Wang et al. 2022), evaluate irrigation requirements (Klein et al. 2014; Chauhdary et al. 2019), and propose fertilizer and pesticide applications (Moreira Barradas et al. 2012). There are also tools to provide advice on optimal arable crop rotations (Schönhart et al. 2011), which may model a period of around 5 to 8 years. In forestry, there are tree- and forest growth models (Pretzsch et al. 2002; Nightingale et al. 2008), tree selection models, management (pruning) models (Porté and Bartelink 2002), and economic assessments, and many of these are based on changes over decadal or even century evaluations (Maréchaux et al. 2021) and the estimation of carbon storage.

Within the development of digital tools for agroforestry, a common challenge is how to integrate annual choices regarding crops and grass management, with changes in tree yields over periods typically exceeding 20 years. At the time of writing this paper, the EU-sponsored DigitAF project has developed an online tool catalogue (DigitAF, 2025) that includes 51 agroforestry tools. These includes tools focused on i) tree selection as the "AgroforestTreeAdvice" (Gosme et al. 2025), ii) system design as the RegenWorks (Regen Farmer, 2018), iii) biophysical performance such as Yield-SAFE (Burgess & Graves, 2023) and Hi-SAFE (Dupraz et al. 2019). There are also tools focused in iv) economics such as Farm-SAFE (Graves et al. 2007), AgroforstRechner (Böhm, 2018), and INTACT (Carton et al., 2024), and v) carbon sequestration such as OpenCarbonCalculator (Regen Farmer, 2024), CARAT (Vanneste et al., 2025) or CarboCatch (Space4Good, 2021). Some of these digital tools can be used directly by farmers for practical applications (e.g. CARAT, AgroforstRechner) or extension services (e.g. Regen Works Tool), while other tools (e.g. Hi-SAFE) have been developed explicitly by and for the scientific community and therefore - depending on the research question - are more complicated to use or require further development and active programming. All these tools are designed to help farmers in their decision-making process and provide a reliable basis what has often been just a 'gut feeling' (Roberti et al. 2025).

So, digital agroforestry tools have the potential to encourage the adoption of agroforestry practices. However, some studies highlight that the current state of these digital tools remains unclear.

The use and adoption of digital technologies in agricultural systems have been widely studied (Pierpaoli et al. 2013; Barnes 2019; Heitkämper et al. 2023). However, adoption rates remain generally low and fragmented (EU Commission 2023; Osrof et al. 2023). Osrof et al. (2023) offer a comprehensive overview of key factors (individual, organisational, technological, and external) that influence the adoption of digital technologies. They also highlight that most existing research has primarily focused on farmers, leaving a gap in multi-stakeholder perspectives regarding digital technology adoption. Moreover, adoption barriers and drivers are likely to differ across cultural contexts, yet relatively few studies have taken a cross-country comparative approach. As such, further research is needed to address this gap through cross-national studies (Osrof et al. 2023). In contrast, the digitalisation of agroecological systems remains an underexplored area in literature. Petraki et al. (2025) recently analysed the potential of decision-making tools in agroforestry systems. The authors found that digital solutions offer significant potential to increase productivity and improve environmental outcomes, yet that their adoption remains limited due to barriers such as low digital literacy, lack of infrastructure and concerns about effectiveness in real farming conditions. They therefore conclude by emphasising the role of digital tools in agroecology and highlighting the need for continued research to assess their long-term potential in terms of the agroecological transition. Another aspect influencing farmers' decisions in the context of digital transformation is concerns about data protection and data security (Reissig et al., 2024), which is also to be expected in the context of the adoption of agroforestry tools.

It is worth mentioning that using digital tools is seen both positively and negatively. Technical concerns, willingness to use, and need for use are often discussed. Reissig (2023), Heitkämper et al. (2023) and Reissig and Siegrist (2025) evaluated the use of digital tools in agriculture. As agriculture enters a “transformative phase” driven by technological innovation, the adoption of digital farming tools is becoming increasingly widespread. In response to this trend, farmers are faced with the need to make informed decisions about whether and how to incorporate these new technologies into their practices. The acceptance of these novel technologies, however, is a complex process influenced by a multitude of factors rooted in technological, social, economic, and environmental dimensions (Reissig and Siegrist 2025).

In a recent study, Tranchina et al. (2024) asked agroforestry stakeholders, including farmers, extension agents and beneficiaries from eight European countries, about their knowledge, needs and wishes regarding agroforestry tools. They found that stakeholders were largely unaware of current digital options for agroforestry assessment, design or modeling, but would like to use user-friendly and practical tools. By contrast, where tools are used for research, the level of “user-friendliness” is less critical. This paper builds on that study with the objectives of determining i) the status of usage of digital agroforestry tools in Europe; ii) farmers’ intentions to use them within the next five years, and iii) the factors influencing how farmers might use digital agroforestry technologies.

2. Material and Methods

2.1 Survey

The status, anticipated levels of future use, and the factors affecting the use of digital agroforestry tools in Europe were examined using a survey. The survey, which included two phases, was developed by members of the DigitAF project consortium which included a network of six living labs in Czechia, Finland, Germany, Italy, the Netherlands, and the United Kingdom (Tranchina et al., 2024). The first phase of the survey consisted of five major sections: 1) general characteristics of the respondents, 2) current use of tools and data, 3) agroforestry knowledge, 4) details on policy-related, technical issues and tree, crop and animal interactions, and 5) socio-psychological self-assessment. The survey was a self-administered online form using Google Forms. It was designed in English and translated into Czech, German, Dutch, Finnish and Italian. Stakeholders were asked to answer the questionnaire between March and June 2023. All answers were translated back into English. This paper analyses farmers' positions in this sample we have pioneer farmers.

In the second phase, a shortened questionnaire consisting of sections 1 and 5 and selected questions from sections 2 and 3 was produced in the original format of an online Google form. It was translated into Spanish and French in addition to the existing six languages. Between September 2024 and January 2025, the survey was sent beyond the original six living labs, to farmers and land users in other countries in Europe who had established or were interested in establishing agroforestry plots. A total of 119 responses were recorded and evaluated.

2.2 Measures

To investigate the social and psychological factors influencing the adoption of precision agroforestry technologies, a structured survey consisting of 16 main questions encompassing demographic, technical, psychological, motivational, and attitudinal aspects was developed. The questionnaire included both self-constructed and adapted items from existing literature. All items were measured using a 5-point Likert scale including "1: Do not agree at all", "2: Do not agree", "3: Rather agree", "4: Agree", "5: Totally agree", and with the option "I prefer not to say".

Current and future use of digital agroforestry tools

The current use of digital agroforestry tools was determined by their selection of a response defined by six statements on the 5-step Likert scale alongside the option to say, "I prefer not to say". With the following question, we analyzed use of digital agroforestry applications. It had to be answered on a 6-step scale: "I know what the term "digitalization in agroforestry" means", "I already know that digital technologies are used in agroforestry.", "However, I don't know the details yet and don't feel the need for more detailed information.", "I know that digital technologies are used in agroforestry and am already looking for information.", "I am familiar with digital tools in agroforestry and have evaluated their advantages and disadvantages for me and decide for or against using a particular technology.", "I use

digital tools in agroforestry to a limited extent and am looking for further information on this topic.” and “I regularly use digital tools in agroforestry.”.

Intention to use digital agroforestry tools in the future

To assess farmers’ intention to adopt digital agroforestry tools in the future, participants responded to the following two questions: (1) Do you intend to use precision agroforestry tools on your farm in the next 5 years? (2) How strong is your intention to use precision agroforestry tools on your farm in the next 5 years? Responses were given on a 5-point Likert-type scale ranging from (*1 = does not apply at all to 5 = applies completely*).

Farm and household character

The financial situation was measured using a single item assessing perceived financial situation on a 5-point scale ranging from *very bad* to *very good*. Additionally, two items assessed the adequacy of digital infrastructure (internet connection and mobile reception) on a 5-point Likert scale (*1 = do not agree at all to 5 = totally agree*).

Motivation and attitudes toward digitalization

Participants' general and domain-specific attitudes toward digitalization in agriculture and agroforestry were captured using two single items each rated on a 5-point Likert scale (*1 = rejecting to 5 = facing*).

Personality traits

A set of 10 items assessed individual personality characteristics aligned with five personality dimensions (Rammstedt et al., 2012). Respondents rated their agreement with each item on a 5-point Likert scale (*1 = does not apply at all to 5 = applies completely*). Two of the five personality dimensions were selected for the analysis, according to the literature. “Extraversion” was measured by (1) “I am rather reserved.” (Recoded) and (2) “I get out of myself, am sociable.” and “Openness” by (1) “I have little artistic interest.” (Recoded) and (2) “I have an active imagination, am imaginative.”.

Autonomy and independence

Three items measured the importance of autonomy-related values (e.g., being one’s own boss, self-maintenance of equipment, independence from experts), each rated on a 5-point Likert scale (*1 = totally unimportant to 5 = totally important*).

Workload

Overall workload perception was assessed with a single item asking respondents to rate their workload on a 5-point Likert scale (*1 = much too little to much too much*).

Technology affinity

To measure respondents' general orientation toward technology, a set of nine items was included. The "Affinity for technology interaction 9 item scale (ATI)" developed by Franke et al. (2019) to measure human and technology interaction. The following items from this study by Franke et al. (2018) were used to measure the construct: (1) "I like to occupy myself in greater detail with technical systems." (2) "I like testing the functions of new technical systems. (3) "I predominantly deal with technical systems because I have to." (4) "When I have a new technical system in front of me, I try it out intensively." (5) "I enjoy spending time becoming acquainted with a new technical system. (6) "It is enough for me that a technical system works; I don't care how or why." (7) "I try to understand how a technical system exactly works. (8) "It is enough for me to know the basic functions of a technical system." (9) "I try to make full use of the capabilities of a technical system." The participants could indicate their agreement with the statements, using a scale ranging from 1 (*not agree at all*) to 5 (*completely agree*). The answers to the three negatively formulated items (items 3, 6 and 8) were inverted.

Data usage and Privacy attitudes

Several items addressed the participants' current use of digital data and their knowledge about data collection and privacy agreements with service providers. Further, respondents were asked to rate their willingness to share farm data (e.g., operational, fertilizer/pesticide, and production data) with various entities (e.g., technology providers, governmental authorities), their consent preferences, and willingness to pay for data ownership or exchange it for reduced costs. These were measured using 5-point Likert scales adapted to the context (*1 = Does not apply at all, 5 = Applies completely*).

Trust in Data Security

To assess trust in data privacy and protection, two items measured confidence in service providers' data handling practices, specifically regarding confidentiality and third-party sharing. These were rated on a 5-point trust scale (*1 = no trust at all to 5 = high trust*).

2.3 Data Analysis

Data preparation and analysis were performed using RStudio version 4.3.3 (RStudio-Team 2020) and the packages *dplyr* (Wickham et al. 2025). All plots were drawn with the package *ggPlot2* (Wickham 2016).

Linear mixed-effect models were built using the function *lmer* from the package *lme4* (Bates et al. 2015). In model 1 the "state of adoption of digital tools" was used as response variable. As explanatory variables "Knowledge of Agroforestry", "Education", "Workload", "Affinity to Technology Interaction", "Autonomy", "Internet connection", "Age", "Financial situation", "Attitude towards digital agriculture", "Extraversion" and "Openness" were used. For model 2, the response variable "Intention to use digital agroforestry tools" was square transformed to assure a normal distribution of the residuals. As explanatory variables we used the same variables as in model 1.

For both lme models the variable "Country" was used as random factor since no structural differences between countries were expected. Collinearity among variables was checked using Pearson's

correlations (r) (see Appendix Figure A1). Two variables with $r > 0.6$ were never included as explanatory variables in the same model (Appendix Figure A1). To check for the assumption of the models, the residuals were checked visual of the residual plots an QQ plot and were tested for normality with the Saphiro Wilk test. Homoscedasticity was tested with the *levene.test* from the package *car* (Fox and Weisberg, 2019).

3. Results

3.1 Sample description

A total of 119 responses from eight European countries were recorded and evaluated. Amongst this group, 17% and 37% had received primary and secondary school education as their highest qualification respectively, 14% and 5% have attained a bachelor's or master's degree respectively, and 26% had a PhD (Fig. 1A), accounting for more than a third of the total sample at 36.7%. In second place comes the group with a doctorate (PhD, 25.7%) followed by primary degree (17.4%) and degrees at Bachelor's (13.7%) and master's level (4.6%). This distribution indicates a heterogeneous composition of the sample in terms of formal education level, with both low and highly qualified groups. The relatively high number of people with a PhD could indicate a selective participation structure, e.g. through the greater participation of academically orientated target groups. At the same time, tertiary educational qualifications are underrepresented overall.

Most participants are in the middle age groups: 34.86% of respondents are between 51 and 65 years old, closely followed by the 36–50 age group with 33.94%. The younger age group (18–35 years) is represented by 22.94%, while the group of over 66-year-olds makes up a comparatively small proportion at just 8.26% (Fig. 1B). This distribution indicates a clear overrepresentation of the middle age segments, while older and younger people are underrepresented in the sample. That is in line with the agricultural structure, farmers over 66 are mainly retired and the average age of farmers in Europe taking over a farm is typically between 35 and 40 years (Eurostat, 2025).

Most participants rated their knowledge of agroforestry as medium to high as shown in Fig. 1C. Medium high knowledge (4) was the most frequent value with 36.7%, followed by level 3 (medium knowledge) with 31.2%. A high level of knowledge (5, 17.4%) and a low level of knowledge is much rarer: only 12.8% of participants chose level 2, while 1.8% rated their knowledge as 1. This distribution suggests that a large proportion of the sample is already familiar with the concept of agroforestry. At the same time, the relatively low number of people with a low self-assessment level indicates that a certain basic understanding is widespread in the target group. This is due to the participants selection ("agroforestry pioneers") and can be interpreted as an indicator of a relatively high level of prior knowledge overall.

Most participants come from Germany (40.4%), Czech Republic (25.7%), and Switzerland (13.7%) (Fig. 1D). The participation from France was only 1%, while the other countries were between 3 to 6%.

3.2 Attitude towards and use of digital agroforestry tools

Nearly half of the respondents (49.5%) reported a “rather facing” attitude, indicating a generally positive stance toward digital agricultural technologies (Fig. 2A). An additional 22% expressed a fully “facing” attitude. Meanwhile, 22% of participants reported a neutral attitude. Only a minority of respondents indicated a negative orientation, with 4.6% being “rather rejecting” and just 0.9% being fully “rejecting.” These findings suggest that the majority of participants are receptive to digital agriculture, while a very small proportion demonstrates clear opposition.

The innovation adoption level towards digital tools (Fig. 2B) is divided into six categories including the still unknown, perception, interest, evaluation, experimentation, and adoption phases. The largest proportion of participants (28.4%) falls into the unknown category; these participants have not yet heard of digital agroforestry technologies. Another third of participants have merely heard of these technologies, while 10.1% are in the perception phase and a further 22.9% in the interest phase. Many participants are already testing the tools with 8.3% in the evaluation phase and 17.4% in the experimentation phase. With only 7.3% (adoption phase), just a small number of farmers regularly applying a digital agroforestry tool in their farm work.

The largest number of participants (36.7%) indicated that the statement “I intend to adopt digital agroforestry tools within five years” (Fig. 2C) applies to them, followed by 30.3% who expressed a neutral stance. A smaller share of respondents reported that the statement applies completely (13.8%). In contrast, fewer participants stated that the intention does not apply (11.9%) or does not apply at all (7.3%). These results suggest that while a majority of respondents are either favorable or neutral toward adopting digital agroforestry technologies in the near future, only a minority fully reject the idea.

3.3 Factors to support adoption digital agroforestry

The key question is which factors play a role in adopting digital agroforestry tools, explaining the current use and the intention for future use. The correlations between dependent and independent variables are presented in Appendix.

A multiple regression analysis was conducted to examine the factors influencing farmers’ current state of adoption of digital agroforestry technologies (Table 1). The model included several predictors, with the adoption state as the dependent variable. The analysis revealed that the model explained a moderate proportion of variance in the adoption behavior, with a marginal R^2 of 0.388 (fixed effects only) and a conditional R^2 of 0.485 (including random effects). The number of observations was $n = 90$.

Among the predictors, two variables showed statistically significant positive effects. Knowledge about agroforestry emerged as a strong predictor ($\beta = 0.699$, $SE = 0.146$, $t = 4.774$, $p < .001$), indicating that greater knowledge is associated with a higher likelihood of adopting digital agroforestry technologies. Similarly, a positive attitude towards digital agriculture significantly predicted adoption ($\beta = 0.876$, $SE = 0.216$, $t = 4.064$, $p < .001$).

Other variables, such as education level, workload, affinity for technology interaction, perceived autonomy, personality, internet connection quality, age, and financial situation, did not show statistically

significant effects ($p > 0.05$), suggesting that these factors alone were not strong predictors of adoption in this model.

Table 1
Results of a multiple regression analysis of farmers' adoption state of digital agroforestry technologies as dependent variable and various variables as independent variables.

term	estimate	std.error	statistic	df	p.value	
(Intercept)	-4.003	1.818	-2.201	78	0.031	
Knowledge agroforestry	0.699	0.146	4.774	76	< 0.001	***
Education	0.192	0.125	1.535	77	0.129	
Workload	-0.093	0.152	-0.610	75	0.544	
Affinity technology interaction	0.362	0.343	1.057	71	0.294	
Autonomy	0.138	0.214	0.644	76	0.522	
Internet connection	-0.191	0.120	-1.586	76	0.117	
Age	-0.002	0.160	-0.015	73	0.988	
Financial situation	-0.226	0.149	-1.520	76	0.133	
Attitude towards digital agriculture	0.876	0.216	4.064	76	< 0.00	1***
Extraversion	-0.051	0.172	-0.294	76	0.770	
Openness	0.262	0.158	1.661	75	0.101	
Note: Marginal R^2 (fixed effects only): 0.300 Conditional R^2 (fixed + random): 0.300 n = 90						

A multiple regression analysis of the factors influencing farmers' intention ($n = 90$) to adopt digital agroforestry technologies within the next five years was able to explain 30% of the variation (Table 2). Among the independent variables, attitude towards digital agriculture was the only significant predictor ($\beta = 11.372$, $SE = 3.376$, $t = 3.368$, $p < .001$), highlighting a potential role of positive perceptions in shaping future adoption intentions. In contrast, variables such as knowledge about agroforestry, education level, workload, affinity for technology interaction, perceived autonomy, personality, internet connection, age, and financial situation did not significantly predict adoption intention ($p > 0.05$), suggesting limited influence of these factors in this model.

Table 2
Results of a multiple regression analysis of farmers' intention to adopt digital agroforestry technologies within five years as dependent variable and various variables as independent variables.

term	estimate	std.error	t statistic	df	p.value	
(Intercept)	-78.40	28.13	-2.79	78	0.007	**
Knowledge of agroforestry	2.40	2.28	1.05	78	0.296	
Education	2.62	1.97	1.33	78	0.188	
Workload	2.37	2.39	0.99	78	0.326	
Affinity to technology interaction	5.80	5.50	1.06	78	0.294	
Autonomy	3.93	3.26	1.20	78	0.232	
Internet connection	1.45	1.84	0.81	78	0.420	
Age	4.32	2.55	1.69	78	0.095	.
Financial situation	-0.95	2.34	-0.41	78	0.684	
Attitude towards digital agriculture	11.37	3.38	3.37	78	0.001	**
Extraversion	3.83	2.73	1.40	78	0.165	
Openness	-0.64	2.46	-0.26	78	0.795	
Note: Marginal R ² (fixed effects only): 0.300 Conditional R ² (fixed + random): 0.300 n = 90						

The association between participants' self-reported knowledge of agroforestry and their current level of digital agroforestry adoption suggests that increased knowledge could facilitate the adoption process or that the adoption level affects the level of knowledge (Fig. 3A). The causal relationship may occur also in the other direction. Adopting agroforestry leads to a higher level of knowledge about agroforestry.

The results of the relationship between financial situation and the level of digital agroforestry technology adoption suggest variation in adoption levels across financial situations (Fig. 3B). While digital agroforestry adoption occurs across all financial categories, farmers reporting a better financial situation (score 5) are more frequent in the adoption or Experimentation phases. In contrast, lower financial categories (scores 1–2) are more commonly associated with earlier adoption stages or unknown levels. This pattern appears to reflect the influence of financial resources and progression through the digital agroforestry adoption process, but it was not statistically significant in the regression analysis.

The association between participants education level and their intention to adopt digital agroforestry tool within the next five years turned out to be not significant in the regression analysis when taking other factors into account (Fig. 3C). Moreover, the correlation between participants self-reported attitude towards digital agriculture and their intention to adopt digital agroforestry tools within the next five years

indicates a clear trend (Fig. 3D). Attitude towards digital technologies plays a facilitating role in the intention to adopt digital agroforestry tools, a trend confirmed by the regression analysis.

4. Discussion

The objectives of this study were to examine the current and future intended use of digital agroforestry tools, and the factors affected the use of the digital agroforestry tools, based on a survey of 90–119 respondents across seven countries in Europe.

The respondents were derived from nine countries across Europe. In six countries, the respondents were linked to Living Labs focused on the use of digital tools in agroforestry. In each country, the respondents were linked to researchers working on agroforestry. Hence 85% of the respondents indicated that they had a medium, medium-high or high level of knowledge about agroforestry (Fig. 1C). About 57% of the respondents were less than the age of 50 years, which is younger than the average age of 57 years for farmers in the European Union. Hence our survey cohort is younger than the typical European farmer. Following a younger farmer cohort will help to introduce digital technologies, while the European Commission is working on providing opportunities for younger farmers (Directorate-General for Communication of the European Commission, 2025).

The survey indicates a positive correlation between knowledge of agroforestry and the adoption of digital agroforestry tools. This relationship could be driven both by knowledge of agroforestry, and the use of digital agroforestry tools creating a greater knowledge of agroforestry. Certainly, in the research space, the use of digital tools is commonly used to systematically express the current status of knowledge through algorithms.

In line with research questions i), Tranchina et al. (2024) demonstrate that stakeholders' perception of the benefits of digital tools for agroforestry far exceeds their awareness of the tools currently available. This signals either a clear mismatch between perception and reality, or that tools currently available on the market are not accessible to stakeholders. In addition to a general lack of promotion and marketing, this could be because the existing tools focus on science and therefore address different stakeholders.

While previous studies with agroforestry stakeholders have indicated a general willingness to adopt agroforestry practices if profitability issues and practical issues are resolved (Rois-Díaz et al. 2018), these studies have also highlighted various problems, ranging from high administrative costs and bureaucratic complexity (García de Jalón et al. 2018) to the risk of losing Common Agricultural Policy (CAP) payments (Camilli et al. 2018). Based on the current literature, low financial rewards and high legal complications seem to be the main reasons for non-adoption (Tranchina et al. 2024). However, our study revealed that a key factor previously not considered is the lack of agroforestry knowledge among the group of non-adopters. Our results indicate that agroforestry knowledge is correlated with the implementation of digital agroforestry tools. Without agroforestry knowledge, it is difficult to imagine getting started in this form of agriculture, but with increasing development, the tools will be able to take over this knowledge.

This is particularly evident in long-term farm decisions. So Jagannathan et al. (2023) evaluated how long-term climate projections can be used in decision-making processes on almond tree farms. They revealed that farmers use the information to make decisions when it is provided in an understandable format. Similar results were found in a study from Australia (Malakar et al. 2024).

In general, there is an increasing demand for tools and long-term forecasts in agriculture, especially agroforestry. For instance, the European Carbon Farming Initiative (European Parliament, 2024) asks for results of three individual tools to calculate and model carbon storage capacity to comply with legal requirements. Digital tools will therefore be used also by farmers involved in agroforestry.

Since our results show that only one-third of participating farmers already use digital agroforestry tools, but about 50 percent intend to use additional digital agroforestry tools in the near future, the trend toward increasing use is clear. No comparable results have been found so far in the literature. This upward trend highlights a growing recognition of the relevance and potential of digital solutions in complex, multifunctional farming systems. This aligns with broader developments in digital agriculture. Digital technologies such as remote sensing, precision farming, and decision-support systems are increasingly being adopted to improve farm productivity, environmental monitoring, and resource management (Wolfert et al. 2017; Klerkx et al. 2019). In agroforestry, where spatial and temporal complexity is high, digital tools may provide critical support for managing tree-crop-livestock interactions, planning land use, and optimizing long-term productivity (Fagerholm et al. 2016; Stewart et al. 2022).

At the same time, it is clear that two factors are crucial for the current use of digital agroforestry tools: knowledge of agroforestry and a positive attitude towards digital farming technologies. This was also shown by other studies on the adoption of digital farming technologies (Pierpaoli et al. 2013; Barnes 2019; Heitkämper et al. 2023; Reissig and Siegrist 2025), and thus pointing the way forward for the implementation of digital agroforestry technologies. Given that our respondent group can probably be described as agroforestry pioneers with higher agroforestry knowledge than farmers which are not yet in agroforestry. They need to be trained in agroforestry to promote the planning and use of agroforestry. Digital agroforestry tools can help to gain this knowledge and in apply it the agroforestry practice. The role of agroforestry-specific knowledge suggests that domain-specific expertise is crucial for recognizing the benefits of digital tools for agroforestry and how digital tools can be effectively integrated into these systems on the one hand. A positive attitude towards digital agriculture, on the other hand, reflects a general openness to innovation, often considered a key enabler of technology diffusion in farming contexts (Rose et al. 2021).

In contrast, when considering the intention to adopt digital agroforestry technologies in the future, only attitude towards digital agriculture remains statistically significant. This suggests that positive attitudes serve as a consistent driver of both current and future adoption. It is known, that attitude towards digital farming is explained in turn by farmers' characteristics, such as age, technology interaction affinity, education level, and digital competence, alongside their financial situation (Reissig and Siegrist 2025).

This suggests that attitudes can be influenced via these variables and thus also the use of digital agroforestry technologies, through training. While the findings of Reissig and Siegrist (2025) show that the intention to introduce digital agricultural tools in animal husbandry is influenced by farm characteristics (size, labor force), farmers' perceptions (attitudes toward digital agriculture), digital literacy, and risk-benefit perceptions (perceived risks and benefits of digital technologies by farmers), in agroforestry we find mainly attitude influencing the usage decision. In arable farming, acceptance was influenced by farmers' perceptions, level of education, and risk-benefit perceptions. The aspect of risk-benefit perceptions of digital agroforestry tools was not part of this study and should be considered in future research for agroforestry systems itself and the potential usable tools. Especially when the tools take on the role of deciding on certain practices. While our results show, that knowledge or agroforestry and financial capacity are not significant against the expectations from literature (Klerkx and Jansen 2010; Eastwood et al. 2019). The authors were showing that financial constraints and lack of technical understanding often inhibit the practical adoption of agricultural innovations, what is according to our results not valid for digital agroforestry tools.

Interestingly, structural factors that have been shown relevant in previous studies on the adoption of digital farming technologies, such as age (Alvarez and Nuthall 2001; Alpass et al. 2004; Tey and Brindal 2012; Pierpaoli et al. 2013; Torrez et al. 2016; Charness et al. 2018; Groher et al. 2020; Makinde 2020; Marescotti et al. 2021), workload (Hansen 2015), technology interaction affinity (Reissig, 2025), and internet connection (Giua et al. 2022) did not significantly predict current adoption or future intention of digital agroforestry tools. This supports the notion that behavioral and cognitive variables rather than structural ones play a more decisive role in technology uptake in agriculture (Barnes 2019). Moreover, it highlights the need to move beyond conventional assumptions that younger or more formally educated farmers are necessarily more open to innovation (Pierpaoli et al. 2013; Barnes 2019). And again, stigmatization of farmers who are committed to innovation is a factor in agriculture, as demonstrated by Lähdesmäki et al. (2019) in a study of pioneer farmers in organic farming. These farmers were able to manage the perceived stigma and experience it as an empowering process. The issue of stigmatization can certainly also be experienced in the adoption of the innovative agroforestry farming system and in the adoption of digital tools in this sector, seen by some farmers as something from the past, e.g. before land consolidation, although, of course, the use of digital agroforestry tools is less visible than the use of agroforestry itself. This was not taken into account here.

Furthermore, we assume that this is due to the dual innovative nature of digital agroforestry. The respondent's universe is innovative because they have already adopted or plan to adopt an innovative farming system, which sets them apart from the majority of farmers. In addition, one third are already using digital agroforestry technologies and half plan to do so within five years. This group of farmers can be considered highly competent in their field. This provides us with information about the key requirements for the adoption of digital agroforestry technologies.

From a practical perspective, the findings suggest that policy and advisory efforts should go beyond providing technical training and actively promote positive attitudes toward digital transformation in

agroforestry to stimulate the uptake of digital agroforestry tools. Initiatives such as awareness campaigns, peer-to-peer learning, and participatory demonstration projects can help demystify digital tools and build farmers' confidence and competence (Lasdun et al., 2025). Even if our results show no significant influence of financial situation on future adoption in our agroforestry pioneer sample, the relevance of financial situation should be measured for a sample not yet involved in agroforestry to show if targeted subsidies or shared-use equipment programs and data, to reduce barriers for smaller farms for the adoption of new technologies (Reissig and Siegrist, 2025) are also helpful to promote the use of digital agroforestry tools.

Limitations and Future research

This research was conducted within the framework of a European Horizon Project, the focus was on digital tools in agroforestry. These tools represent a significant innovation in agroforestry, and the adoption of this technology was investigated here. Within our scope, it was not possible to investigate the adoption of agroforestry as such.

A probable bias in selecting the respondents, thus limiting the applicability of results to the more general population of European farmers was, that the research is conducted with agroforestry pioneer farmers, with farmers overcoming the challenges and barriers that come with using these farming systems and who are willing to bear the same costs for new technologies. A larger sample and more divers typology of farmers should be chosen for further research. In order to discuss the use of digital technologies in agroforestry, data on the ecological environment of farmers interested in agroforestry is necessary. In a further step, it would be interesting to see whether farms could use digital tools to break down barriers and find it easier to get started in agroforestry.

In future research, it would be desirable to investigate the dimension of this dual innovation, the use of the innovative agroforestry farming system and the use of digital technologies. Our results suggest that a certain spirit of innovation and expanded skills are necessary to use digital technologies in agroforestry. This leads to the hypothesis that these characteristics are also helpful and necessary for the adoption of agroforestry as such. However, this must be confirmed through future research.

5. Conclusion

Agroforestry is an innovative farming system that requires long-term commitment. For that reason, many farmers still find it difficult to decide whether to adopt it. Existing and developing digital agroforestry tools will facilitate e.g. the planning of agroforestry systems, forecasting yields and costs, and estimation of carbon storage. Using these tools requires a pioneering spirit, a positive attitude towards digital technologies and an in-depth knowledge of agroforestry. However, the complexity of the tools and the need for new skills may initially increase this complexity. This makes it clear that the job requirements for farmers are also becoming more diverse, as there are requirements regarding software usage competences, even though the digital tool developers' job would be to make tools that do not increase the complexity of farmer's lives. While the tools could facilitate farmers lives by long-term

planning and oversight of agroforestry work. It can be concluded, that digital farming tools have a large potential to facilitate decision-making of farmers lives, but they need initial cognitive investment to learn how to use the them. The living lab is supposed to put tool developpers in closer contact with farmers, so that they can develop tools that better answer to their needs and that are more user-friendly for farmers.

This, in turn, has consequences for the training and advice provided to farmers. The results have shown that farmers with agroforestry knowledge have adopted digital agroforestry tools. Knowledge exchange platforms, where farmers can learn from each other and exchange ideas with other interest groups (such as researchers, politicians, and advisers) can support these developments. It is desirable to look for similar platforms in the future in order to learn from each other through transdisciplinary collaboration and thus enable us to promote digital tools for agroforestry, as well as the agroforestry system itself.

Declarations

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Author Contribution

All authors contributed substantially to the development of the survey, providing input and drafting topic-specific questions throughout an iterative process involving multiple meetings. L.R., S.K., and G.R. designed the final study protocol and survey, collected and analysed the data, and drafted the manuscript. B.L., P.B., M.H., R.H., and M.G. contributed to data collection. G.R. prepared the figures. All authors critically reviewed the manuscript and approved the final version.

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Data Availability

It is hereby declared that no personal data has been stored in the course of this scientific research. The data utilized in this study exclusively consists of anonymized or aggregated information, ensuring the

privacy and confidentiality of individuals involved. Respondents gave informed consent on data collection, storage, and utilization in compliance with the GDPR framework.

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Figures

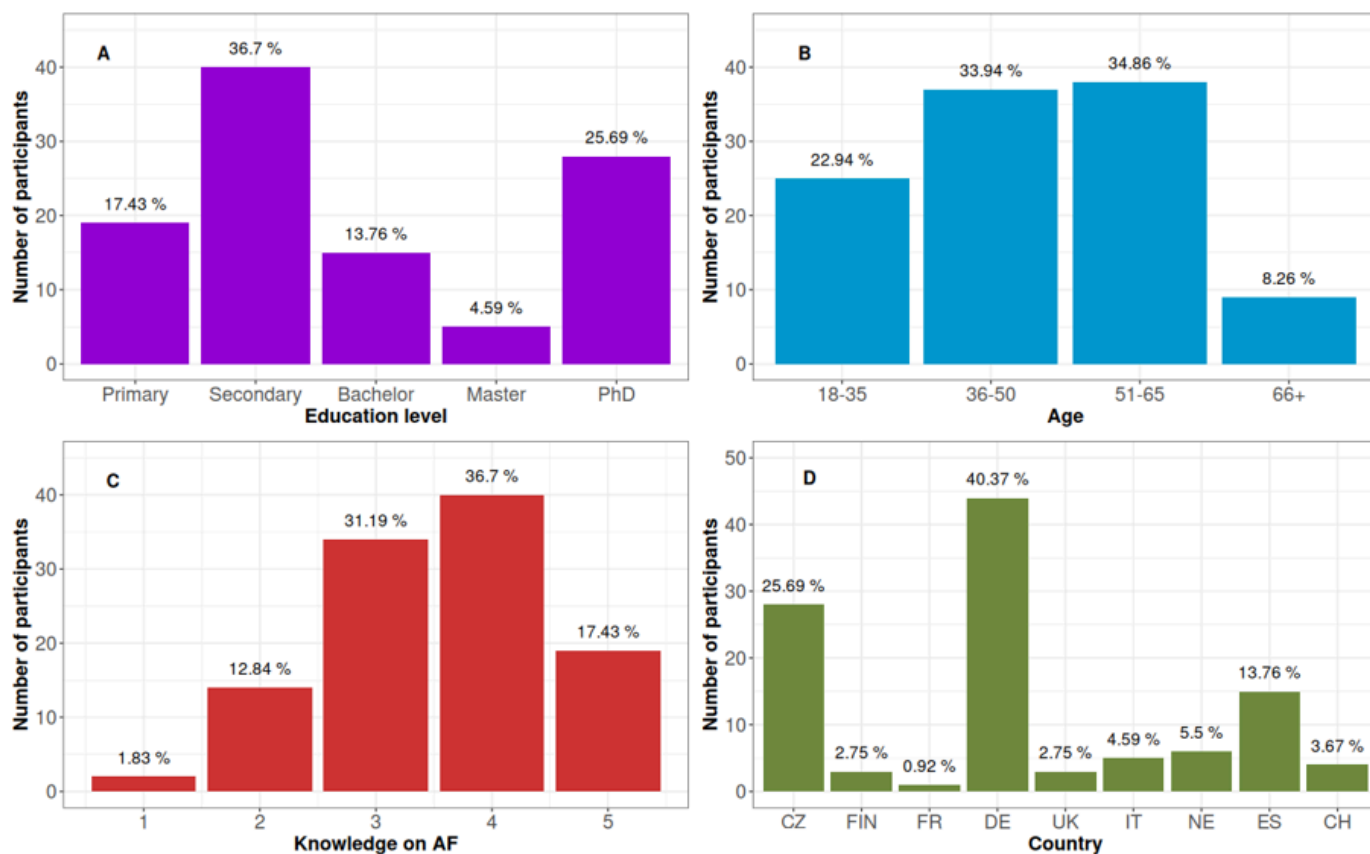


Figure 1

Profile of the respondents. A: participants level of education; B: participants age level, C: participants knowledge of agroforestry; D: countries of participants

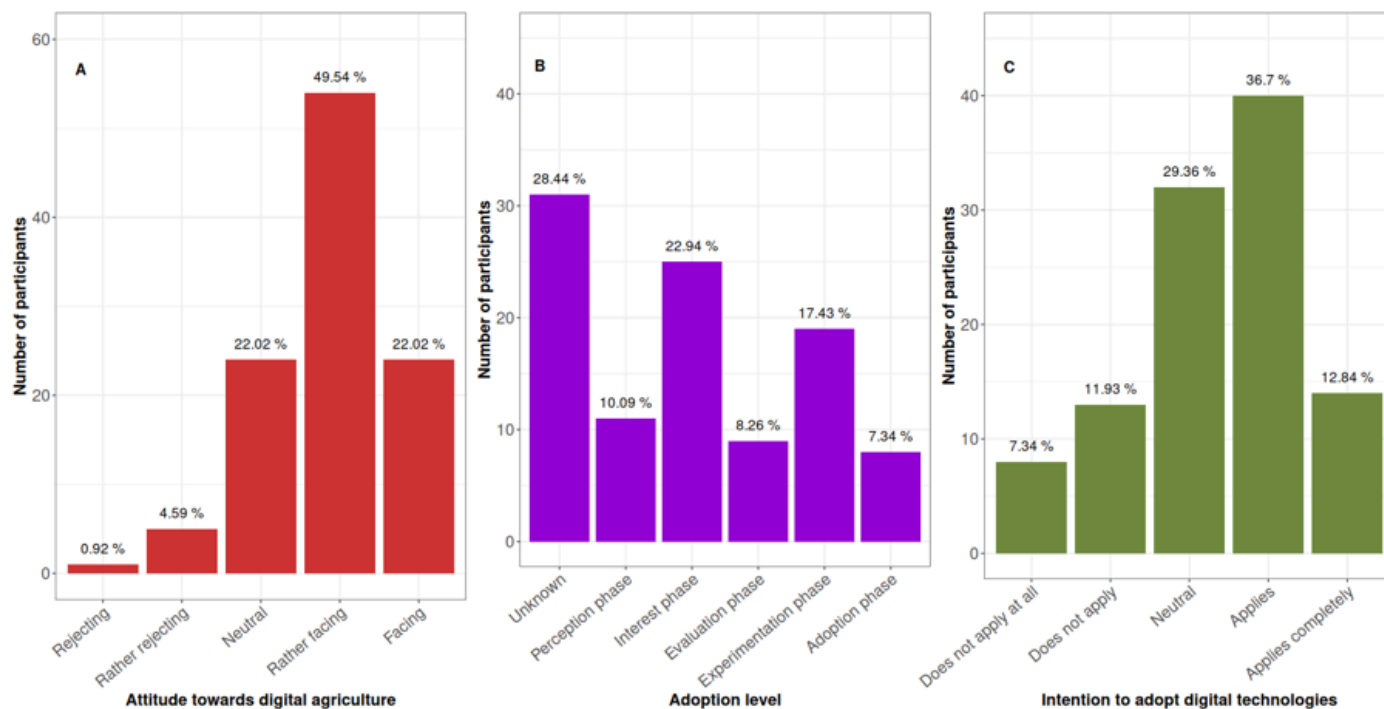


Figure 2

Distribution of: (A) participants attitude towards digital tools, across adoption levels of digital agroforestry technologies, (B) participants adoption level of digital agroforestry technologies, and (C) intention level to adopt digital agroforestry technologies

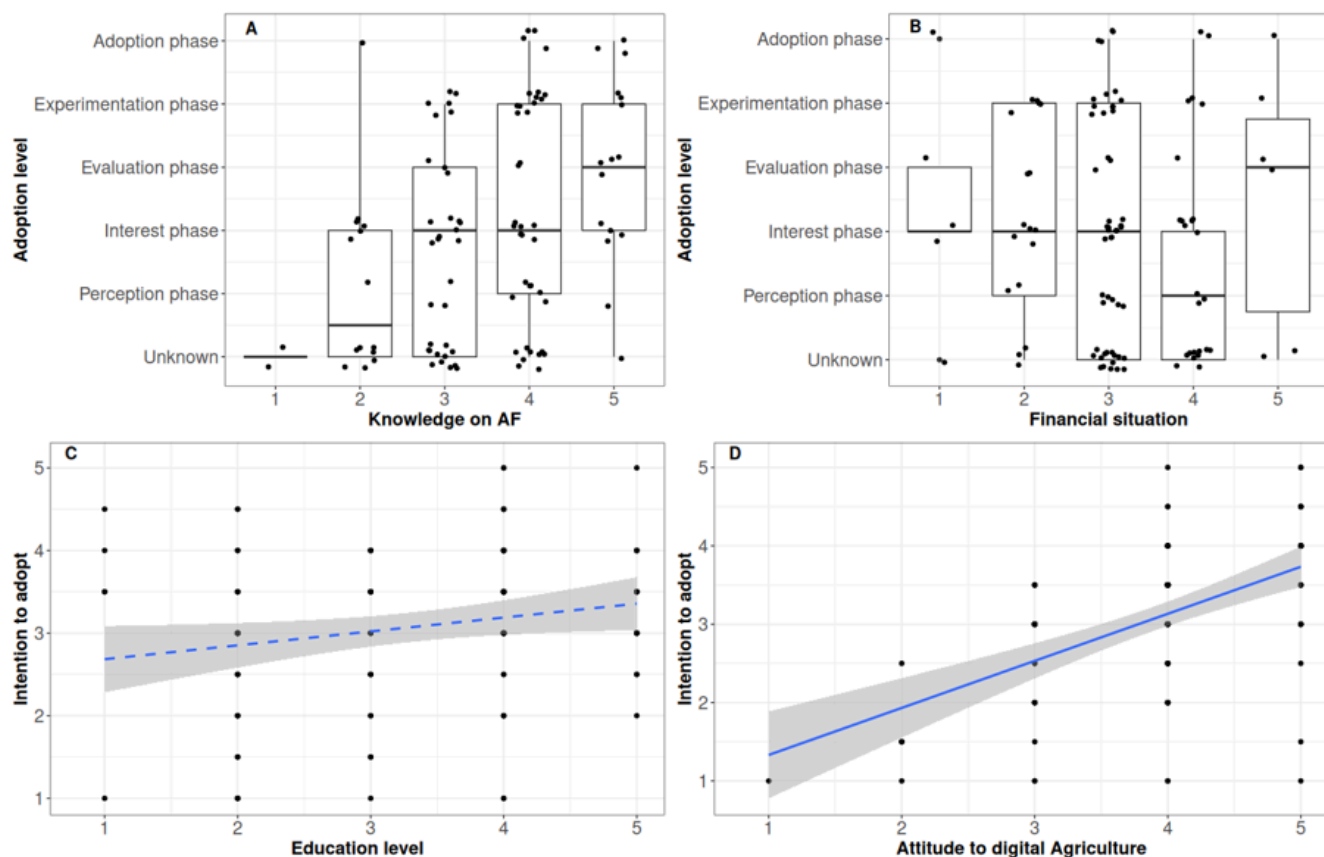


Figure 3

Relationship between adoption level and knowledge of agroforestry (A) and financial situation (B), the intention to adopt digital agroforestry tools within the next five years and education level (C), and the attitude toward digital agroforestry tools (D)

Supplementary Files

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