Agroforest Syst (2025) 99:130
https://doi.org/10.1007/s10457-025-01208-6

AgroforesTreeAdvice: a decision support tool combining heterogeneous knowledge resources for tree species selection in agroforestry systems

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Received: 14 December 2024 / Accepted: 23 April 2025

Abstract Selecting the right tree species is a crucial step in designing sustainable and effective agroforestry systems. To support this process, several decision support systems (DSS) have been developed in various countries to help farmers and advisors choose appropriate species. However, these tools are often limited in reach—typically used only within the country where they were created—and tend to focus on different aspects of adaptation to local conditions or achieving specific farming objectives. In this context, we introduce a new framework for agroforestry tree species selection. Its goals are twofold: (i) to compile and organize the knowledge embedded in existing tree selection tools, and (ii) to offer an intuitive, user-friendly graphical interface—AgroforesTreeAdvice. This tool allows users to input local parameters such as soil type, climate, biotic factors, and farm-level or socio-economic constraints, alongside production goals (e.g., timber, fruits) and ecosystem service

Supplementary Information The online version supplementary material available at https://doi.org/10.1007/s10457-025-01208-6.

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objectives (e.g., soil conservation, carbon storage). The unified system successfully integrates eight existing agroforestry DSS, improving their (i) findability by centralizing them in one location, (ii) accessibility through a standardized and user-friendly interface, (iii) interoperability by enabling API-based queries across all tools, and (iv) reusability for future DSS development. Finally, we present early user feedback from pilot deployments in three countries, highlighting the tool's benefits and outlining next steps toward further harmonization of agroforestry databases.

Keywords DSS · Ecosystem services · Suitability · Digital tool

Introduction

The selection of tree species is a pivotal step in designing sustainable and effective agroforestry systems, and farmers and advisors have expressed a significant need for decision support systems (DSS) to aid in this process. In a survey conducted across six European countries to assess stakeholder needs, the most highly rated topic in terms of perceived usefulness was the development of a tool for selecting appropriate tree species or varieties for agroforestry systems (Tranchina et al. 2024). However, 84% of respondents (among which 57.61% were farmers, landowners or farm advisors), were not aware of any existing tool. Indeed, farmers face several challenges when designing agroforestry systems, starting with a need for knowledge about tree characteristics and performance in a specific context and a changing climate, in order to make appropriate choices on the right species, varieties and combinations. However, this knowledge is largely missing for agroforestry (Ellis et al. 2000). Additionally, the myriad potential combinations of tree and crop species, coupled with the scarcity of scientific data and demonstration plots for many of these combinations, pose a significant obstacle (Wolz and DeLucia 2018). Furthermore, while agroforestry systems can provide a range of ecosystem services (Jose 2009), the effectiveness of these services is contingent upon the specific service, the agroforestry system under study, and the local conditions (Torralba et al. 2016). Lastly, in line with agroecological principles, agroforestry systems should be tailored to local conditions to minimize reliance on external inputs like irrigation, fertilization or plant protection, and should leverage farmers' knowledge (Wezel et al. 2015) to develop sustainable and resilient agroforestry systems.

These challenges are not new, and over the years, various approaches have been developed to support tree species selection. These approaches can be broadly categorized into three types: participatory, trait-based, and model-based (including ecological niche modeling) approaches. Participatory approaches engage stakeholders directly, utilizing methods such as surveys with semi-structured questionnaires to gather farmers' preferences (Sebuliba et al. 2022). Other participatory techniques include species ranking exercises, where stakeholders evaluate and prioritize different species based on specific criteria (Van Der Wolf et al. 2016; Kheiri et al. 2024). An example of a participatory technique is the pebble distribution method, which involves stakeholders distributing pebbles to indicate their preferences and priorities for various species (Notaro et al. 2022). Trait-based approaches focus on the characteristics of tree species, such as aerial or root traits, to determine their suitability for specific agroforestry systems (Isaac et al. 2024). These approaches rely on detailed biological and ecological data to match tree species with the requirements and constraints of particular agroforestry settings. Model-based approaches, including ecological niche modeling, use computational tools based on GIS methods to combine soil and climate maps, to predict the suitability of different tree species for various environments. These models take into account a range of environmental and ecological variables to simulate potential outcomes and guide species selection (Ellis et al. 2005; Ranjitkar et al. 2016; Borucke et al. 2020; Tyndall 2022; Shea and Wolz 2024). They can be complemented with information on ecosystem services provided by trees, in order to further refine the choice of tree species.

Once the knowledge is available, it needs to be delivered to users (farmers, landowners, extensionists) as an easy-to-use DSS. The survey by Tranchina et al. (2024) provided the characteristics that stakeholders expect for a DSS to be usable and useful, tailored to their needs and preferences. In particular, it was important

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to stakeholders that the tools were (i) simple and clear, (ii) intuitive, (iii) accessible on-site, (iv) easy to use and reliable, and (v) compatible and flexible. Another feature that was not mentioned in the survey (because it is so obvious that it stayed implicit), is the support of the user's language. Existing tools, even when they are available on the web, are often not usable in other countries due to language barriers. Furthermore, they all have a different interface (or no interface if they are in the form of a simple table of tree characteristics), which means that users have to learn how to use each tool. Last but not least, they are not interoperable, meaning that it is not possible to query the content of another tool from a given tool. Integrating several tree selection tools would therefore increase their accessibility by a range of stakeholders across Europe, as well as allowing sharing knowledge across tools.

Our objective was to develop a framework for agroforestry tree selection that would (i) gather and organize the knowledge contained in existing tree selection tools and (ii) provide an intuitive, user-friendly interface to identify tree species, varieties, and rootstocks when needed, adapted to local conditions and effective in fulfilling the farmer's objectives. We created a unified framework that could integrate various agroforestry tree selection tools, enhancing their (i) findability by consolidating all tools in a single location, (ii) accessibility through a common interface with a consistent look and feel, (iii) interoperability by enabling API (Application Programming Interface) requests to query all tools, and (iv) reusability for other decision support systems (DSS). The following section presents the framework we developed, detailing its agronomical and ecological rationale. We demonstrated its versatility by integrating eight previously developed tree selection DSS and ensured its accessibility via a graphical user interface, called AgroforesTreeAdvice. Finally, we discuss initial user feedback from its deployment in three countries, the benefits derived from this initiative and future work based on further unification of the databases.

Material and methods

Data collection

Identification of existing decision support systems (DSS)

The first step in our process was to identify existing DSS relevant to agroforestry tree selection. We employed a multi-faceted approach to achieve this goal, combining: (i) the expert knowledge of the initial group of authors, who have extensive experience in agroforestry; (ii) a literature review that included both scientific publications and grey literature, such as technical reports, conference proceedings, and other non-peer-reviewed sources; and (iii) stakeholder consultations, involving discussions with agricultural extensionists and other agroforestry professionals to gather insights and recommendations on existing decision support systems (DSS). Although the work is meant to be an on-going process and to include more and more DSS, the results presented here came from the analysis of eight existing tools: a Czech trees characteristics database (Weger et al. 2022), Deciduous (Warlop et al. 2024), the German GoÖko-Heckenmanager (Tsonkova et al. 2019), DENTRO (Reubens et al. 2024), JBOJP (de Kleijn 2024), SCSM (K. Rønn-Anderson, pers. comm.), ShadeTreeAdvice (Rigal et al. 2022), a Finnish tree suitability database (Mattila and Ujula 2023).

The Czech database of trees for agroforestry systems was developed as part of the research project "Agroforestry systems for protection and restoration of landscape functions endangered by the effects of the climate change and human activity" (TH04030409, 2019–2022, funded by TACR). The database consists of two parts—tables: (i) List of recommended skeletal trees (58 deciduous, 1 conifer, 13 fruit) and (ii) List of supplemental trees (36 shrubs, small trees) both of which contains 30 parameters for each tree covering its taxonomy, legislation, utilisation, growth dynamics and soil-climate-light (site) requirements for good growth. The List of skeletal trees was used as basis for a list of trees recommended and funded by the new subsidy for establishment of agroforestry systems in the Czech Republic (national strategic plan of CAP, 2023+). On the practical level, the Czech database (in the form of spreadsheets) has been used by experts and advisers for designing agroforestry systems for farmers interested in planting trees on their fields.

Deciduous was developed for all farmers interested in integrating fruit trees in their arable plots or pastures. Fruit trees are fragile trees and need more attention than timber trees but are more profitable. Attention has to be paid to frost risk, soil characteristics, time available, tree height, etc. More than 20 French experts have been committed for building a strong database providing a significant support for tree choice, either for silvopasture or alley cropping systems.

The GoÖko Hedgerow Manager is an online DSS tool for the management and planning of hedges in agricultural areas, taking sustainability aspects into account (Tsonkova et al. 2019). In addition to a step-by-step guide, the web application also includes a woody plant database. BTU Cottbus-Senftenberg developed the hedgerow manager between 2019 and 2021 as part of the "GoÖko" project. The woody plant database includes 59 tree and shrub species. The location and climate requirements, habitats of the woody plants, utilization aspects, landscape aesthetic and cultural significance as well as the indicator values according to Ellenberg are compiled in the database. The decision support tool is based on this, for example when selecting the right tree species for a specific location. Once the target area has been selected, hedges can be managed, transformed or entirely replanted. The ecosystem services are evaluated in relation to the status quo. Finally, a pdf is generated that covers all previously defined planning aspects, including a planting plan and order lists for obtaining quotations. The hedgerow manager can be used free of charge on the DeFAF website https://hecken-landschaft.de/start.

DENTRO was initially developed as an Excel based tree species matrix scoring a list of nearly 60 tree species suited for agroforestry in Flanders on over 30 characteristics. It is intended to support farmers, advisors and other stakeholders in making well-considered choices when selecting tree species and cultivars for their agroforestry systems. While DENTRO was initially part of a broader decision support tool for agroforestry plan development (called BETULA), it can now also be consulted separately. It is a dynamically evolving tool: the current version is mainly aimed at tree selection at species level, however, the developers intend to extent the applicability to selection at cultivar or rootstock level. Simultaneously, there are concrete plans to expand the parameter list at species level, by adding e.g. tree growth information, fruit productivity, wood density data, etc. As such, the DENTRO database could become a database not only to be consulted for tree species selection but also for other modeling modules such as carbon storage prediction or economic tools. DENTRO is part of the modular decision support system "Agroforestry Planner". It can be consulted through https://www.agroforestryvlaanderen.be/en/agroforestry-planner-2.

JBOJP ("De Juiste Boom op de Juiste Plek") is a Dutch tree selection tool that was developed by Jade Reforestry, Stichting ReGeneratie/Van Eijk: Consultantree, Louis Bolk Instituut, and Hogeschool Van Hall Larenstein. The name of the tool translates as "the right tree in the right place" and was developed because of a need for better decision support systems with advice on tree species selection and tree management. It is an excel-based tool with 90 tree- and shrub species integrated. Users can specify their groundwater levels, soil types, and economic objectives, and the tool advices a list of suitable species. The groundwater and soil type categories follow publicly available spatial datasets from the "Basisregistratie Ondergrond". The economic objectives are "food production" (having the option to choose more common species, or less common species), "system support", and "wood production". The advice follows a "traffic light" logic. The green list indicates the immediately suitable species. The orange list indicate species that could be suitable, but only under the condition that specific interventions around tree planting or maintenance are taken in order to have the best chance at a high survival rate, high productivity, etc. For instance, for one species in this orange list, drought stress could be a limitation, and the tool suggests six measures that can be taken to alleviate drought stress. For another species in the orange list, anaerobic conditions could be a limitation, and the tool suggest four measures for aeration. All limitations are: drought stress, water logging, poor soils, compaction/anaerobic conditions, species invasiveness, weak rootstock, inaptness for peat soils. For all limitations, measures are suggested.

SCSM was initially developed in node.js as part of the RegenWorks agroforestry design software (https://regenfarmer.com/agroforestry-plann ing-software/). The species selection model uses hardiness zones and climate zones as a way to identify suitable species for a particular climate. The main approach for this model was to have a global dataset and an adjoined model that can be used to screen a wide range of species for a specific climate. Because of the simple nature of the model, it is not well suited to determine suitable species for a specific piece of land, but rather can be used as a screening tool to explore alternative species and narrow the scope of potential species.

ShadeTreeAdvice (shortened to STA in the tables) is an online decision-support tool launched in 2016, initially focusing on tree species selection for coffee agroforestry in Uganda (Van Der Wolf et al. 2016). Since then, it has been used in over 10 studies worldwide, primarily in coffee and cocoa agroforestry but with potential for other crops, including temperate ones (Rigal et al. 2022). The tool aggregates and consolidates farmers' local ecological knowledge, gathering their experiences with different tree species and assigning scores to each species based on their efficiency to provide different services (e.g., soil fertility, weather protection, added revenue). On the online tool, farmers can select the services they desire most from shade trees, and the tool ranks tree species by suitability for those needs.

The Finnish tree suitability database was developed by Juha Ujula and Iiris Mattila as part of a book project (Mattila and Ujula 2023) which was one of the first initiatives of collecting information on the possibilities for agroforestry in Finland. The database was developed to help farmers with an interest in agroforestry to select tree species suitable to the Finnish climate as well as to find species which would match the objectives of the farmer, be it for example wood, fruit, fodder, biomass production, or delivery of ecosystem services. The database was compiled by reviewing available literature on tree species suitable to Finland and contains data on tree products (wood, fruit, sap, nuts, biomass), use of the trees (grazing, alley cropping, buffer strip, windbreak), soil (humidity, soil fertility, soil texture), tree size, site orientation (sunny, shady), and Finnish climate zone (I-VIII, ranging from temperate to sub-arctic). Since it was not meant to be a stand-alone database, it has no name; in this manuscript, we will call it FTSDB.

Decomposition of identified tools

Once the relevant DSS were identified, we systematically deconstructed each tool into three primary components (Fig. 1):

1. **Database of tree characteristics:** We extracted the underlying database from each DSS, considering all the tree characteristics that were documented in each tool. This step ensured that all relevant data points were considered, such as species traits, growth requirements, and ecological benefits. We kept as close as possible to the initial structure of the database, to allow easy maintenance in case of future database update. However, in case of complex databases, we had to translate column headers into English to facilitate data management.
2. **Interface description:** We analyzed the user interfaces of each DSS, documenting the required user inputs and their types (e.g., text entries, dropdown selections, checkboxes, and numerical inputs). This analysis helped in understanding how users interact with each tool and what information is necessary for tool operation.
3. **Suitability scoring model (if it existed):** We examined the models used by each DSS to compute species suitability scores. This involved understanding the algorithms and methodologies employed to match user inputs with tree characteristics, ultimately determining the suitability of various tree species for specific agroforestry conditions.

Data organization and homogenization

In order to integrate the diverse data and functionalities of the individual DSS into a coherent system, we developed a unified framework. Our hypothesis was

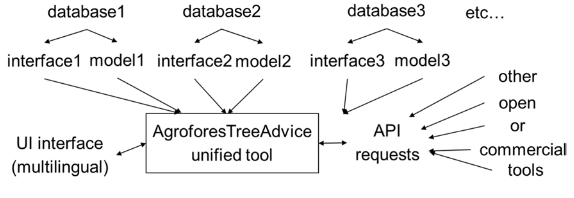

Fig. 1 Schematics of data collected and links between them

that all tree selection tools work by matching tree traits to selection criteria defined by the user in order to provide a suitability score for each tree species, and that the selection criteria, although being different between different tools, could be organised in a structured way to make comparisons between tools possible. We considered that tree suitability depends on (i) adaptation to local conditions and (ii) efficiency at providing the desired benefits (tree products and/or ecosystem services (ES)). Based on the trait-function-service framework (Violle et al. 2007), we organized the data according to two types of tree traits: response traits (causing the response of the tree to its environment, and so driving its adaptation to local conditions) and effect traits (allowing the tree to perform functions leading to the production of ES, e.g. fulfilling the farmer's objectives).

Traits linked to farmers' objectives

Criteria linked to the provision of ES (and therefore the matching effect traits) were organized following the CICES 5.1 classification (Haines-Young and Potschin 2018) at the highest levels. Most criteria fell into either "cultivated terrestrial plants for nutrition, materials or energy", or "Biotic regulation of physical, chemical, biological conditions" (Fig. 2). Subsequent levels were added when more details were needed (e.g. distinguishing between different uses of wood).

Traits linked to the farmers' constraints

In the absence of internationally recognized classification of criteria linked to the adaptation to local conditions, these criteria were organized as adaptation to soil, climate, biotic context, constraints at plot scale, constraints at farm scale and constraints at socio-economic level (Fig. 3). As for ES, we classified these criteria in a hierarchical manner, allowing different levels of details according to the focus of each tool.

Species

Trees and shrubs were described by their binomial name (Genus species), and, when available, variety and rootstock. Plant species name resolution is still an unresolved issue, and recent work has showed that the four main plant name checklists are equally imperfect, but sufficient to deal with the most common species (Schellenberger Costa et al. 2023). Therefore, we used the WFO database (Borsch et al. 2020) to check for species name spelling and identify potential synonyms used in the different tools, because WFO provides a convenient R package to retrieve information (Kindt 2020).

Scoring functions

Each tool has its own scoring algorithm, in the form of an R function that takes as arguments a vector of user inputs (i.e. selected values for the different criteria) and a data.frame of tree species' characteristics (i.e. the database of a given tool). In case the tool was a simple spreadsheet of tree characteristics (e.g. the Czech and Finnish tables of tree characteristics), we developed a standard algorithm that computes the species scores based on user input and tree characteristics table. The score of each species is simply the sum of the scores of individual criteria (one criteria per column in the tree characteristics table). The function used to compute the score of each criteria is chosen according to the type of user input (single value, range of values, single modality, list of modalities) and to the type of tree characteristics (single value, range of values, single modality, list of modalities). Table 1 presents these functions.

The other tools had their own scoring function, which can be classified into two types: quantitative or qualitative. In (semi-)quantitative tools (DENTRO, ShadeTreeAdvice), each combination of tree species and modality of the criteria is given a suitability score (continuous value from 0 to 5 in the case of ShadeTreeAdvice, integer number from 1 to 7 in the case of DENTRO). In qualitative tools, each tree is either compatible or incompatible with each modality, with sometimes one intermediate category such as partially compatible. One tool (DECIDUOUS) also included a weighting of criteria, allowing to give more importance to some criteria than to other. However, the weights were determined by expert knowledge and were not modifiable by the user. As a result, in AgroforesTreeAdvice, we included the weights in the scoring function itself and not in the user interface, which actually means this tool is a quantitative tool. One tool (JBOJP) introduced the notion of "corrective actions": in the initial tool, trees that were incompatible with the user conditions, but for which

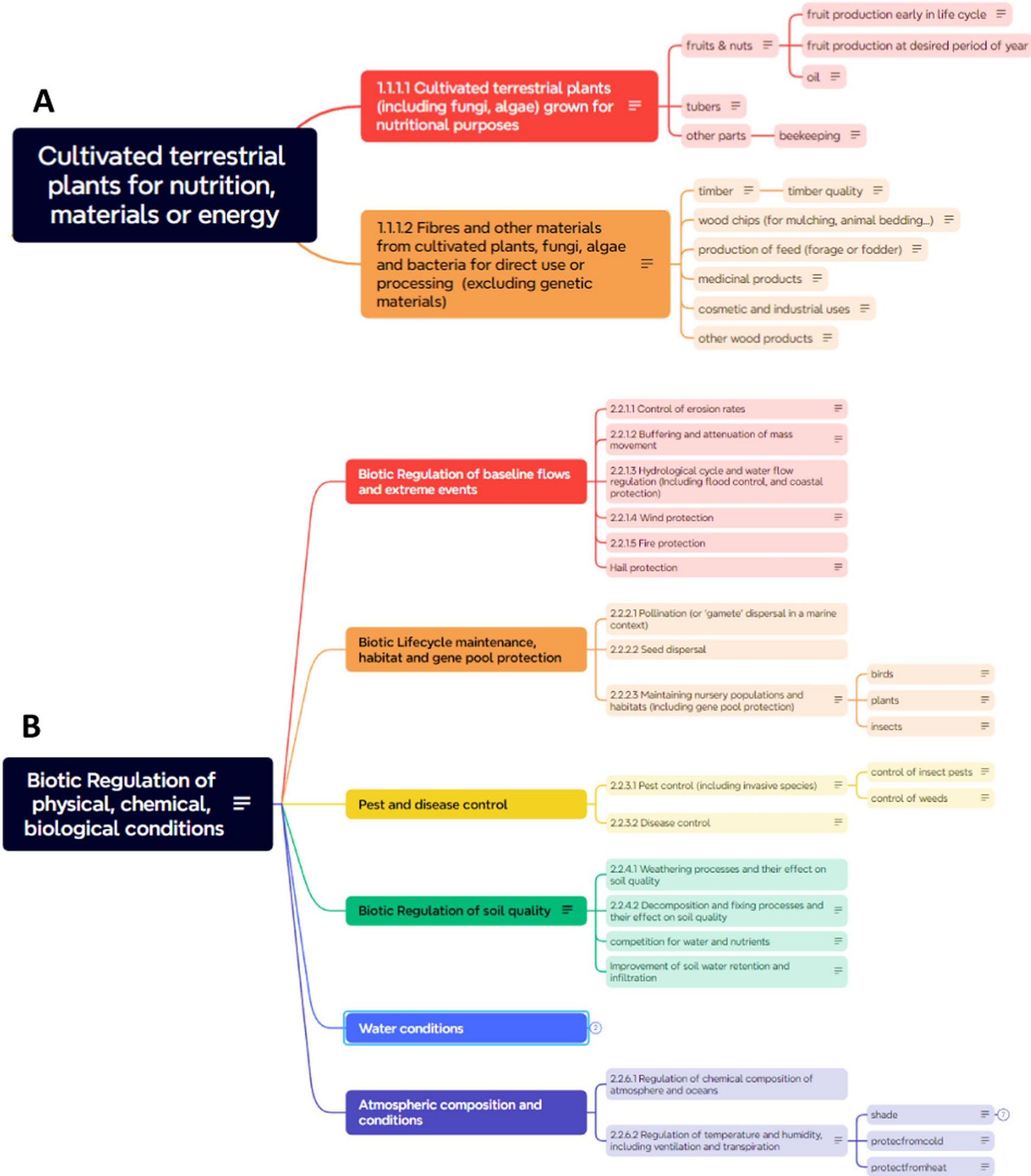

Fig. 2 Hierarchy of criteria linked to the efficiency of a species at providing ecosystem services, for the provision of nutrition, materials or energy (**A**) and regulation of physical, chemical, biological conditions (**B**). Items with a note (indicated with three lines on the left) are referenced by at least one tool (see details in Supplementary Table 1). The folded "shade" item contains several subdivisions related to intensity, timing, shape and beneficiaries of the shade such as workers, animals or crops

the criteria causing this incompatibility could be remediated, where classified as "partly compatible"

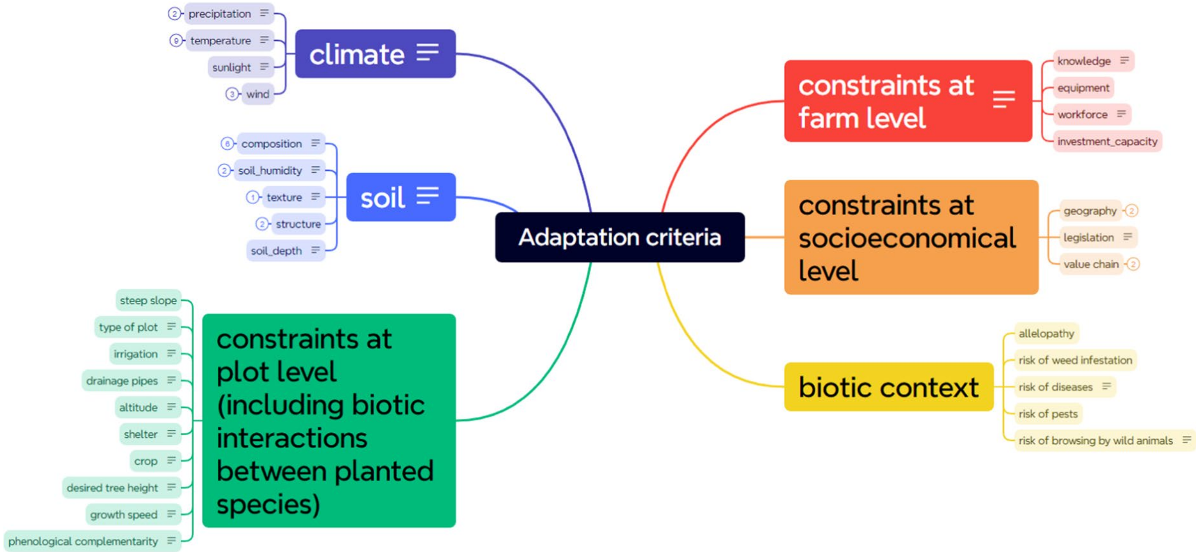

Fig. 3 Hierarchy of adaptation criteria (only the first two levels are shown). For a detailed view of the criteria and the models taking them into account, see Supplementary Table 1

Table 1 Scoring function according to type of user input and type of tree characteristics, used when the tool was a simple table of tree characteristics

User input	Corresponding column in tree database	Score
1 item in a drop-down list or 1 checked checkbox	n logical columns (1 for each item)	1 if the tree has this characteristic, 0 otherwise
	1 column containing 1 item	
1 or several items in a set of checkboxes	n logical columns (1 for each item)	#(Selected items ∩ characteristics of the tree)/#selected items
	1 column containing 1 or more items	
1 or several items in a drop-down list or set of checkboxes, or one checked checkbox	n numeric columns (1 for each item)	Sum for all selected items of the tree values
1 numerical value	1 column containing a unique value	1-abs(user value -tree value)/(max(tree values)-min(tree values))
	1 column containing a range of values in the format: (x)-(y)	1 if the user value is within the range, 0 otherwise
A range of values	1 column containing a unique value	1 if the user range contains the tree value, 0 otherwise

and the user was provided with a list of corrective actions that could be implemented to create favorable conditions for the tree. In AgroforestryAdvice, we included the availability of these corrective actions as criteria on their own in the farm scale constraints/opportunities section (because they depend on farmer knowledge, available equipment and/or capacity of investment), and gave a score of 0.5 to the species for each of the criteria causing an initial incompatibility (because corrective actions necessitate extra effort/costs).

Results

Data collation

Almost all the 254 criteria mentioned in the eight existing DSS for tree species/rootstock selection were easily linked to the different levels of the hierarchy of criteria that we had designed (but see the few counterexamples in the discussion section). It is obvious from Table 2, which shows the number of criteria of each top category in each tool, that the eight DSS had

Table 2 Number of criteria of each type in each tool

Criteria		Tool								
Type	Category	Czech	DECID-UOUS	GoÖko	DENTRO	JBOJP	SCSM	STA	FTSDB	Total
Adaptation	Constraints at socioeconomical level	1	0	0	1	0	0	1	0	3
	Constraints at farm level	0	1	0	0	3	1	3	0	8
	Constraints at plot level	4	3	3	2	2	1	6	3	24
	Biotic context	0	0	3	2	0	0	0	0	5
	Soil	2	3	5	4	5	0	0	5	24
	Climate	4	2	7	10	0	2	2	2	29
Efficiency	Provisioning (Biotic)	13	1	4	5	3	7	23	5	61
	Provisioning (Abiotic)	0	0	0	0	0	0	0	0	0
	Regulation & Maintenance (Biotic)	1	0	4	10	1	2	69	2	89
	Regulation & Maintenance (Abiotic)	0	0	0	0	0	0	0	0	0
	Cultural (Biotic)	3	0	7	0	0	1	0	0	11
	Cultural (Abiotic)	0	0	0	0	0	0	0	0	0

[a]This table is made on the initial criteria of the tools, before cleaning and removing duplicates

varied intensity of focus on different categories of adaptation and efficiency criteria. In terms of adaptation, all tools had constraints at plot level, all tools except JBOJP had criteria related to climate and all tools except SCSM and STA had criteria related to soil. Biotic context and constraints at the socioeconomical level were rarely considered. In terms of efficiency at providing ecosystem services, unsurprisingly for tools developed for farmers, all tools take into account provisioning by trees and shrubs. Regulation and maintenance services are at the core of ShadeTreeAdvice, and are well represented in DENTRO, but not much in other tools. Finally, cultural services (linked to the aesthetic aspect of trees) are the focus of GoÖko, and less developed in other tools.

Among the 679 species included in the eight analysed tree species selection tools, only 10 species were present in all tools except STA, which was developed for tropical agroforestry systems, and DECIDUOUS, which focuses only on orchards (Table 3). These are *Prunus avium, Pyrus communis, Alnus glutinosa, Betula pendula, Carpinus betulus, Fagus sylvatica, Fraxinus excelsior, Quercus robur, Sorbus aucuparia* and *Tilia cordata*. However, 131 species were present in at least two tools, which means that AgroforesTreeAdvice can enrich the data presented to users on these species, compared to using a single DSS.

FAIRness scoring of the AgroforesTreeAdvice tool

AgroforesTreeAdvice was assessed for FAIRness using the FAIRness self-assessment tool developed within the DigitAF project (https://digitaf.eu/tools-data-and-projects-catalogue/tools/fairness_self_assessment). This tool gave us the score of AgroforesTreeAdvice on the four aspects of FAIRness: Findability: 67%, Accessibility: 80%, Interoperability: 63% and Reusability: 75% (Fig. 4), and allows identifying avenues for improving FAIRness.

Findability

AgroforestryAdvice is present on github, as a repository of EURAF organization (https://github.com/euraf/agroforestreeadvice), to give it better visibility and increase the probability of future development beyond the duration of the project during which it was initiated. It is referenced by SoftwareHeritage (SWHID), HAL (Gosme et al. 2024) and in the DigitAF tool and data catalogue (https://digitaf.eu/tools-data-and-projects-catalogue/). In the future, we will improve the findability score by developing the documentation of the tool.

Table 3 Presence or absence of the 40 most common species in the eight analysed agroforestry tree (or shrub) species selection tools

Species	Czech	DECIDUOUS	GoÖko	DENTRO	JBOJP	SCSM	STA	FTSDB	Total number of tools
Total number of species	58	6	71	69	74	441	188	38	
Prunus avium	X	X	X	X	X	X		X	7
Pyrus communis	X	X	X	X	X	X		X	7
Alnus glutinosa	X		X	X	X	X		X	6
Betula pendula	X		X	X	X	X		X	6
Carpinus betulus	X		X	X	X	X		X	6
Fagus sylvatica	X		X	X	X	X		X	6
Fraxinus excelsior	X		X	X	X	X		X	6
Malus domestica	X	X	X		X	X		X	6
Quercus robur	X		X	X	X	X		X	6
Sambucus nigra			X	X	X	X	X	X	6
Sorbus aucuparia	X		X	X	X	X		X	6
Tilia cordata	X		X	X	X	X		X	6
Acer platanoides	X		X	X		X		X	5
Acer pseudoplatanus	X		X	X	X	X			5
Castanea sativa	X		X	X	X	X			5
Corylus avellana			X	X	X	X		X	5
Hippophae rhamnoides			X	X	X	X		X	5
Juglans nigra	X			X	X	X		X	5
Juglans regia	X		X	X	X	X			5
Malus sylvestris	X		X	X	X	X			5
Pinus sylvestris	X			X	X	X		X	5
Populus nigra	X		X	X	X	X			5
Prunus domestica	X	X			X	X		X	5
Prunus persica	X	X			X	X	X		5
Salix alba	X		X	X	X	X			5
Ulmus laevis	X		X	X	X			X	5
Acer campestre	X		X	X		X			4
Alnus incana			X	X		X		X	4
Betula pubescens			X	X	X	X			4
Corylus colurna	X			X		X		X	4
Crataegus monogyna			X	X	X	X			4
Populus alba	X		X	X		X			4
Populus tremula	X		X	X		X			4
Prunus padus	X		X	X	X				4
Quercus petraea	X		X	X	X				4
Robinia pseudoacacia			X	X	X	X			4
Salix caprea			X	X	X	X			4
Sorbus aria	X		X	X		X			4
Tilia platyphyllos	X		X	X	X				4
Ulmus glabra	X		X	X				X	4
Other	26	1	36	32	42	406	186	17	< 3

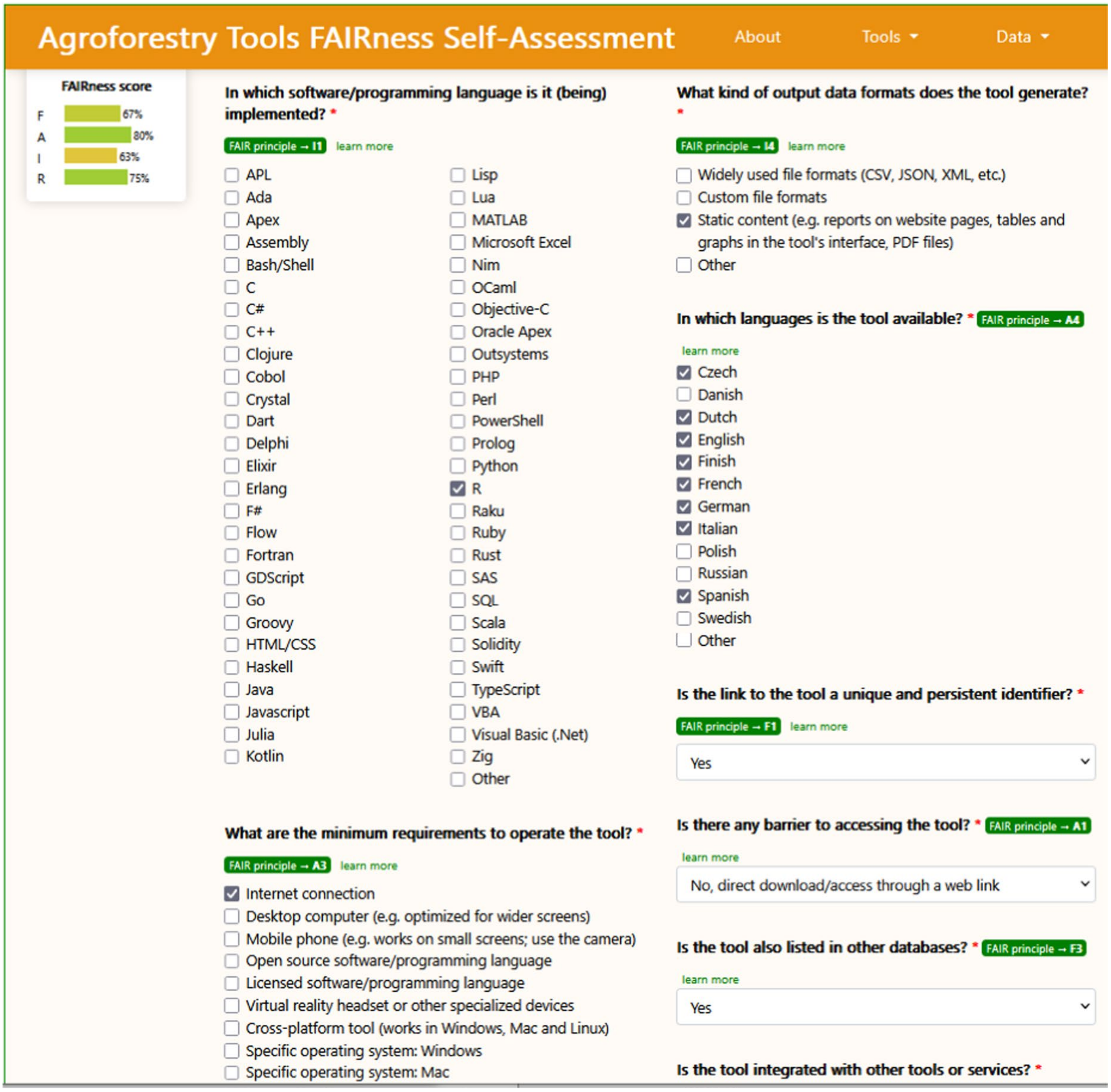

Fig. 4 Fairness self-assessment sheet of the AgroforesTreeAdvice tool

Accessibility

The data can be accessed as raw csv files on github. We developed a shiny app using this common framework to interface with several tree selection tools through a web interface (https://agroforestreeadvice.sk8.inrae.fr/). The shiny app allows users to define their site conditions and objectives, compute the adaptation and efficiency scores of each tree species and visualize the results in graph or table form; it also supports URL requests. It is available in eight languages. The interface was developed to be user-friendly, ensuring consistency in user experience across different DSS. The Graphical User Interface has a minimalist design (Fig. 5). The tree species can be ordered by adaptation to the site (with different components of the score, like adaptation to soil, adaptation to climate etc.) or by efficiency at reaching the objectives, in terms of productivity or other ecosystem

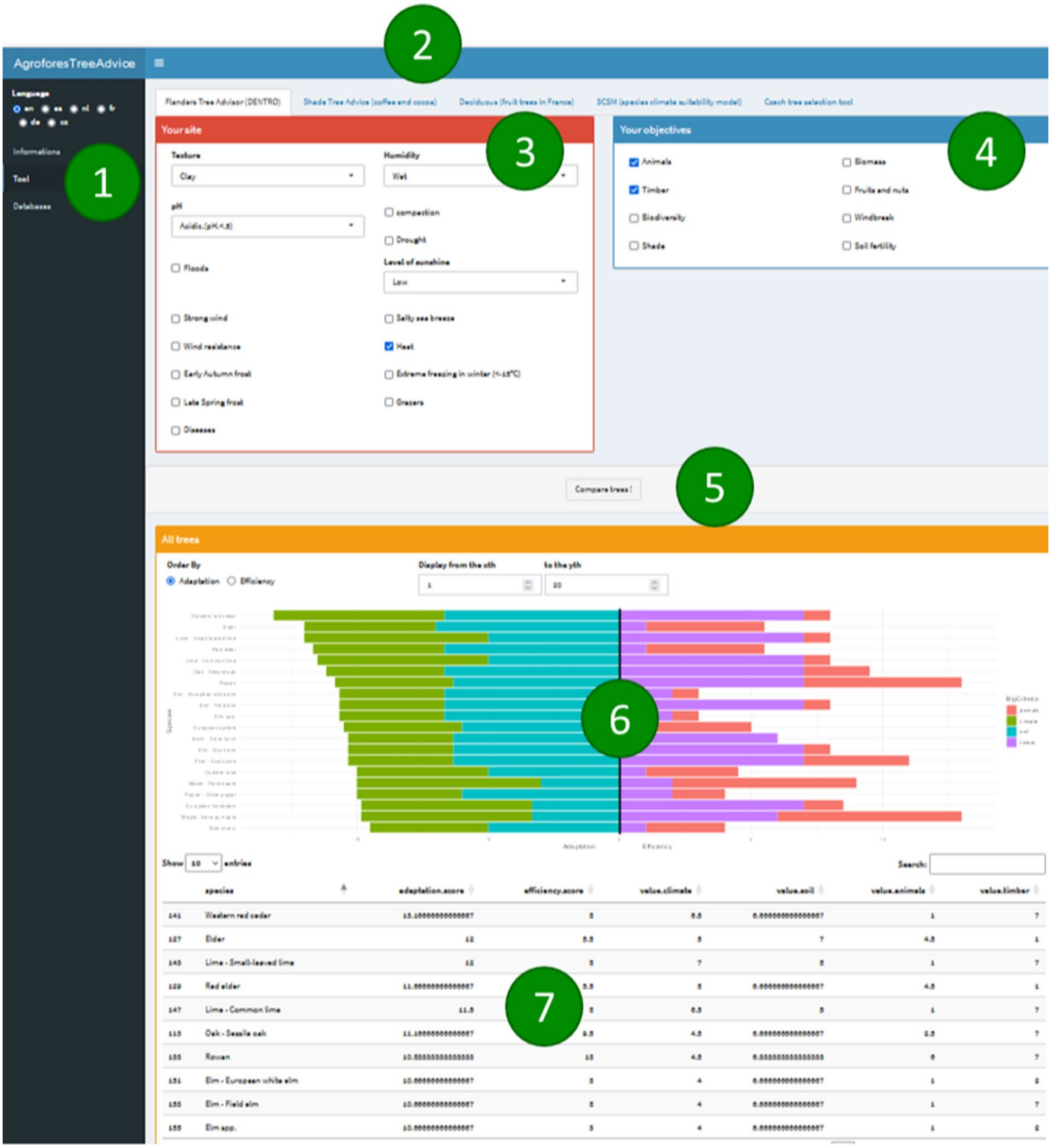

Fig. 5 Screenshot of the common interface. Numbers in circles indicate the steps for using it: (1): Select the desired language (en, nl, fr, de, cz, it, es, fi) (2) Select the tool you want to use, (3) Describe your site, (4) Describe your objectives, (5) Click on « Compare trees», (6) Visualize the ranking of trees and shrubs according to their adaptation to your site conditions or to their efficiency at producing the desired objectives, (7) Get the details of the scores in each subcategory

services. The same result is also available in table form below, and can be downloaded as a csv file. A demo video showing the use of the tool has been published on EURAF youtube channel https://www.youtube.com/watch?v=mbajuVJQ9bk). The accessibility score will be improved once the documentation will be completed.

Interoperability

The tool is programmed in R statistical language (R Core Team 2024), a programming language that is widely used in agricultural sciences (Tippmann 2015), ecology (Lai et al. 2019) and forestry (Lai et al. 2023). Furthermore, packages such as reticulate (Ushey et al. 2017) allow seamless integration of R objects into Python code, further increasing the potential interoperability. The Input data can be entered either manually through the GUI, or programmatically using query string parameters in the URL (e.g. https://agroforestreeadvice.sk8.inrae.fr/?model=Czech&soil_water=soil_water_waterlogged&fruit=fruit will open the Czech database of tree characteristics and return a table of tree species scores for adaptation to waterlogged soil and production of fruits). The current limitation for interoperability is that the return table has to be downloaded and saved, and that the argument names and possible values cannot be queried through an URL request (but they are available in the files describing each tool interface in the github folder). Thanks to git versioning, previous versions of AgroforesTreeAdvice remain available. Finally, AgroforesTreeAdvice has not yet been integrated into other tools, but there are plans to integrate the AgroforesTreeAdvice tool with other agroforestry design software such as RegenWorks (Skyum 2024).

Reusability

The tool is by construction reusable. Actually, the story of its development illustrates its genericity. Initially, ShadeTreeAdvice tool inspired us to develop a simplified interface for DENTRO. ShadeTreeAdvice was developed for shade tree selection for coffee and cocoa agroforestry systems in Cameroon, China, Columbia, Ghana, Laos, Nicaragua, Tanzania, Uganda and Vietnam, while DENTRO focusses on tree selection for silvoarable and silvopastoral system in Flanders. Thus, our tool was meant to be very generic from the start. Following the first prototype, we identified several other tree selection DSS that had been developed independently, in different countries and for different agroforestry systems. These are, by chronological order of integration, SCSM (soil and climate suitability model for a range of trees and shrubs worldwide), DECIDUOUS (species/rootstock selection for fruit trees in France), the Czech tree characteristics database, JBOJP (agroforestry tree selection for the Netherlands), GoÖko (trees and shrubs for hedgerows in Germany), and the Finnish tree suitability database. All eight tools are now integrated into the common interface, which proves the reusability of the framework. The steps to include a new tool with minimal effort in the common interface is documented on github (see the how to add a new model guide https://github.com/euraf/agroforestreeadvice/blob/main/CONTRIBUTING.md#add-a-new-model) and we welcome contributions (adding new languages, adding new tools, improving code). The code is licensed under the MIT license, allowing reuse for any purposes. The present paper should allow gaining the last points of the reusability score, by documenting the development process and provenance of data.

Discussion

Genericity and limits of the framework

The framework of hierarchical criteria for adaptation to local conditions and efficiency at providing ecosystem services proved to be flexible enough to easily accommodate almost all criteria present in eight independently developed tree species selection tools for agroforestry. In terms of species coverage, the combined dataset from all Europe-based tools (excluding ShadeTreeAdvice and SCSM, which focus on tropical or global regions) includes 157 tree and shrub species. This represents a substantial portion of the species commonly used in European agroforestry systems. For comparison, the Agroforestry Map of Europe (Hübner and Tylkowski 2024), lists 135 tree species and 56 shrub species or genera. The unified tool represents an improvement in terms of FAIRness scoring compared to previously existing tools for most criteria (Table 4).

Due to the flexibility of the hierarchical framework to organize criteria, the integration of other existing tools should be feasible relatively easily. These might include USDA's TreeAdvisor (Bentrup and Dosskey 2022), which includes 90 species of trees and shrubs that are rated for 14 different purposes, including alley cropping. Indeed, the authors also used a trait-function-service approach for developing this tool aimed at selecting multipurpose trees,

Table 4 FAIRness assessment score of the previously existing tools or data sheets

Tool	F	A	I	R
Czech (data)	0	25	10	17
DECIDUOUS	100 [100]	40 [60]	40 [50]	0 [63]
GoÖko	100	77	60	63
DENTRO (data)	65	75	10	83
JBOJP	33	55	24	13
SCSM[a]	–	–	–	–
STA	33	40	30	50
FTSDB (data)	67	100	50	67
AgroforesTreeAdvice	67	80	63	75

Please note that the criteria for data and tools FAIRness are not exactly the same, so FAIRness scores of data (in italics) and tools cannot be compared. Some tools have significantly progressed in terms of FAIRness during the process of this work, in which case the values in brackets are the most recent values

[a]SCSM is not a standalone tool, but it is data belonging to a larger software, so it was not assessed individually

considering 25 attributes including morphological traits, growth characteristics, environmental tolerances, wildlife benefits, potential economic products, and visual aesthetics. They consider only five traits for alley cropping: low competition to alley crops through (i) short crown and (ii) low shade to minimize shade over the alley crop, (iii) low soil water use and (iv) deep rooting pattern to avoid water competition, and (v) production of a high-value product. However, many of the other attributes that they consider for other main purposes are also relevant for agroforestry, so the database of this tool could further enrich AgroforesTreeAdvice regarding currently less-developed aspects such as aesthetic services, carbon sequestration, or wildlife support. Reciprocally, AgroforesTreeAdvice could be an interesting resource for developing the adaptation part of their tool. Indeed, currently TreeAdvisor focuses only on ecosystem services but their user feedback indicated that users would like to select species also according to local (e.g. soil) conditions. Another interesting tool to include could be the Tree Species Guide for UK Agroforestry Systems (Staton et al. 2024), which contains 15 attributes for 33 tree species. This guide is in the form of a pdf document, but the authors are considering converting it into an online tool. AgroforesTreeAdvice would be an easy way to do this. Inclusion of model-based tools could also be done, either by querying the tool with inputs organized according to the hierarchy of traits (if the model had API capabilities), or by performing preliminary runs of the model for a wide range of situations and apply metamodeling techniques (e.g. classification and regression trees) on the results.

However, it was sometimes difficult and somehow arbitrary to attribute some criteria to the hierarchy of traits. For example, we decided to put ‘form’ under landscape amenities because it relates to the shape of the tree, but it is not clear if this criterion is important for agroforestry tree selection. Lifespan was put under the constraints at farm level because a long lifespan means that there is no need to replant any time soon, so saving money and workforce. Some traits can even be linked to criteria both on the context side and on the objective side. For example, the trait “rooting depth” drives both the response to the presence of a deep water table (which favors deep-rooted trees), and the effectiveness at improving soil infiltrability. The trait “growth speed” influences how quickly ecosystem services can be delivered, which is especially important for biomass energy production. It also relates to the farm’s economic capacity to wait before trees begin yielding products. Additionally, growth speed affects species compatibility—helping to avoid situations where slower-growing trees are overshadowed by faster ones, or, conversely, allowing farmers to take advantage of complementary growth rates to generate income at different intervals. Height (or classsyntropic_strata) is linked to both the ability to deal with light competition from neighboring plants and the capacity to produce shade. Therefore, we needed a consistent rule to place these traits on one side or the other: traits driving competition and complementarity between plants (such as tree height, rooting pattern) were linked to constraints at plot level, traits driving facilitation (such as improvement of cocoa quality) were linked to biotic regulation services. However, these distinctions are arbitrary and do not allow taking into account more holistic approaches such as syntropic agroforestry (or dynamic agroforestry) because the notions of strata and system lifecycle stages do not fit well in this framework.

This difficulty was partly due to the fact that, actually, the analyzed tools did not consider the full trait-function-service relationship, but used shortcuts linking traits directly to suitability or adaptation scores.

Therefore, some traits could be linked to the adaptation to site constraints by some tools, and to the efficiency at providing services by others. For example, rooting depth was considered either as driving the response to the presence of a water table, or as driving belowground tree-crop competitions. A possible solution to this difficulty could be to fully exploit the trait-function-service concept, by adding an intermediate layer corresponding to the functions, with a given traits possibly linked to several functions. This would also allow exploiting trait databases to compute automatically the service score according to the underlying functions. This approach has been used by Elie Najm for selecting cover crop species (Najm et al. 2024).

User rating of the interface

Post-deployment, we collected user feedback to assess the usability, usefulness, and overall satisfaction regarding AgroforesTreeAdvice. This feedback is and will remain instrumental in identifying areas for improvement and iteratively refining the system to better meet user needs. Up to now, DigitAF Living Labs in three countries tested it: the Netherlands (feedback from 4 advisors), the Czech Republic (3 farmers, 3 advisors, 5 academics), and Finland (3 farmers, 3 advisors, 5 academics). In the Netherland, we first presented stakeholders with the tool, without previous explanation of its use, in order to test the tool's user-friendliness in an intuitive way. We asked the users to rate the tool on a 0 to 5 scale for two aspects: usefulness and usability. The rating results show that in the Netherlands, opinions diverged regarding the usefulness of the tool, with the usefulness score ranging from 1 to 5 (mean 2.75). The score for user-friendliness was more consensual, showing intermediate user friendliness (mean 3). In the Czech Republic the tool was rated relatively high for usefulness (mean 4.1), which can be explained by the high demand for establishment of new agroforestry systems under the national subsidy scheme since 2023 and also for education programs. The rating was lower for usability (mean 3.2) mainly due to some logical ambiguities in the meaning of some criteria (from habitat conditions or tree requirements). In Finland, the usefulness and user friendliness were not quantitatively rated, but potential users highlighted the usefulness of this type of tool for ongoing agroforestry projects and education. They particularly appreciated having a central source of information rather than having to dig in multiple sources for information regarding species selection. All users were able to use the tool and found it useful without a need for directions.

Users' suggestions for further improvements

After this initial test of the tool by users, we gave some explanations on the tool's objectives, development process and intended use and then let the users further explore the possibilities of the tool. An open discussion then allowed collecting the users' opinions about the main benefits they saw in using the tool and suggestions for improvements. User comments and suggestions for improvement were related both to the content of the eight individual tools, and to the AgroforesTreeAdvice unified tool. Concerning the individual tools, the users particularly appreciated the fact that some tools considered not only the species, but also the varieties and the rootstock. They also appreciated the fact that constraints at the farm level, in particular the workload, was taken into account, and that management was mentioned in one tool. Concerning the unified tool, they appreciated that it was multilingual and that it allowed them access to information from other countries, allowing them to learn about species that were not in the local tool, and completing the information of different tools about the same species, thus allowing to better define the conditions that allow growing a given species.

Users made several suggestions to improve the attractiveness of the tool, by adding pictures of trees, using colors (green/orange/red) and/or pictograms instead of scores to make it both more attractive and easier to understand (the fact that the score is unitless perturbed some users). They also asked for more explanation on the difference between adaptation and efficiency scores, and asked that units should be added for all numeric inputs. They also proposed that the tool should provide a shortlist of suitable species with detailed explanation of the characteristics of each shortlisted species, and links to case studies for particular tree species. Some participants were also interested in the value of wood for timber species. We will implement the suggested improvements to the user interface aesthetics in the next version of AgroforesTreeAdvice, and we will test, with users, different visualization options for the multicriteria assessment of the shortlisted species, showing the advantages and disadvantages of each tree species. For this, we could find inspiration in USDA's Tree Advisor Individual Species Attribute module, which allows a user to view a species' attributes (Bentrup and Dosskey 2022).

One user regretted that the tool is not transparent, in that it does not provide the users with the references to the data sources. This would be necessary to show the reliability of the information and allow the user to judge for themselves whether the information applies to them. Scientific references could be added in future versions of AgroforesTreeAdvice since some of the individual databases contain this information (GoÖko, DENTRO, UK guide, FTSDB). However, this could clutter the interface and make it less user-friendly. Another solution, adopted by USDA's TreeAdvisor is to provide supporting PDF documents to provide background information including the plant attributes and rating algorithms, to support transparency and credibility.

One user suggested allowing weighing criteria. Actually, some of the individual tools do consider different weights for different criteria (e.g. Deciduous), but these weights are defined by expert knowledge and are included in the suitability function, and as such are not modifiable by users. A first step towards this functionality could be to simply allow the user to unselect the criteria that they do not want to consider. We are currently testing this possibility within the Czech Living Lab.

A user was disappointed that it is not possible to query all tools at the same time, and hoped that there will be a combined database regrouping all criteria from all tools. This would be a clear improvement not only for facilitating user queries, but also because it would open up the possibility of statistical analysis of the unified database, e.g. allowing filling of missing data by statistical inference. This is thus clearly in our plans for the next steps, but it is not easy because it requires more intensive cleaning of the data, and, in case there are interactions between traits, it requires a detailed analysis of the data and the scoring algorithm to reformat the information in a meaningful way. In the meantime, the interface initial page should better explain what each individual tool could do, and guide the user towards the tool or set of tools best adapted to their needs (this was also a request from a user).

Finally, a user wondered how to take into account interactions between species, and how to design combinations of plant species, rather than selecting species one by one. This is a very relevant question because agroecology is about making use of interactions between species. Furthermore, considering interactions between species will open up possibilities to address the question of spatial design: which species can/should be next to each other. This has been the subject of recent research concerning vegetable gardening in agroforestry (Challand et al. 2025), but unfortunately data is missing concerning interactions between trees. In addition, tools do not yet represent much interactions between trees and crops (except for shadeTreeAdvice, which is specialized in two crops). This user also mentioned that the species should be considered in conjunction with the system into which it is inserted, including system management. This is indeed a weakness of the current version of the tool, and even of the overall framework. We need to better formalize the effect of agricultural practices on tree suitability. Our database was not ideal for exploring this aspect, since only JBOJP integrates the notion of agroforestry system management by mentioning corrective actions able to overcome some of the soil constraints. This is an important avenue for future research.

Perspectives

Beyond the improvements suggested by users, we could imagine other improvements of the user interface, or of the underlying data and algorithms. For example, we could add functionalities like automatic query of soil/climate databases to fill in the corresponding criteria automatically based on farm location. This co-design process also allowed identifying knowledge and information gaps, for example a lack of tools including the effects of trees and shrubs on biodiversity. We can also see that adaptation to the biotic context, constraints at plot or farm level, or information on tree root traits are rare. It is indeed remarkable that the effect of tree root traits is largely under represented despite its importance in agroforestry systems (Schroth 1995). Furthermore, none of the analyzed tools considers the effect of management on the agroforestry system's efficiency at producing ecosystem services, although tree performance depends on management. Therefore, this work gives both new avenues of research, and a framework to collect future data.

Now that we have collected the data of several existing tree species selection tool, we can ask new questions from this data and maybe provide new insights into what drives species suitability for agroforestry. In order to do this, we will need to combine the data of all existing tools into in a unique database. This process requires several adaptations of the available data. These include aligning input variables—for example, converting qualitative variables into quantitative ranges on a common scale—and standardizing scores by rescaling them to a 0–1 range. It also involves pre-computing scores that are otherwise generated dynamically by specific tools' suitability algorithms, and encoding how these scores depend on environmental or management conditions, as well as on specific cultivars or rootstocks. This is a substantial work, but this would open up the possibility not only to allow querying all data sources at the same time, as was requested in the user feedback, but also to analyze the relationships between tree taxonomies and/or traits, and suitability for agroforestry systems in different conditions and for different objectives.

Conclusion

Getting involved in this co-design process was a good learning experience for both the researchers/tool developers and the stakeholders. For the authors, this work was a good opportunity to "clean" the data (e.g. misspelled species names, duplicated data, etc.). For example, Shade Tree Advice initially contained many near-synonyms due to the fact that it already aggregates several studies in different countries, without an effort to homogenize the nomenclature of ecosystem services. It also allowed a comparison of tools: we can already see that the different tools have a different focus and thus are more or less detailed concerning different criteria. Thus, their combination shows promising complementarities. Furthermore, comparison of tools was also a good opportunity to get inspiration from the work of others, in particular for researchers whose work on tree species characterization was not yet formalized into a digital tool. The development process, driven by user needs and feedbacks, allowed us to prioritize future developments to best suit the users, while identifying new avenues for future research. For stakeholders involved in the process, this work was a good opportunity to discover the state of the art in the DSS for tree species selection in different countries, and also to motivate potential users to contribute to further tool development, for example by complementing the database with species which were not yet included. In addition, sharing ideas with the other workshop participants was a good opportunity to get to know peers with a similar interest, which can potentially lead to new collaboration initiatives in the future. A further positive outcome is to make farmers and agroforestry planners aware of potential alternative tree and shrub species that may help to adapt to climate change and provide novel business opportunities. Thus, the combination of diverse knowledge sources into a unified tool allowed enriching the characterization of tree species, increasing the range of species, and eventually providing better advice for users. Our ambition for AgroforesTreeAdvice is to make it the central hub for interoperability of all tree species selection tools for agroforestry, providing the underlying information (database and model) in a homogenized way, allowing interoperability with other tools facilitating agroforestry system design and management.

Acknowledgements This work was supported by the DigitAF project (Grant Agreement N° 101059794), co-funded by the European Commission, European Research Agency, within the Horizon Europe programme, Cluster 6: "Food, bioeconomy, natural resources, agriculture and environment". The views and opinions expressed in this paper are purely those of the writers and may not in any circumstances be regarded as stating an official position of the European Commission.

Author contributions Conceptualization: MG Methodology: MG Software: MG, TS, CR, RP, BS Investigation: CR, KR-A, FW, SC, PP, JW, AM, LU, RH Validation: WT, MdH, JH, BL Writing—original draft: MG Writing—review and editing: TS, CR, RP, BS, KR-A, WT, JH, BL, MdH, FW, SC, PP, JW, AM, LU, RH, AT, SK, BR Funding acquisition: MG, SK, BR.

Funding Open access funding provided by CIRAD. This work was supported by the DigitAF project (Grant Agreement N° 101059794).

Data availability The code of the interface, the code of the suitability scoring functions and the underlying databases of tree characteristics are available on github https://github.com/euraf/agroforestreeadvice.

Declarations

Conflict of interest The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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