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RESEARCH ARTICLE

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Food tree species selection for nutrition-sensitive forest landscape restoration in Burkina Faso

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Societal Impact Statement

Modern food systems push agriculture to focus on a small number of commercial crops, while there is a very large diversity of untapped edible plants that could be used to address food security and nutrition. Poor and monotonous diets are closely linked to the complex burden of multiple forms of malnutrition and dietary risk. In some contexts, such as West Africa, micronutrient deficiency risks are particularly pronounced. Hence, there is an urgent need to provide people with healthy diets supported by sustainable food systems. Within this context, using nutrition-sensitive forest landscape restoration to combat environmental degradation could contribute towards ensuring the year-round availability of nutritious tree-based food.

Summary

- Diverse diets are important to deliver adequate amounts of the nutrients essential to human health. The consumption of a diversity of food groups is challenging in sub-Saharan Africa. Trees play an important role in the direct provision of nutritious food items. Forest landscape restoration presents an opportunity to reverse the loss of useful trees, due to degradation, and increase representation of food tree species in the landscape.
- Here we focused on characterizing the contributions that different food products from trees can make to improving diet diversity in Burkina Faso. A scoring system was developed, based on seasonal availability of edible products and food groups covered, and was integrated into a freely available decision-making tool that enables carrying out context-specific, optimal choices of tree species to be considered in forest landscape restoration.
- Our inventory included 56 food tree species, largely Fabaceae (18 species), providing 81 edible products, mainly fruits (supplied by 79% of tree species), followed by seeds (52%) and leaves (41%). The main food groups represented are 'Other fruits' (other than vitamin A-rich fruits) (covering 52% of the edible products) and dark-

green leafy vegetables (29%). About two thirds of the species listed produce more than a single edible product, a few up to four. A total of 11 species supplied edible products throughout the year.

- Our results clearly show that seasonal scarcity of food and nutrients in Burkina Faso can be partly mitigated by consuming edible tree products. The methodology can be easily scaled to other geographies.

KEYWORDS

decision-making tool, nutrition security, sub-Saharan Africa, underutilized tree species, wild tree species

1 | INTRODUCTION

Global diets connect human health and environmental sustainability but currently imperil both (Béné et al., 2019; Haddad et al., 2016; Steffen et al., 2015; Willett et al., 2019). Modern food systems push agriculture to focus on a small number of commercial crops (with rice, maize and wheat providing more than 50% of the calories consumed globally; Reeves et al., 2016), while there is a very large diversity of untapped edible plants that could be used to address food security and nutrition (more than 7000 edible plant species; Ulian et al., 2020). Thus, global diets are becoming more homogeneous, with a considerable decrease (69%) in variation between food supplies in different countries (Khoury et al., 2014). Diet quality is closely linked to the complex burden of multiple forms of malnutrition and dietary risk factors are the primary cause of morbidity and mortality worldwide (Forouzanfar et al., 2015). Poor diet quality contributes to stunting in children under 5 years, micronutrient deficiencies, overweight/obesity, and diet-related noncommunicable diseases (Development Initiatives, 2017). According to recent estimates, around two billion people globally are affected by micronutrient deficiencies, also called "hidden hunger" (Bailey et al., 2015). In sub-Saharan Africa, micronutrient deficiencies are quite pronounced (Joy et al., 2014), particularly in Sahelian belt countries where critical wasting prevalence is concentrated (Local Burden of Disease Child Growth Failure Collaborators, 2020), and in rural populations (Green et al., 2016).

Providing the global population with healthy diets supported by sustainable food systems is an urgent need. A diverse diet increases the likelihood of consuming adequate amounts of the full range of nutrients essential to human health (World Health Organization, 2003). Moreover, evidence shows that certain foods, most notably fruits and vegetables, contribute to the prevention of diet-related diseases such as cancer, diabetes, and cardiovascular diseases, which cannot be explained by adding up nutrients alone (Angelino et al., 2019; Boeing et al., 2012; Dauchet et al., 2009; Mozaffarian & Ludwig, 2010). Dietary guidelines around the world recommend a varied diet rich in fruits, vegetables, whole grains, nuts, seeds, and legumes for optimal health (Gonzalez Fischer & Garnett, 2016). Increasing their consumption increases the likelihood of consuming adequate amounts of the full range of nutrients essential to human health and protects against many forms of non-communicable disease.

Diet quality can be directly influenced by diversified livelihood strategies, such as agroforestry and harvesting of wild food tree products (Ruel et al., 2018). A rich diversity of neglected and underutilized species (NUS) offers opportunities for more sustainable food production and healthier diets (Borelli et al., 2020; Hunter et al., 2019; Meldrum & Padulosi, 2017; Padulosi et al., 2021). NUS are domesticated, semi-domesticated, or wild species and plant varieties that are marginalized or ignored by research, breeding programs, and policy-making. However, they often have a significant sociocultural value, as they are part of a common cultural heritage (Vasudeva et al., 2015). Indigenous people living within and nearby forests or other tree-based systems have strong cultural ties to forest foods (Chamberlain et al., 2020; Thomas et al., 2009), and edible tree products are a subject of gendered knowledge and preferences (Gachuiri et al., 2022). The precise number of NUS that can help addressing issues of erosion of diversity in food systems and enhance nutritious food production is uncertain, but attempts have been made by Meldrum et al. (2018) to examine more than a thousand vegetable species that could be used to diversify agricultural systems for improved nutrition (Lachat et al., 2017), while major knowledge gaps remain for other NUS, such fruits, cereals, pulses, and roots and tubers (Hunter et al., 2019). Recent estimates indicate that there are more than 7000 edible plant species (Ulian et al., 2020). To assess the nutritional properties of such a large number of species would be a daunting task, although attempts have been made to use phylogenetic information targeting more than 6400 edible plants lacking nutritional data to identify plants with the greatest potential to support strategies alleviating B-vitamin deficiencies (Cantwell-Jones et al., 2022).

Fruits and vegetables are good sources of micronutrients, and *trees play an important role in the direct provision of nutritious foods, such as nuts, oils, vegetables (leaves, flowers, and roots), fruits, and berries* (Jamnadass et al., 2015). The evidence that forests, trees, and agroforests provide essential nutrients has grown significantly in recent years (Fungo et al., 2016; Gitz et al., 2021; Ickowitz et al., 2021; Rasolofoson et al., 2018; Vinceti et al., 2013). In addition, there is growing awareness of the indirect role that forests, trees, and agroforestry systems play in food security and nutrition by supplying wood fuel for cooking and boiling water, by generating employment and income opportunities that enable purchasing food from other sources, and by providing ecosystem services that sustain food production and agricultural activities (Gitz et al., 2021). However, forest edible products tend to be unaccounted for in official statistics, given the informal nature of markets and consumption. In addition, trees tend to be largely neglected in nutrition-related interventions.

In the face of worldwide increasing deforestation and forest degradation, global initiatives triggered by the Bonn Challenge have driven major efforts to mobilize stakeholders and funding to launch large-scale forest restoration, with a target of initiating the restoration of 350 million hectares by 2030 (Saint-Laurent et al., 2020). The resulting forest landscape restoration (FLR) efforts are an important opportunity to enhance the availability, access and use of food tree species (Jansen et al., 2020).

In some contexts, such as West Africa, nutrition security is quite prominent among tree-based ecosystem services, given that many tree species supply edible products, among other non-timber forest products such as medicines (Hahn et al., 2018; Hahn et al., 2019; Zizka, Thiombiano, Dressler, Nacoulma, Ouédraogo, Ouédraogo, Ouédraogo, et al., 2015). Therefore, FLR projects in such regions and beyond must become nutrition-sensitive by promoting optimal tree combinations that ensure year-round availability of nutritious tree-based food. However, translating the concept of sustainable diets into action has proven to be very difficult, and the implementation of nutrition-sensitive restoration is likely to be no exception. Among critical obstacles are the limited availability of actionable, cross-sector data that can support location-specific actions, simultaneously addressing synergies and trade-off between health, economic, and environmental aspects of food systems.

In particular, nutritional data on tree foods (e.g., content of vitamins, proteins, and minerals) do not lend themselves to direct use in practical applications, without proper translation into concrete recommendations. First, large gaps exist in the nutritional characterization of edible products from tree species. Second, nutritional values from different data sources can be highly variable and of inconsistent quality (see the systematic review conducted on a well-documented food tree species in West Africa, *Parkia biglobosa*, by Termote et al., 2022). Thus, the aggregation of existing nutritional data requires careful screening and harmonization (e.g., in terms of units of measurement, sampling, and laboratory methodologies), whenever possible (e.g., when sufficient information is provided about the methods used for chemical analyses). Finally, most people make diet choices based on foods rather than nutrients, so focusing on foods rather than on individual nutrients to achieve nutrient-related positive outcomes is more accessible and amenable to translation in practice (Tapsell et al., 2016).

An alternative, more practical approach to evaluate the potential nutritional role of food tree products, overcoming the limitations of nutritional data, is the use of food groups, a nutrition-sensitive classification of foods, commonly used in food consumption surveys to determine diet diversity or to develop food-based dietary guidelines (Herforth et al., 2019). As tree foods vary between countries and regions, the use of food groups enables comparing information on dietary quality without losing detailed information. In addition, the timing of availability of nutrient-rich foods, such as fruits and vegetables, should be seen in the context of seasonal fluctuations in food and nutrient availability. The intra-annual variation in food availability is well captured in seasonal food calendars (Lochetti et al., 2020), food tree portfolios (McMullin et al., 2019), or other visual materials that promote enhancement of diet quality through consumption of a range of locally available seasonal foods, supporting nutrition education and awareness raising.

Here, we focused on the contributions that different tree food products can make to improving diet diversity of otherwise mostly monotonous staple-based diets prevalent in Burkina Faso. More specifically, we developed a methodology that enables carrying out context-specific choices of tree species to be considered in FLR to optimize year-round availability of different food groups, complementing the locally available main crops, such as grains (sorghum, pearl millet, maize and rice, and fonio), root and tubers (e.g., yam and sweet potato) and pulses (e.g., Bambara nut and black-eyed peas). We used Burkina Faso as a model case, integrating the methodology into a freely available decision-making tool called Diversity for Restoration (D4R; www.diversityforrestoration.org; see Box 1), but the methodology can be scaled to other geographies. D4R aims at supporting tree-planting decisions in a broad sense, by including a wide range of tree-planting objectives (e.g., restoration based on ecological principles, biodiversity conservation, timber production, and production of non-timber forest products) and covering different possible configurations (including woodlots, agroforestry systems, and hedgerows). The word 'restoration' in the name of the tool refers more generally to the prospect of restoring ecosystem functions on degraded land previously forested or occupied by tree-based systems. Guiding principles are the use of a diverse portfolio of well-adapted species and properly selected tree seed sources.

We demonstrate how the careful selection of locally adapted food trees could contribute to mitigate local nutritional gaps through FLR initiatives. More specifically, we aimed at developing a methodology to select a portfolio of tree species that optimizes (i) availability of edible products through complementarity in seasonality (i.e., maximizing product availability throughout the year) and (ii) diet diversity through complementarity in the food groups represented by the different edible products (i.e., maximizing diet diversification).

2 | MATERIALS AND METHODS

2.1 | Vegetation in Burkina Faso

Burkina Faso is characterized by two main ecoregions. About a third of the country is part of the Sahelian ecoregion (300–700 mm of annual precipitation, with a dry season of 7–8 months), and the remaining area is part of the Sudanian ecoregion (700–1100 mm of annual precipitation, with a dry season of <6 months) (Boussim, 2010; Guinko, 1984). The main characteristics of the Sahelian ecoregion are a low cover of woody vegetation, generally dominated by thorny trees and shrubs, and a discontinuous herbaceous layer dominated by annual grasses. The Sudanian ecoregion presents a greater cover of woody vegetation and a dense and tall herbaceous layer, sometimes with perennial grasses. The diversity of species increases from north to south, along a climatic gradient, mainly driven by annual precipitation and the length of the rainy season (Bognounou et al., 2009).

The flora of Burkina Faso has a very large number of food plants, either growing spontaneously or cultivated, playing a critical role in the diets and income generation of the rural population (Zizka, Thiombiano, Dressler, Nacoulma, Ouédraogo, Ouédraogo, Ouédraogo, et al., 2015). The various edible parts of plants are consumed in different ways (Thiombiano et al., 2010): raw, cooked (e.g., leaves of baobab, *Adansonia digitata*, or flowers of the red kapok tree, *Bombax costatum*), or further processed (e.g., shea butter from the shea tree, *Vitellaria paradoxa*, or the sauce derived from the fermentation of the seeds of nerè, *P. biglobosa*). The plants used, as well as the recipes, vary considerably from one location to another due to differences in cultural background and plant species locally available (Gouwakinnou et al., 2011; Pawera et al., 2020; Reyes-García et al., 2015).

2.2 | Building a dataset of edible products from trees

The steps taken to identify and characterize food tree species with potential for restoration are presented in Figure 1. First, a set of priority tree species, considered important for local livelihoods in Burkina Faso for providing desirable goods and services, was assembled based on the literature (Sop et al., 2012; Zizka, Thiombiano, Dressler, Nacoulma, Ouédraogo, Ouédraogo, Zizka, et al., 2015) and interviews with farmers and local experts, within the frame of different projects and initiatives (e.g., Gaisberger et al., 2018). After excluding those species without edible products, a list of 56 food tree species was retained. Species taxonomy follows the WorldFlora database (WFO, 2022).

In a next step, information was gathered for each identified food tree species about the specific parts consumed by humans (fruit, leaves, gum, shoot, root, and sap) and their culinary uses (ways of consumption in different dishes or as specific products, e.g., as a cooked vegetable, as a condiment, and as raw fruit). In addition, for each edible product, the seasonality was recorded (months of the year the product is available). The seasonal picture provided is an underestimate of availability, as it does not consider edible items which can be stored for a long time (e.g., dried baobab leaves). Data were partly harvested from scientific literature (Lamien et al., 2018; Parkouda et al., 2018; Zizka, Thiombiano, Dressler, Nacoulma, Ouédraogo, Ouédraogo, Ouédraogo, et al., 2015; Supporting Information with additional references), but most importantly were compiled by local experts who are co-authors on this paper (nutritionists, botanists, ethnobotanists, and foresters), especially for the lesser known species.

We considered that the contribution of edible products from trees in meeting local nutritional needs should be based on two key aspects. One aspect is the extent to which edible products from trees cover different *food groups*, thus contributing to diet diversification. The second aspect is the *seasonal availability* of edible products, particularly in relation to critical food and nutrient gaps. Diets tend to differ substantially according to the availability of agricultural products during the different seasons, especially if access to staple foods and the possibility to cover the nutritional needs of a population depends primarily on local agricultural production. In Burkina Faso, this seasonal variation in the diet is observed both in rural and urban populations (Becquey et al., 2012 for Ouagadougou; Arsenault et al., 2014 for the rural environment). Regarding cultivated plants, the harvest of

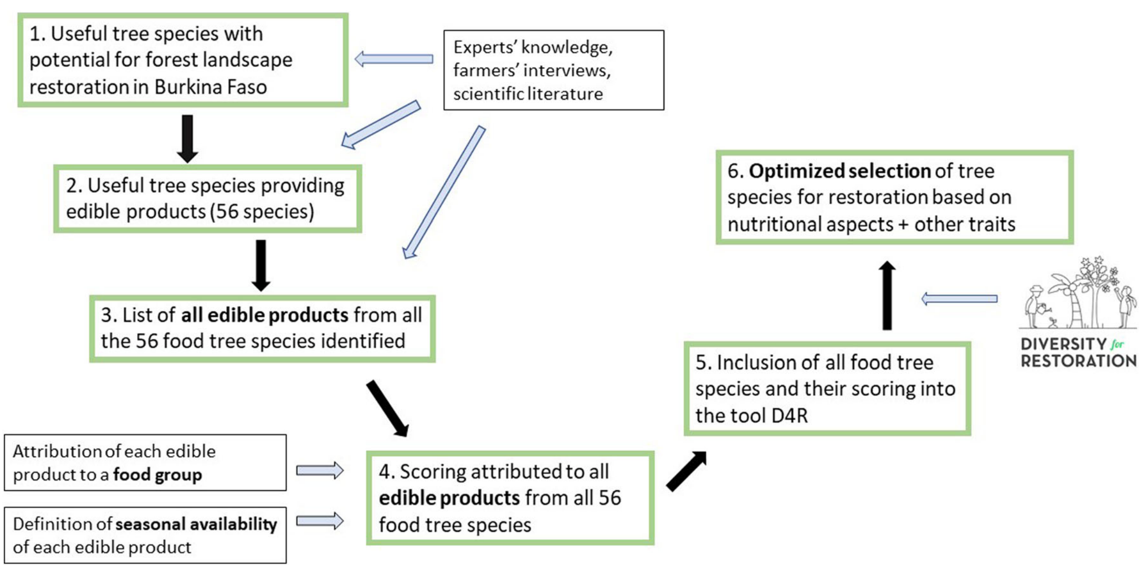


FIGURE 1 Methodological steps followed from the identification of the target food tree species in Burkina Faso to their integration in D4R, a decision-support tool designed to optimize selection of tree species for restoration interventions. Black arrows indicate the main steps in the methodology; light blue arrows relate to data sourcing and data treatment procedures illustrated in the paper.

rainfed crops takes place between October and December, while horticultural crops (mainly onions and tomatoes) are harvested from January to May (Lourme-Ruiz et al., 2021; Somé & Jones, 2018). The critical months in terms of food availability (mainly cereals) coincide with the peak of the lean season (June–August), while the lowest diversity of food groups consumed tends to coincide with the post-harvest season (lowest in January, but generally low from August to January), based on research covering a broad range of edible products (de Kok et al., 2021; Lourme-Ruiz et al., 2021; Somé & Jones, 2018). Despite this clear general pattern, variability among households is largely influenced by the level of diversity of own production on farm, the degree of access to purchased food, and the degree of reliance on foraging by gathering, hunting, or fishing (Lourme-Ruiz et al., 2021).

For our purposes, the seasonal availability of different edible products from trees was defined based on phenological data provided by experts. However, for some products, these data presented minor discrepancies among experts, owing to ecoregional variations in phenology and climatic changes, and we merged data from different sources.

Then, all edible products from the targeted tree species were assigned to a food group. We used the food groups employed to enumerate the Minimum Dietary Diversity for Women of reproductive age (MDD-W; FAO, 2021). This is a validated population-based indicator used as proxy to assess micronutrient adequacy of diet of women of reproductive age in multiple countries and contexts (Arimond et al., 2010). The MDD-W consists of 10 food groups: grains; white roots and tubers and plantains; pulses (beans, peas and lentils); nuts and seeds; milk and milk products; meat, poultry, and fish; eggs; dark-green leafy vegetables; other vitamin A-rich fruits and vegetables; other vegetables; and other fruits. We retained all six food groups that can be provided by trees: white roots and tubers and plantains; nuts and seeds; dark-green leafy vegetables; vitamin A-rich fruits and vegetables; other vegetables; and other fruits. Furthermore, we considered two food groups that are optional in the MDD-W indicator, namely, "red palm oil" and "other oils and fats." An explanation of each of the food groups is given in Table 1.

Foods such as condiments and spices, gums, sweets/chewing gum, or leaves and flowers to make tea were included in the tool among the species considered for the general "food" objective. Yet they were excluded from the objective "maximize nutritional diversity" (see below) as they are not typically considered among the abovementioned food groups, based on FAO (2021).

2.3 | Species selection for restoration

All food tree species identified were included in the online tool D4R (see Box 1). As a first filter, the tool uses species distribution models

TABLE 1 Examples of food groups and their corresponding edible products from trees in Burkina Faso. Descriptions of food groups are derived from FAO definitions

Food group	Description (adapted from FAO, 2021)	Example of edible products from trees	Images
White roots and tubers and plantains	This group includes potatoes, white-fleshed sweet potatoes, white yams, yucca and white-fleshed plantains/white-fleshed bananas. Plantains/white-fleshed banana (a fruit) and cooking bananas are included in this group because they share a similar nutrient profile to some roots and tubers and play the same role in diets as a starchy staple food.	Hypocotyls of *Borassus aethiopum*	 © B. Vinceti
Nuts and seeds	This group includes tree nuts, groundnuts (peanuts), other seeds when consumed in substantial quantities; nuts and seed butters, when consumed in substantial amounts (more than 15 grams per day). Rich in unsaturated fatty acids, vegetable protein, fiber, minerals, tocopherols, phytosterols, and phenolic compounds.	Fermented seeds of *Parkia biglobosa*	 © B. Vinceti
Dark-green leafy vegetables	Leaves consumed may vary widely by country and region and include both cultivated and wild and foraged species. All medium-to-dark-green leafy vegetables are vitamin A-rich and are therefore included here, and many are also rich in folate and several other micronutrients.	Ground leaves of *Adansonia digitata*	 © B. Vinceti

(Continues)

TABLE 1 (Continued)

Food group	Description (adapted from FAO, 2021)	Example of edible products from trees	Images
Vitamin A-rich fruits, vegetables, roots, and tubers	The group includes both vitamin A-rich fruits (e.g., ripe mango and ripe papaya, red palm fruit/pulp, passion fruit, apricot, and several types of melon) and a small but diverse group of vitamin A-rich vegetables other than leafy greens (e.g., orange-fleshed sweet potato, carrot, pumpkin, and deep yellow- or orange-fleshed squash). These foods may also be good sources of vitamin C and/or folate and/or other micronutrients.	Fruit of *Saba senegalensis*	 © M. Valette
Other vegetables	The group includes vegetables that have not been counted as dark-green leafy vegetables or as other vitamin A-rich vegetables. They still contain a range of bioactive compounds including phenolics, flavonoids and fiber.	Calyx from the flower of *Bombax costatum*	 © M. Schmidt
Other fruits	The group includes most fruits (both fresh and dried), excluding vitamin A-rich fruits. As with vegetables, commonly consumed fruits vary widely with geography and can include foraged as well as cultivated fruits.	Peeled fruits of *Tamarindus indica*	 © B. Vinceti
Red palm oil	Oil pressed from African oil palm (*Elaeis guinensis*) fruits, unless further refined to white palm oil. Considered separately from other oils and fats (see below) because of its very high vitamin A content.	Oil made from *Elaeis guinensis* fruits	 © B. Vinceti
Other oils and fats	All oils and fats other than red palm oil.	Oil made from kernels of *Vitellaria paradoxa*	 © B. Vinceti

Note: Descriptions of food groups are derived from FAO definitions.

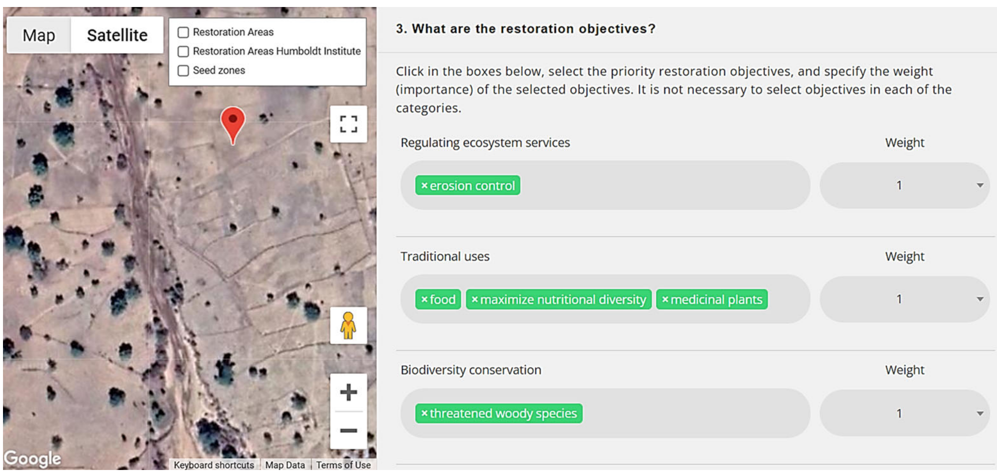
to identify the species that can grow under the environmental conditions at the planting site under present and future climate. Species distribution models under current and future conditions were based on available occurrence data gathered from different sources (BIEN, 2020; Global Biodiversity Information Facility [GBIF], 2020; plot data from association Tiipaalga; Brandis et al., 2007; Brunken et al., 2008; Herbarium of the University of Aarhus, 2020; Heubes, 2012; Schmidt et al., 2012) and climate models for AfriClim (Platts et al., 2014). Data were processed following a standard pipeline (Fremout et al., 2022). Next, the tool uses a range of species traits (including functional traits and local uses) to score how well each of the retained species are able to establish and persist under the site conditions (e.g., compacted soils, grazing pressure, and steep slopes) and match the restoration objectives (e.g., erosion control, bird conservation, and timber production). Trait data were extracted from the literature (Arbonnier, 2004; Orwa et al., 2009; Sacande et al., 2016; Schmidt et al., 2013; see full list of references in Dataset S1) and from interviews with experts from rural communities and local scientists. Further details about the trait-based species scoring are provided in Fremout et al. (2022). While food was already included as a restoration objective in the original D4R tool, species were only scored in a binary way (i.e., providing edible products or not). In the improved tool for Burkina Faso presented here, tree species "aptness scores" for the restoration objective "food" are calculated as the number of "food group months," with one "food group month" referring to the availability of one food group in 1 month. For example, if a tree species provides both vitamin A-rich fruits and dark-green leafy vegetables in April, this counts as two "food group months." Hence, species scores increase both with increasing number of food groups and increasing number of months with edible products available.

Next, the tool jointly optimizes the abovementioned species aptness scores and a diversity metric. By default, the tool optimizes a functional diversity metric (Fremout et al., 2022). As part of the improvement of the tool for nutrition-sensitive restoration, we added the optimization of nutritional diversity as an additional objective. To take into account both the diversity in food groups and "phenological diversity" (i.e., differences between species in terms of availability of food groups throughout the year), the diversity metric to be optimized consists of the average of a "food group dissimilarity" matrix, containing the Sørensen dissimilarities between species based on a binary species-by-food group matrix, and a "phenological dissimilarity" matrix, containing the Sørensen dissimilarities between species based on a binary matrix expressing the availability of food products per month.

The joint optimization of species aptness scores and the abovementioned diversity metric is carried out with the "selectSpecies"

Box 1 Diversity for Restoration (D4R), a tool assisting in tree species and seed source selection for restoration initiatives

D4R (https://www.diversityforrestoration.org/; Fremout et al., 2022) is a user-friendly online tool that is designed to assist decision-makers and restoration practitioners with the selection of tree species and seed sources that are adapted to the restoration site conditions and meet the restoration objectives. Depending on the planting site location, restoration site conditions and restoration objectives (see example in the screenshot included), the user receives recommendations on combinations of species to plant, where to get the seeds, and how to propagate the species. The tool is currently operational for the tropical dry forests of Colombia and northwestern Peru–southern Ecuador, the highland forests of western Oromia in Ethiopia, and the countries of Burkina Faso and Cameroon, while further expansion is underway. The tool integrates (i) species habitat suitability maps under current and future climatic conditions; (ii) analysis of functional trait data, local ecological knowledge, and other relevant species characteristics, such as species threat status, to score how well species match the site conditions and restoration objectives; (iii) optimization of functional trait diversity or phylogenetic diversity to foster complementarity effects; and (iv) development of seed zone maps to guide the sourcing of planting material adapted to present and expected future environmental conditions. Acknowledging the wide range of meanings and goals of restoration, the tool is intended to support decision-making for anyone interested in tree-based restoration in tropical forest landscapes, regardless of the purpose, and it fosters the achievement of multiple objectives via optimal combinations of species traits (adapted from Fremout et al., 2022).



User interface of the D4R tool, with a map-based visualization of the restoration site and the filters for selecting different objectives of the restoration initiative to be implemented.

function of the "Select" package (Laughlin et al., 2018); this results in a species assemblage in which both species composition and suggested relative planting abundances are optimized. This function allows to select species assemblages that simultaneously maximize a diversity metric and converge the average trait value (in this case the "trait" used was the species aptness score, that is, the number of "food group months" for the restoration objective "food") of the species assemblage on a predefined value. The package provides two measures of diversity that can be optimized: entropy H′, a species diversity index (Shipley et al., 2006, also known as the Shannon diversity index) and quadratic entropy Q (Pavoine, 2012; Rao, 1982), a functional diversity index (here the average of the "food group dissimilarity" and "phenological dissimilarity," as explained above). For a given a set of species and an "optimal" trait (i.e., the species aptness score) value, maximizing H′ results in an assemblage of species whose average trait values converge on this value, with relative species abundances distributed as evenly as possible, whereas maximizing Q maximizes the relative abundances of the most dissimilar species (i.e., resulting in a species assemblage without species with "intermediate" trait values) (Laughlin et al., 2018). Given that neither option is optimal for many restoration applications, Laughlin et al. (2018) provide the option to maximize both metrics simultaneously, with the φ parameter weighting the importance of Q (i.e., a φ value of 1 results in only maximizing Q), leading to results lying between the two extremes mentioned above. Recognizing that there are no silver bullet solutions to species selection, the D4R tool provides three options of recommended species. The first combination strikes a balance between species aptness scores and diversity (with the aptness score S set at the 0.80 quantile of the aptness scores and φ set at 0.50), the second focuses on diversity (with S set at the 0.60 quantile of the aptness scores and φ set at 0.70), and the third one focuses on the degree of species aptness for the selected site conditions and restoration objectives (with S set at the 0.95 quantile of the aptness scores and φ set at 0.30).

3 | RESULTS

3.1 | Characterization of edible products from trees

Data on edible products were collected for 56 food tree species (see all details in Dataset S2). Species span across 28 botanical families; the largest share is represented by Fabaceae (18 species), followed by Anacardiaceae (6), Combretaceae (5), Arecaceae (4), and Capparaceae (4). About two thirds of the species listed produce more than a single edible product. Most species supply two edible products (30 species), but some provide up to four.

Of the 56 food tree species examined, 43 supply edible products that are consumed in quantities above 15 g and can be categorized under different food groups, based on FAO (2021). Considering these 43 food tree species together, the availability of their edible products is the highest between December and July, with the total number of products ranging between 30 and 34 (Figures 2 and 3). This peak is driven by the availability of dark-green leafy vegetables, nuts and seeds, Vitamin A-rich fruits, and other fruits, which all reach highest availability in these months. Interestingly, this period of the year coincides with the first part of the lean season (associated with a scarcity of cereals). September and October are the months in which the diversity of food groups covered by food tree products in our inventory is lowest. This period coincides with the end of the rainy season and the start of the harvest season.

We found high variability in the number of months during which food products of individual tree species are available. A total of 11 species supplies edible products throughout the year (e.g., fruit of *Gardenia erubescens*, leaves and seeds of *Moringa oleifera*, and leaves of *Combretum glutinosum*).

From the 56 food trees documented in Burkina Faso, 81 edible items can be used as food. These are mostly fruits (supplied by 79% of tree species), followed by seeds (52%) and leaves (41%). Regarding the subset of 43 tree species, the main food groups represented are "Other fruits" (other than vitamin A-rich fruits) (covering 52% of the edible products) and dark-green leafy vegetables (29%).

Ways of consumption vary considerably. The most common culinary uses reported for different edible parts of the targeted species are the following (see Dataset S2): (a) fruits are commonly consumed raw, more rarely they are boiled or used to prepare beverages; (b) seeds are treated in different ways: occasionally consumed raw, but more commonly consumed after boiling, roasting or fermenting, while kernels are in some cases processed to extract oil or butter; (c) leaves are often consumed as vegetables or to prepare condiments; (d) roots are normally consumed after boiling; (e) flowers are often used as condiments; and (f) gum is used as sweet snack.

For some edible products, the daily quantity consumed is often below 15 g; this is usually the case when edible products (generally

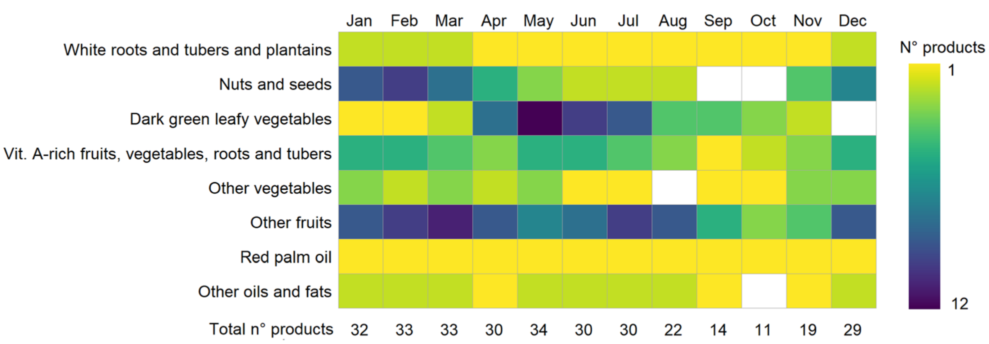


FIGURE 2 Availability of edible products from 43 food tree species in Burkina Faso targeted in this study, whose edible parts are consumed in quantities above 15 g and can be categorized under food groups, based on FAO (2021). Empty cells indicate that no edible tree products are available in particular food groups and specific months.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
White roots and tubers	B. aet B. ake	B. aet B. ake	B. aet B. ake	B. ake	C. afr	C. afr	C. afr	C. afr	C. afr	C. afr	B. aet	B. aet B. ake
Nuts and seeds	A. dig B. aeg B. ret C. cor F. alb H. the M. ole S. mac S. sen	A. dig A. occ B. aeg B. ret C. cor F. alb H. the M. ole S. mac S. sen	A. dig A. occ B. aeg B. ret F. alb H. the M. ole	A. dig A. occ F. alb H. the M. ole	B. sap H. the S. bir	B. sap S. bir	B. sap S. bir	B. sap S. bir			H. the M. ole S. mac S. sen	B. aeg B. ret C. cor H. the M. ole S. mac S. sen
Dark green leafy vegetables	D. mes	D. mes	D. mes P. luc	A. afr B. aeg B. ret B. afr D. mes P. luc S. spi V. don	A. dig A. afr B. aeg B. cos B. ret B. afr D. mes M. cra M. ole P. luc S. spi V. don	A. dig A. afr B. aeg B. cos B. ret D. mes M. cra M. ole S. spi V. don	A. dig A. afr B. aeg B. cos B. ret D. mes M. ole S. spi V. don	A. dig B. ret D. mes M. ole	A. dig B. ret D. mes M. ole	A. dig D. mes M. ole	D. mes M. ole	D. mes
Other vitamin A-rich fruits and vegetables	B. aet B. ake D. mes E. gui S. spi	B. aet B. ake D. mes E. gui S. spi	B. aet B. ake D. mes E. gui	B. ake E. gui P. big	A. sen E. gui P. big S. sen S. bir	A. sen E. gui P. big S. sen S. bir	A. sen E. gui S. sen S. bir	E. gui S. sen S. bir	E. gui	E. gui S. spi	B. aet E. gui S. spi	B. aet B. ake D. mes E. gui S. spi
Other vegetables	B. cos C. pen M. ole	A. sen M. ole	A. sen P. luc V. nil	P. luc V. nil	B. aeg P. luc B. aeg	B. aeg	B. aeg		A. afr	A. afr	A. afr B. cos M. ole	B. cos C. pen M. ole
Other fruits	A. dig B. aeg B. ret B. ruf D. mic F. alb G. eru H. the V. tor Z. mau	A. dig A. occ B. aeg B. ret B. ruf D. mic F. alb G. eru H. the V. tor Z. mau	A. dig A. occ B. aeg B. ret B. ruf D. mic F. alb G. eru H. the L. aci V. tor Z. mau	A. dig A. occ B. ruf D. mic F. alb F. syc G. eru H. the L. aci V. tor	B. ruf F. syc G. eru H. the L. mic V. par X. ame	B. ruf B. sen F. syc G. eru L. mic V. par V. mad X. ame	B. ruf B. sen F. syc G. eru L. mic S. lat V. par V. don V. mad X. ame	B. sen F. syc G. eru L. mic S. lat V. par V. don V. mad X. ame	G. eru S. lat V. par V. don X. ame	G. eru S. lat X. ame	G. eru H. the M. cra Z. mau	A. dig B. aeg B. ret B. ruf F. alb G. eru H. the M. cra V. tor Z. mau
Red palm oil	E. gui	E. gui	E. gui	E. gui	E. gui	E. gui	E. gui	E. gui	E. gui	E. gui	E. gui	E. gui
Other oils/fats	B. aeg M. ole	B. aeg M. ole	B. aeg M. ole	M. ole	S. bir V. par	S. bir V. par	S. bir V. par	S. bir V. par	V. par		M. ole	B. aeg M. ole
Total n° of products	32	33	33	30	34	30	30	22	14	11	19	29
Rainy season												
Lean season												

FIGURE 3 Seasonal contribution of each of the 43 food tree species in Burkina Faso targeted in this study, whose edible parts are consumed in quantities above 15 g and can be mapped against foods groups. Rainy season and lean period are also indicated in the annual calendar (darker colors indicate peaks). Abbreviations of species' names: *A. afr* = *Afzelia africana*; *A. dig* = *Adansonia digitata*; *A. occ* = *Anacardium occidentale*; *A. sen* = *Annona senegalensis*; *B. aeg* = *Balanites aegyptiaca*; *B. aet* = *Borassus aethiopum*; *B. afr* = *Burkea africana*; *B. ake* = *Borassus akeassii*; *B. cos* = *Bombax costatum*; *B. ruf* = *Bauhinia rufescens*; *B. sap* = *Blighia sapida*; *B. sen* = *Boscia senegalensis*; *C. afr* = *Commiphora africana*; *C. cor* = *Cola cordifolia*; *C. pen* = *Ceiba pentandra*; *D. mes* = *Diospyros mespiliformis*; *D. mic* = *Detarium microcarpum*; *E. gui* = *Elaeis guineensis*; *F. alb* = *Faidherbia albida*; *F. syc* = *Ficus sycomorus*; *G. eru* = *Gardenia erubescens*; *H. the* = *Hyphaene thebaica*; *L. aci* = *Lannea acida*; *L. mic* = *Lannea microcarpa*; *M. cra* = *Maerua crassifolia*; *M. ole* = *Moringa oleifera*; *P. big* = *Parkia biglobosa*; *P. luc* = *Pterocarpus lucens*; *P. ret* = *Piliostigma reticulatum*; *S. bir* = *Sclerocarya birrea*; *S. lat* = *Sarcocephalus latifolius*; *S. mac* = *Senegalia macrostachya*; *Sa. Sen* = *Saba senegalensis*; *Se. sen* = *Senegalia senegal*; *S. spi* = *Strychnos spinosa*; *T. ind* = *Tamarindus indica*; *V. don* = *Vitex doniana*; *V. mad* = *Vitex madiensis*; *V. nil* = *Vachellia nilotica*; *V. par* = *Vitellaria paradoxa*; *V. tor* = *Vachellia tortilis*; *X. ame* = *Ximenia americana*; *Z. mau* = *Ziziphus mauritiana*.

leaves, flowers, seeds, gums, and resins) are consumed as sweets, spices, infusions or tea, acidifiers, and taste enhancers.

3.2 | Pilot optimization of species selection with the D4R tool

To illustrate the output generated by the D4R tool, we ran it to simulate the nutrition-sensitive selection of tree species for a FLR project in a randomly selected site in northern Burkina Faso. The project aimed, among other objectives, to maximize the nutritional diversity provided by the edible products supplied by the tree species planted. The settings of the tool were the following ones:

- Location: near Dori (Sahelian ecoregion); coordinates: 14.06°N, 0.09°S
- Site conditions: grazing pressure
- Priority restoration objectives:
  - Agroforestry and commercial uses: (i) live fences and hedgerows and (ii) silvopastoral systems
  - Traditional uses: (i) food and (ii) optimize nutritional diversity
- Number of tree species selected: 10

The tool generated an output consisting of three portfolios of tree species best aligned with these settings (see Table S1), one of which (focus on nutritional diversity) is shown in Figure 4.

The pilot test of D4R recommends a portfolio of tree species for planting which ensures a continuous availability of edible products through the year, based on the phenology of the species identified, while at the same time optimizing the delivery of other specified products and services desired (priority to agroforestry and commercial species, priority to species with traditional uses), and types of interventions planned (live fences and hedgerows, silvopastoral systems or forage/fodder production, and food production). The D4R output report includes also more information about culinary uses of edible products from each species recommended (Table S2).

4 | DISCUSSION

4.1 | Improving local diets with nutrition-sensitive FLR

The decision-support tool presented here addresses two key aspects in relation to food and nutrition security, which are the seasonality of

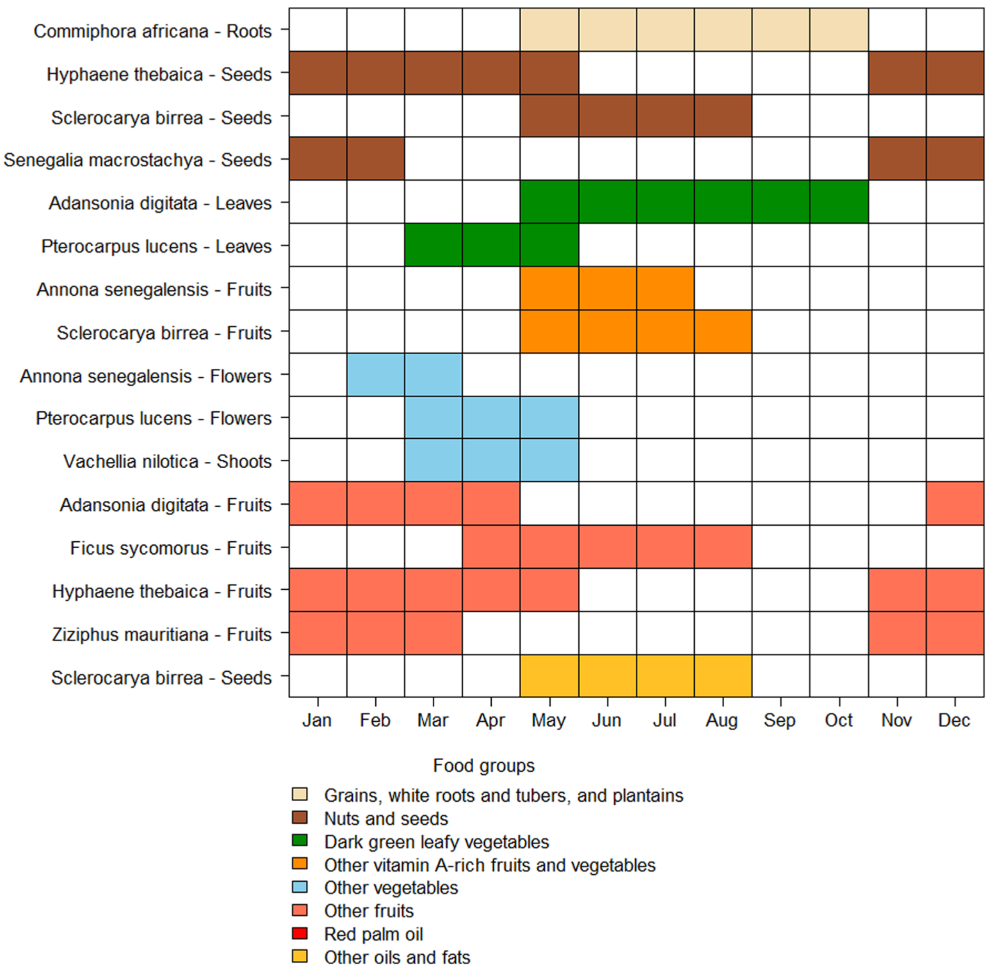


FIGURE 4 The tool Diversity for Restoration (D4R) recommends portfolios of tree species to be planted based on the objectives specified by the user, and their relative weight. The table shows the results from a pilot test of the tool in a site in Burkina Faso (full results in Tables S1 and S2). The recommended combination of food tree species, listed with their respective multiple edible products, contributes to maximize year-round nutritional diversity (represented by the different color-coded food groups).

dietary and nutritional gaps, and the low dietary diversity found in rural settings in sub-Saharan Africa (SSA), with significant deficiencies in micronutrients. Consuming a varied and diverse diet that provides enough micronutrients is challenging in SSA (Somé & Jones, 2018). Research findings indicate that dietary diversity is low in Burkina Faso, with mean dietary diversity scores of 2 out of 9 food groups and <25% of the population meeting the minimum dietary diversity recommended (at least four food groups per day) (Nikièma et al., 2017). The diet of rural residents usually consists in a thick, cereal-based porridge consumed with a sauce made of leafy vegetables and condiments, such as chili or soumbala (i.e., fermented seeds of African locust bean, *P. biglobosa*), occasionally accompanied by dried fish (Lykke et al., 2002). Our results show that the use of food tree species in FLR can make an important contribution to increase the number of food groups consumed, as a variety of products is available during most of the year (Figures 2 and 3). This is in line with studies elsewhere in Africa that have found a significant positive relationship between tree cover and dietary diversity in Africa (Galway et al., 2018; Ickowitz et al., 2014). Further evidence from Tanzania has shown how deforestation tends to reduce fruit and vegetable consumption (Hall et al., 2022). As a source of nutrients, trees present advantages compared to annual crops as they are perennial, long-lived, more resilient in the face of annual climatic fluctuations, and are less subject to missed harvests. Additionally, these characteristics of edible trees provide clear advantages in contributing a safety net in conflict-ridden areas—currently on the rise in Burkina Faso—where planting of annual crops is often not possible.

In most of Burkina Faso, food security follows a seasonal pattern, due to fluctuations in food availability and accessibility (Somé & Jones, 2018; Turner et al., 2021); therefore, *seasonal differences in availability of diverse foods, and the associated variation in nutritional risks, need to be considered in designing interventions to improve food and nutrition security*. The peak of the lean season covers the months of June–August that coincide with the planting season and precede the harvest which occurs from mid-September to mid-December (Somé & Jones, 2018). The lean season is the most critical period for child survival, because it also overlaps with the malaria season (Sié et al., 2018). Shortages of staple foods and increased market prices for many food commodities in both rural and urban areas begin already in April–May and become progressively more pronounced in the following months. To partly mitigate the effects of the lean season, consumption of foraged foods (e.g., green leaves and wild fruits) by food-insecure households appears to be greater during that period, especially in rural areas (Frongillo & Nanama, 2006). In addition, several fruits are available in from the beginning of the lean season, as shown also by our data (Figure 3): between June and August, when the lean season is most pronounced, between 20 and 30 edible products are supplied by a portfolio of around 25 food trees. Dietary diversity does not decline sensibly during the lean season, mainly due to the availability of gathered foods (e.g., sheanuts, fruits, and wild leafy vegetables), and the harvest of early crops (e.g., vegetables, fresh beans, and corn) (Somé & Jones, 2018). The diversity of the diets appears to decline in the post-harvest season and during the most critical month of January, 27 food trees in the D4R catalogue are supplying either edible seeds (14 species), fruits (20 species), leaves (10 species), or other edible products (flowers, shoots, roots, etc.).

Food trees are already part of traditional diets in Burkina Faso (Vinceti et al., 2018). However, *growing demographic and climatic pressures are increasingly threatening the remaining tree cover and affecting the availability of indigenous food tree species*, as shown in a species-specific and spatially explicit threat analysis carried out for 16 priority food tree species occurring in Burkina Faso (Gaisberger et al., 2018). Other critical factors may contribute to reduced availability of useful indigenous food tree species: the lack of a tradition to actively plant trees, particularly for women (Gausset et al., 2005; Kiptot & Franzel, 2011), the lack of clear land tenure rights that discourages investments in tree planting or leads to equating tree planting with claiming ownership of the land (Gausset et al., 2003), complex tree tenure arrangements that limit access to valuable trees (Tomomatsu, 2014; Pehou et al., 2020), and customs and taboos associated to some species, based on cultural norms (Balima et al., 2018; Kiptot & Franzel, 2011). Recent investigations have shown that land use intensity (especially grazing and agricultural practices) and dispersal limitation are inhibiting regeneration of tree species in the Sahel, leading to shifts in functional composition, with land use intensity positively associated with an increasing dominance of shorter vegetation, with smaller seeds and more conservative traits (such as high-density wood and thick leaves) which make plants less palatable and help them to better tolerate mechanical disturbance and drought (Lohbeck et al., 2020). The observed shifts in species composition towards a greater representation of highly drought-tolerant shrubs and exotic tree species is accompanied by a decline in traditionally used multipurpose species and larger trees, significantly altering the ecosystem services provided by trees (Hänke et al., 2016; Herrmann & Tappan, 2013). As a result of these multiple threats, locally valued food trees are currently occurring at too low densities and the lack of regeneration is further constraining their long-term availability.

To fight environmental degradation, Burkina Faso has committed to restore 5 M ha of degraded land by 2030 (Vinceti et al., 2020). *FLR presents an opportunity to reverse the loss of useful food trees and increase their representation in the landscape*, through assisted natural regeneration and planting. Positive evidence in this regard is already emerging from large-scale restoration initiatives implemented in the Sahel, largely based on making use of native plants, considering their direct role in the diet (e.g., fruiting periods and nutritional attributes) and their potential to generated income (Sacande & Muir, 2022). A growing number of FLR projects have been set in place by different stakeholders, because of the restoration pledges of the government and financial support of various donors. Examples are the Great Green Wall for the Sahara and the Sahel Initiative; within which the increase of woody vegetation in farmers' fields has played a key role in building community resilience to climatic and socioeconomic changes (Goffner et al., 2019; Sacande & Muir, 2022).

Decades of initiatives designed to reverse food insecurity trends have shown that the intervention pathways that lead to nutrition security are not straightforward (Fraval et al., 2020) and that the dynamics of food availability and access in rural subsistence settings are complex. Regarding tree resources, stakeholder's rights of access in a context of rapidly changing landscapes play a crucial role (Koffi et al., 2020). At farm level, a growing number of studies confirms the existence of a positive relationship between dietary diversity and the diversity of own crop production (Jones, 2017; M'Kaibi et al., 2015; Powell et al., 2015), while at the same time, studies carried out in SSA emphasized the role of income, through access to purchased food, as a main pathway leading to higher dietary diversity (Dillon et al., 2015; Sibhatu et al., 2015; Somé & Jones, 2018). Certainly, the role of own production and income from cash crops have a complementary role in enabling household to reach nutrition security (Bellon et al., 2020). At the landscape scale, a recent study reviewed evidence on the links between dietary quality and the occurrence in the landscape of tree-based farming systems with different configurations (i.e., trees on farms, home gardens, shifting cultivation, timber/tree–crop plantations, and forest-edge farming), considering a range of pathways through which forests and trees contribute to diets (direct provision of edible and/or marketable products, provision of ecosystem services enhancing agricultural production) (Vansant et al., 2022), and found a positive relations between tree-based systems and better diets, though this association is mediated by biophysical and socioeconomic factors. In addition, landscapes with traditional forms of tree-based farming practiced implemented by indigenous populations seem to be more consistently associated with more diversified diets.

Although the potential pathways at play leading to nutrition security may differ across contexts, the incorporation of an objective to maximize nutritional diversity obtained from food tree species in the D4R tool has the potential to contribute to mitigating seasonal dietary gaps. Other authors have identified optimal combinations of fruit trees for agroforestry systems in Kenya, based on food composition data, with the objective to achieve year-round availability of fresh fruits, addressing specific micronutrient gaps, mainly vitamin A and vitamin C (Stadlmayr et al., 2019). The novelty in the D4R tool presented here is that the optimization of recommended tree portfolios addresses simultaneously a range of different objectives, targeting the improvement of local diets among other envisaged positive outcomes. While inserting in D4R the characteristics of a specific tree-planting project to be implemented, a user can select several objectives to be achieved at the same time (e.g., conservation of threatened species, carbon sequestration, and food supply). The tool screens through the embedded catalogue of tree species and selects optimal sets of species that best match and balance the multiple objectives identified. Moreover, considering that food composition data about edible tree products are very scarce and often of uncertain quality (Termote et al., 2022), our characterization of the nutritional value of edible tree products is based on food groups rather than actual nutritional data. This allows including all food trees, regardless of the availability of nutritional data, and makes the methodology easy to scale to other regions.

4.2 | Practical considerations and study limitations

In case of multiple food alternatives available in the same period of the year, the proposed tree species scoring methodology does not consider preferences and differences in desirability associated with organoleptic properties and neither does it take into account more practical considerations such as ease of harvesting or cooking time. Thus, D4R does not distinguish the so-called "famine" foods, which are consumed in periods when more desirable food alternatives are not available (e.g., *Faidherbia albida*, which can provide edible products for humans, but these are only consumed during famine periods, when alternative products are not available). Food choices are shaped by the food environment but are also affected by individual-based motives (Karanja et al., 2022), so they are closely linked to highly variable and context-specific physiological and sociocultural (Dansi et al., 2008; Ghosh et al., 2021) and generational aspects (van der Hoeven et al., 2013). Including these elements in the D4R tool would quickly become overly complex, making it difficult to obtain robust and complete data on all edible tree products.

The recommendations of the D4R tool are not meant to be followed like a cookbook recipe. The tool provides a knowledge-based starting point for planning nutrition-sensitive FLR projects. It enables to expand the breath of species and objectives that could be achieved and enables forest practitioners to acquire knowledge about nutritional aspects of diversified diets. Whenever possible, the final selection of tree species to plant should happen through a participatory process, taking into account local cultural preferences and availability of planting material of the desired set of tree species, among others. It is key to also consider the critical role of nutrition education that should accompany nutrition-sensitive interventions. It is well known that what is available for consumption is not always consumed unless its nutritional value is fully understood (Jaenicke & Virchow, 2013) and nutrition education can assist in making choices between trade-off in home consumption versus sale of nutrient-rich products.

In assigning edible tree products to different food groups, ways of processing edible ingredients were not considered. For example, leaves were assigned to the food group "dark-green leafy vegetables" regardless of the way they are locally processed, even if the vitamin A content may vary based on this. As part of the participatory process that should accompany the use of the tool, awareness could be raised on aspects related to specific culinary uses and the ways in which the edible tree products are consumed affect their nutrient content. For example, raw dark-green leafy vegetables (leaves) may contain much more vitamin A than cooked ones; however, digestibility will increase with cooking; the same will be valid for other nutrients based on the way the ingredients are processed and specific tests should be carried out (Gidamis et al., 2003; Lee et al., 2018).

Finally, in the dataset, we considered seasonal availability of ripe fruits. We asked the experts to indicate when certain products are available for consumption, but there could be some small local annual fluctuations. It is known that in many products the nutrient content depends on external factors that cannot be controlled, such as, for example, how ripe is a fruit at the time of consumption.

4.3 | Prospects

Despite some general assumptions, the inclusion of dietary-relevant information in a restoration tool offers an opportunity to aggregate useful data not easily found in the literature (expert knowledge) and dispersed across several information sources in a single and easy-to-use platform. It also enables to operationalize nutritionally relevant information into concrete interventions, by recommending planting of optimal portfolios of multipurpose tree species that couple provision of edible products with other important non-timber forest products and ecosystem services. Among the future developments, additional relevant features will be incorporated, such as, for example, the inclusion of ecoregion-specific data, the characterization of tree species based on the potential pollination services they contribute (and honey production), or their suitability to host edible insects which are an important source of proteins (Muvatsi et al., 2018, 2021), to ensure that additional nutrition-related results could be obtained through a targeted selection of specific combinations of tree species in restoration.

The tool has been so far developed for a few countries, in some cases limited to specific ecosystems or regions within countries, and is currently under development for specific settings (e.g., cacao/coffee agroforestry systems). It is also part of a capacity building initiative supported by FAO, as a science-based planning tool. Its user friendliness has been tested with positive results, through a survey targeting potential users (Wiederkehr Guerra & Gotor, 2020). Further work is ongoing to improve customization and promote broad adoption. While the main end users targeted are NGOs, farmer organizations/cooperatives, local governments, and other entities managing restoration projects, a user-friendly version of the tool is being planned to foster direct use also by individuals who might lack technical training.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

BV and CT conceived the study. TF, CT, DFC, CL, and ET contributed to improve the design. LCT, AT, IZ, DL, LS, CP, AH, OO, and HO supplied data. TF, DFC, and BV carried out data compilation and curation. TF carried out data analyses. BV and TF wrote the paper.

DATA AVAILABILITY STATEMENT

The data on edible tree products that support the findings of this study are available in Dataset S2. In an openly accessible publication (10.1111/1365-2664.14079) can be found information on how to access the R scripts and data to run the tool Diversity for Restoration (D4R).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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