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Review

Wild Edible Fruits: A Systematic Review of an Under-Researched Multifunctional NTFP (Non-Timber Forest Product)

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Abstract: Wild edible fruits (WEFs) are among the most widely used non-timber forest products (NTFPs), and important sources of nutrition, medicine, and income for their users. In addition to their use as food, WEF species may also yield fiber, fuel, and a range of processed products. Besides forests, WEF species also thrive in diverse environments, such as agroforestry and urban landscapes, deserts, fallows, natural lands, and plantations. Given the multifunctional, ubiquitous nature of WEFs, we conducted a systematic review on the literature specific to WEFs and highlighted links between different domains of the wider knowledge on NTFPs. We found that literature specific to WEFs was limited, and a majority of it reported ethnobotanical and taxonomic descriptions, with relatively few studies on landscape ecology, economics, and conservation of WEFs. Our review identifies priorities and emerging avenues for research and policymaking to promote sustainable WEF management and use, and subsequent biodiversity and habitat conservation. In particular, we recommend that ecosystem services, economic incentives, market innovations, and stakeholder synergies are incorporated into WEF conservation strategies.

Keywords: conservation; markets; non-timber forest products; policy; research priorities; sustainability; wild edible fruits

1. Introduction

Non-timber forest products (NTFPs) can be defined as biological products, other than high-value timber, harvested by humans from wild biodiversity in natural or human-modified environments [1]. About one billion people worldwide derive livelihoods and food from forests [2], and around 300 million of these people depend extensively on NTFPs [3]. It is estimated that, on average, a quarter of the rural household income in developing nations comes from NTFPs [4]. In central Africa alone, as many as 500 species of plants and 85 species of animals collected from forests and savannas contribute to the household economy [5]. In tropical and low-income countries, NTFPs are widely used for medicine [5–7] and nutrition [8,9]. Bushmeat is an important source of protein for rural and forest-dwelling communities [10], while animal parts are featured in ceremonial practices in various cultures [11]. At the household level, NTFPs improve food security worldwide [9,12–16], through regular, direct consumption of harvested products, as famine foods and safety nets in adverse periods, or through income earned from selling them. Trade in NTFPs allows economically weaker households to maintain financial stability, especially during circumstances of shock and vulnerability [1,17,18].

Wild foods, such as bushmeat, insects, honey, fungi, wild vegetables, and wild edible fruits, (WEFs) are a subset of NTFPs, and an important source of nutrition for one in six people worldwide [19]. Wild foods can provide an open access source of food and income, especially to vulnerable groups such as the poor, malnourished children [20], and those affected by HIV/AIDS [21]. Diets including wild foods often also reflect greater diversity and quality of nutrients compared to those derived from cultivated foods [22]. Wild foods have also been found to improve household food security both under normal circumstances [23] as well as during periods of crop scarcity [24], and in rural [9] as well as urban contexts [25]. Wild foods need not be procured from forests alone, but also from managed landscapes like fallows and agroforestry systems, where they supplement and diversify food production and income, and enhance ecosystem services and climate resilience [19,26,27].

WEFs are among the most commonly used NTFPs [28,29], and some may also possess medicinal properties, and are therefore used in treatment of ailments [30–32]. WEFs are used for a range of other purposes, such as cosmetics [33], crafts [34,35], fiber [36,37], and fuel [38–40]. In the nutrition and pharmaceutical literature, WEFs have been widely studied and recommended as rich sources of antioxidants, minerals, and vitamins [41–43]. We adhere to the definition of the term fruit as any part of the reproductive structure of angiosperms and consider any undomesticated product extracted from wild or managed landscapes as wild. Thus, our definition of WEFs excludes mushrooms and horticulturally grown species such as apples, but includes undomesticated species from agroforestry systems, vacant lands, and private and public gardens.

In this review, we analyze the literature focused specifically on WEFs and identify priorities for WEF research and conservation. The questions that frame this review are: 1. What is the state of knowledge regarding the ecology, use, trade, policy, sustainability, and conservation of WEFs? 2. What are the gaps in knowledge about WEF ecology, use, and conservation? 3. What are the commonalities, differences, and relationships between knowledge on WEFs and other wild foods and NTFPs? The results are therefore presented in a manner that narrows down from broader information on NTFPs to wild foods and to specific evidence about WEFs.

2. Methods

The PRISMA protocol [44] was used to retrieve and code the literature. Our research questions are broad, and therefore, our review qualifies as a systematic map [45,46] that summarizes the existing evidence about the different aspects of a particular subject and identifies knowledge gaps and gluts [47,48]. A systematic map is distinct from a meta-analysis, where evidence is statistically analyzed to arrive at conclusions or hypotheses [49], or a systematic review with more specific questions that can employ the population-intervention-outcome-comparator approach [50]. Thus, our search keywords are high sensitivity, low specificity, and restricted to the subject only, and our analysis consists of a single level of coding based on emergent themes.

The combinations 'non' + 'timber' + 'forest' + 'product' + 'fruit' and 'wild' + 'edible' + 'fruit' were used as English language search terms on Scopus and Web of Science, in mid-2017, for all time. Articles were refined to include the topics of agriculture, biology, economics, environmental science and studies, food science, forestry, plant science, social science, and urban studies. Thus, articles related to chemistry, engineering, genetics, immunology, medicine, microbiology, etc., were excluded. Together, these searches yielded a total of 1080 unique results. This literature was screened for relevance to wild edible fruit conservation, ecology, economics, and ethnobotany. At this stage, articles on nutrient composition, historic and horticultural records, and pharmacology and toxicology of wild fruits (598) were excluded. Articles on wider topics such as NTFPs (150), wild edible plants (113), and mushrooms (34) were classified as secondary literature to provide the wider contextual setting for the literature specific to WEFs. The remaining articles (185) were classified into categories based on focus on fruit, and study category (Table 1).

Table 1. Selection and classification criteria for articles.

A. Exclusion Criteria	Explanation
Chemical composition	Articles on chemical and nutrient composition, medicinal and industrial use, and toxicology of wild edible fruits.
History and horticulture	Articles on archaeological evidence, historic use, domestication and cultivation of wild edible fruits.
Wild plants	Articles about various (edible and non-edible) uses of different (non-fruit) parts of wild plants.
Mushrooms	Mushroom sporocarps were not included under the definition of wild edible fruits.
Non-edible uses	Articles describing use of wild fruits other than food.
B. Inclusion Criteria	**Explanation (Fruit = Seed-Bearing Angiosperm Part)**
1. Relevance of Fruit in Study	
Primary study subject is wild edible fruit	Studies on wild edible fruits of single or multiple use species, or wild edible fruits from a range of taxa.
Wild edible fruit is one of multiple study subjects	Studies on multiple use species that also bear wild edible fruit.
2. Category of Study	
Conservation	Studies on sustainability, impacts of harvest across degrees of species and landscape management, threats, and best practices towards wild edible fruit resources.
Description	Articles documenting the regional diversity of wild edible fruit species used in certain regions, the range of uses, morphological characteristics, and regional distribution of taxa.
Ecology	Studies on the ecological dynamics of a taxon and or its ecosystem.
Economics	Articles documenting trade markets and supply chains of wild edible fruits, policy, and governance mechanisms.

We acknowledge that articles that did not use the terms 'non-timber forest product' or 'wild edible' along with 'fruit' in their keywords or title are likely to have been excluded. Examples include articles referring to 'indigenous' or 'exotic' fruits [51,52], those using only common or scientific fruit names [53–55], and those that refer to a range of products of which fruits are a subset [56,57]. However, the 185 shortlisted articles are likely to present a reasonable representation of the knowledge about WEFs across different domains. We supplement this body of literature with articles from our own knowledge.

Studies that fit the inclusion criteria were also classified according to the discipline of their journal, their year of publication, and the region of the respective study sites. Abstracts, findings, and recommendations from these studies were manually summarized in Microsoft Excel 2010. Four emergent themes were identified, based on which articles were classified into categories, namely, conservation, descriptions, ecology, and economics (Table 1). In cases where articles covered more than one of these themes, categories were assigned based on the theme that was most comprehensively addressed in the research questions or findings of the respective article. However, for further analysis, the contents of articles were coded and referred to for important findings in multiple categories if applicable. The process of article selection, summarization, and coding was performed by MS only, resulting in an expected minimum variability.

3. Results

A quarter (n = 46) of the 185 articles on WEFs were found in forestry journals, and a fifth (n = 36) in botany journals (Figure 1), with the fields of genetics, ecology, environment, ethnobiology, and horticulture also contributing significantly. The literature on WEFs has increased over the last three decades (Figure 2). About a third of the articles were based on studies in Africa, and a quarter from South America (Figure 3). Nearly half the articles were ethnobotanical and taxonomic descriptions (Table 2), while just over a quarter focused on the species or landscape ecology of WEF species. Fewer articles were found on conservation and management, and the economics of WEF trade. About a quarter of the 185 articles (n = 47) focused on multi-use species that also bear edible fruits, while the remainder had wild edible fruits as their primary focus.

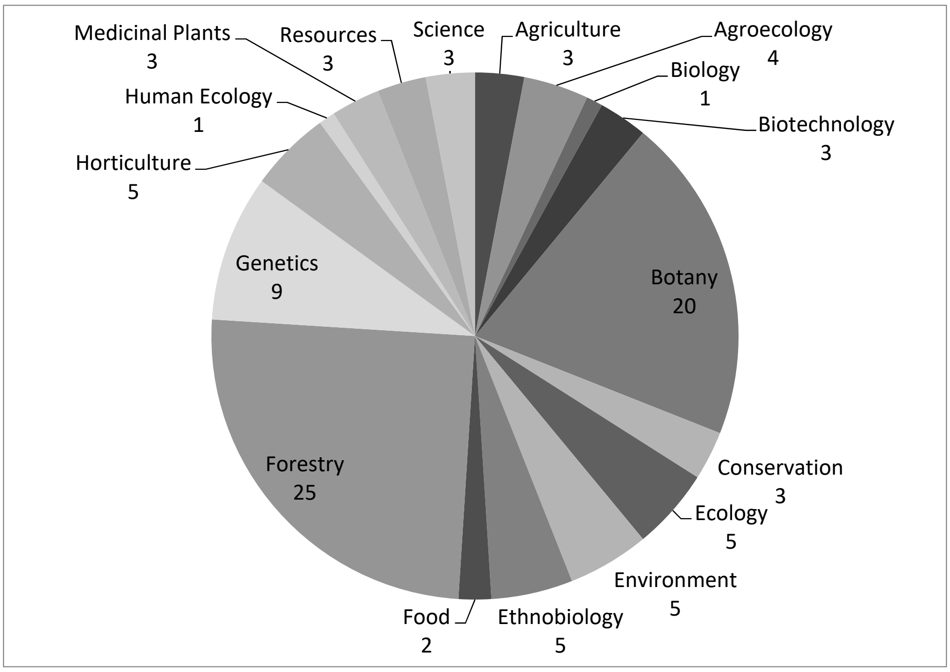

Figure 1. Proportion of articles from journals of different disciplines contributing to the literature on WEFs (wild edible fruits), in percentages (n = 185).

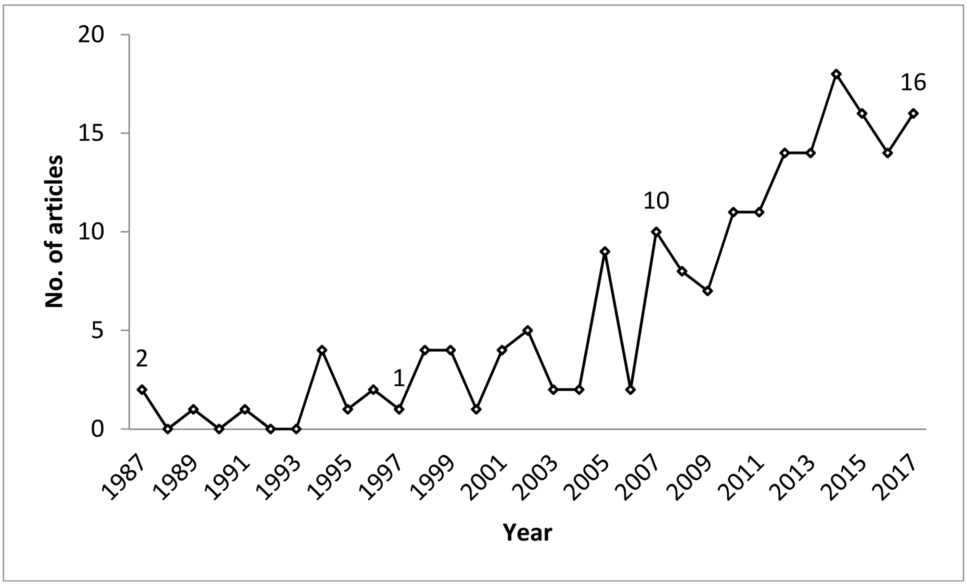

Figure 2. Number of articles per year on wild edible fruits. The count for 2017 was taken in October 2017.

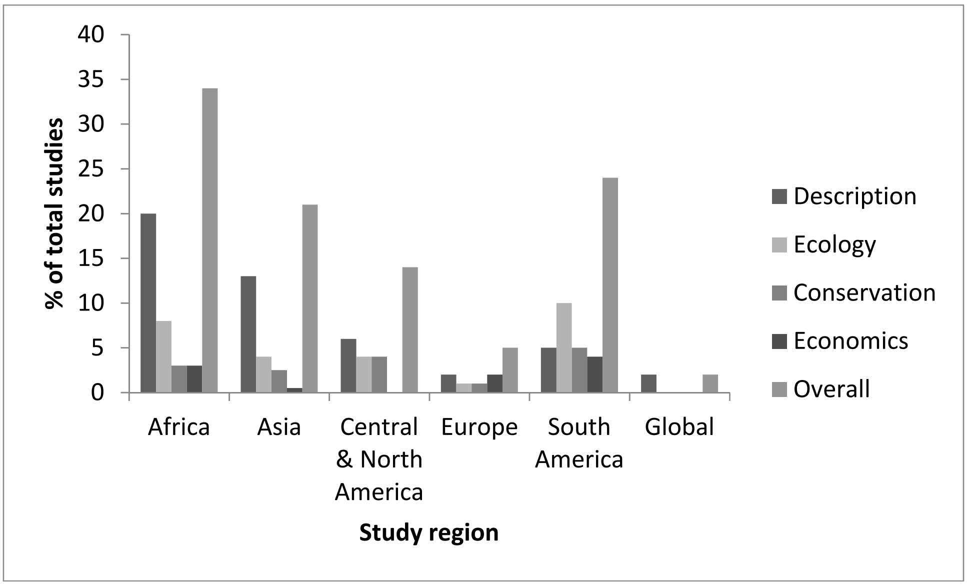

Figure 3. The distribution of study categories by region. Percentages are calculated from n = 185.

Table 2. Numbers of different categories of articles.

Category	Class	Africa	Asia	Central & North America	Europe	South America	World	Total	Percentage
Description	Regional	18	17	0	1	1	0	37	20
	Taxonomic	20	7	11	2	9	4	53	28
Ecology	Species	11	5	8	2	14	0	40	21
	Landscape	3	3	0	0	5	0	11	6
Conservation	Threats	1	2	0	0	2	0	5	3
	Management	5	3	7	1	8	0	24	13
Economics	Supply chain	4	1	0	2	6	0	13	7
	Policy	1	0	0	1	1	0	3	2
Total	All	63	38	26	9	46	4	185	100

3.1. Descriptions

Several of the 90 articles provided ethnobotanical, regional, or taxonomic descriptions of WEF species, while a total of 35 different species of WEFs were the primary subject of 49 articles, and five articles focused on five different WEF genera. The remainder (n = 36) of the descriptive articles surveyed and inventoried the available diversity of WEF species within landscapes ranging from forest communities and small islands to provincial and national levels. About a third (n = 27) of the descriptive articles (27) reviewed the different aspects of a single species over large regions. For example, fruit-bearing palms are important multifunctional species in the Amazon, used in construction of walls and roofs, making of beverages and bags, and breeding of edible insects [58], while *Ficus* spp. are important WEF species in Asia [59], Europe [60], and Africa [61]. In Africa, *Adansonia digitate* L. [41,62,63], *Berchemia discolor* Hemsl., *Diospyros mespiliformis* Hochst. ex A. DC., and *Sclerocarya birrea* Hochst. [64] were identified as priority species. The baobab (*A. digitata*) is reported to have 25 different local uses including food, fodder, medicine, and shelter [65], and also has a growing export market for food, nutrition, and cosmetic products in Europe [66]. Besides the fruit of the marula (*S. birrea*), which is consumed raw or fermented, it is used to extract oil, treat flu and other ailments, as livestock feed, and in making wooden artefacts and utensils [67,68]. Beyond being important contributors to human living and livelihoods, some WEF-bearing trees, such as the baobab [69], marula [67], and some palms [70], are keystone species within their ecosystems. Descriptive studies that document the occurrence and use of WEF resources pave the way for research on plant ecology, resource economics, and conservation.

3.2. Ecology

3.2.1. Species Ecology

The ecology and life history of a species may render it suitable or otherwise for profitable extraction [71,72]. For example, while some palms can survive harvesting of up to 50% of their leaves [73], others can tolerate removal of only 5% or less [74]. High dependence on seed dispersers [75] and low seedling recruitment [76] can potentially hinder recruitment in populations of WEF species. In multiple use species, harvest of one part may affect productivity of another. For example, debarking of *Himatanthus* trees increases fruiting [77], but debarking of *Lannea* trees reduces fruiting [78]. As in the case of the baobab [79], where debarking does not affect fruiting, the vitality and reproduction of some species of NTFPs remain unchanged under harvest [80–83]. Gaoue et al. (2016) [72] prescribe an empirical 40% optimal harvest level, while sustainable harvest levels for some NTFP species have been estimated to be 50% of their leaves [84], 75% of their stems [85], and up to and 90% [69] of their fruits. In particular, fruit harvest has the highest sustainable threshold, ranging between 60% [86] and 92% [87].

3.2.2. Landscape Ecology

Although overexploitation is perceived as a major threat to NTFPs, they may also be at risk from landscape change, such as agricultural or urban expansion, habitat fragmentation, invasive species, fire, and grazing [71]. For example, long-term soil sedimentation may affect yield from WEF species regardless of harvest [88]. NTFPs are often extracted alongside logging for fuelwood and timber, and supplementary to agricultural production [15]. Newton (2008) [71] proposes that NTFP management must be adaptive to address situation-specific threats, failing which a combination of threats could form a feedback cycle of degradation. Examples of such combinations of threats include: Illegal logging and hunting alongside cardamom extraction [89], *Araucaria araucana* (Molina) K. Koch., a protected species threatened by grazing and fire [71], development and deforestation cycles alongside Brazil nut extraction [90,91], livestock and baboon consumption of baobab fruit [69], invasion by *Lantana* and mistletoe in *Phyllanthus* trees [92], forest fragmentation by roads and logging around wild nutmeg habitat [93], elephant trampling and herbivory [94], and fire and browsing livestock in areas of mountain date palm harvest [95]. Ravikanth et al. (2009) [96] speculate that harvesting may reduce the genetic diversity in some populations of NTFP species, and Horn et al. (2012) [97] highlight that lowered genetic stock from harvesting could exacerbate external threats such as those mentioned above. Studies in this review found that management and harvest of WEF species do not constrain genetic flow [98–100], but can render propagules (seeds) more vulnerable in harsh environmental conditions such as low humidity and high solar radiation [101,102].

3.2.3. Sustainability

As in the case of many wildlife resources, sustainable use of NTFPs has time and again been advocated as a strategy to conserve the resource base [103,104]. Although the review by Stanley et al. (2012) [105] concludes that the majority of case studies surmise that NTFP harvests are ecologically sustainable, commercialization of some NTFPs has raised and confirmed concerns [106–108] about the ecological and economic sustainability of NTFPs as a source of income and livelihood. In the attempt to make benefits from NTFPs a viable alternative to deforestation, extraction has, in some cases, assumed a commercial scale, such as the marula (*Sclerocarya birrea*) fruit [68], the Brazil nut (*Bertholletia excelsa* O. Berg.) [91], and the bush mango (*Irvingia gabonensis* Baill. ex Lanen.) [109]. When harvest is lethal to the individual (e.g., extraction of an entire plant, or its root, bushmeat), or market demand for products is high, production may turn intensive. Examples of WEF species domesticated or farmed in monoculture plantations include the cape gooseberry (*Physalis peruviana* L.) in Uganda [110], myrtle (*Myrtus communis* L.) to match demand from the Mediterranean liqueur industry [111], *Allanblackia* trees for their multiple use fruits in central Africa [112], and chiquitania almonds (*Dipteryx alata* Vog.) for their local value in Bolivia [113]. However, Newton (2008) [71] argues that cultivation of NTFPs creates a competing source of products that promotes forest conversion and contradicts the concept of NTFPs as an incentive for forest conservation. Further, certain species like the aguaje palm (*Mauritia flexulosa* L.), though in great demand, are difficult to cultivate *en masse* due to their preference for specific habitats, in this case, marshy lands [56].

On the other hand, nonlethal harvest may lead to reduced productivity or vitality [56,80,93,114], at times driving extraction to become more extensive, i.e., the area of harvest is increased [115]. Landscape level outcomes of NTFP extraction are often speculated, but seldom quantified [70,95,116]. Disturbance in forests may result in lower abundance, diversity, and vitality of plants [117,118] and animals [119,120]. Collection of WEFs may lead to altered light penetration in ecosystems as in the case of Brazil nuts [121], although Hitztaler and Bergen (2013) [122] also show that wild berry collection is more prevalent in degraded forest because light penetration is conducive to berry fruiting. It is hypothesized that collection of some NTFPs can potentially alter ecosystem dynamics by changing understory composition, community structure, and abiotic functions [95,123], but it is difficult and inadvisable to generalize across species and contexts until such time there is a far large meta-dataset. Muler et al. (2014) [70] found that besides changing the light regime, intensive harvesting of *Euterpe* palms also reduces plant species richness. Ruwanza and Shackleton (2017) [124] show that soil nutrients are reduced with increased biomass removal, with fruit harvest resulting in the least nutrient reduction.

Some species of NTFP respond favorably to disturbances such as harvesting [84], grazing [95], and fire [125]. In the case of WEFs, Brazil nut [126] and *Phyllanthus* spp. [127] have been observed to produce more fruits in response to harvest-related lopping. *Lophira lanceolata* Tiegh. trees recruit well in areas under human pressure and disturbance, through fruit abandoned during harvest [128]. However, despite the resilience of such species, they are often overexploited beyond recovery to optimal vitality, as illustrated by 14 of the 25 studies explicitly addressing harvest sustainability in our review.

3.3. Economics

3.3.1. Determinants and Drivers

NTFPs have long been debated as a source of income and a means of poverty alleviation [129–132]. It is argued that to remote rural communities, NTFPs provide a 'natural subsidy' on nutrition, healthcare, shelter, and energy [17,133], and a 'natural insurance' as a response to shock [134], reducing costs for aid that the government would normally be expected to incur. NTFP collection often features as a prominent household income contributor in a suite of diversified seasonal livelihood strategies [4,57]. Dependence on NTFPs has been labelled by some as a 'poverty trap' [18,106], implying that for the poorest users, NTFPs provide subsistence functions of shelter, fuel, and food in times of shortage, while wealthier users benefit from diet enrichment from bushmeat and cash income from high value products. However, more recent literature [115,135] finds no consistent relationship between poverty and NTFP use, and that evidence in support of NTFP poverty traps is scarce [132]. Although benefits of WEFs may accrue with wealthier households [6,136], they are an important source of food and nutritional diversity for remote households [9,91], and during times of food shortage due to drought [137], winter [138], and war [62].

Determinants of NTFP use and trade are usually studied as a function of the household socioeconomic circumstances. For example, poverty level, food security, female labor, household size, education level, ethnicity, and accessibility (road density and proximity) have been variously linked to the prevalence of NTFP trade in different settings [12,18,63,122,139,140]. However, landscape-level drivers of the use and trade of harvested NTFPs, specifically WEFs, are seldom addressed. As broader examples, Newton et al. (2012) [141] demonstrated that the type of forest Amazonian communities are situated in influences their livelihood strategies and the extent of their use of NTFPs, and Weyer et al. (2017) [142] found that natural shocks such as drought and crop failure prompted households to take up NTFP trade as a livelihood in southern Africa. In a more specific context, Cunningham and Shackleton (2004) [28] indicate that rainfall gradient and human-induced dispersal and survival may be linked to WEF use in South Africa, and Fentahun and Hager (2010) [143] found that land shortage, altitude, and slope influenced uptake of WEF integrated into agroforestry landscapes. An understanding of the drivers behind WEF use and trade is likely to aid the formulation of better policy, incentives, and standards for sustainable use and trade.

3.3.2. Trade and Supply Chains

On an average, more than half of the NTFPs harvested (67% plants, 53% bushmeat) in central Africa are traded [5]. About a quarter of the NTFPs collected in eastern Europe and Russia are WEFs, and more than half the harvest is traded for cash [144]. Yet, only 12 studies were found to discuss the economics of WEF trade. Trade in NTFPs can be difficult to quantify, partly due to the often informal nature of transactions [56,145,146]. For example, up to 30% of the harvest of WEFs is exchanged as barter or cultural gifts in Cameroon [5]. Even in cases where NTFP trade is an important contributor to household income, price setting may be uninformed by market dynamics or formal values [147]. Turtiainen and Nuutinen (2012) [148] found that official data for trade in WEFs in European nations is either lacking or inconsistent. Trade in NTFPs is profitable when the formal market value of products is significantly higher than their direct use value. For example, the baobab fruit can be sold at four times its domestic use value [63], and the fruit of *Phytelephas* palms can earn up to 600 times its local market value on the international market [56].

Analysis of NTFP value chains consistently brings up issues of revenue capture by intermediaries, lack of networking and connectivity between stakeholders, gaps in information on sustainable practices, product processing and market value, and shortage of capital [106,135,149–154]. At times, firms with legal permission to harvest overexploit NTFP resources and labor illegally to maximize profits [151], and at others, state control over value chains leads to mismanagement and misappropriation of rights and funds [155]. In cases where NTFP yield is inconsistent or perishable and production costs are dynamic, market prices may not succeed in capturing profit [56,81,109,149,151,156]. One of the two WEF value chains found in this review was the Shea butter (*Vitellaria paradoxa* C. F. Gaertn.) value chain. Jasaw et al. (2015) [157] describe the material used in the value addition processing, while Pouliot (2013) [158] explores the role of women in the chain. Avocèvou-Ayisso et al. (2009) [82] find that the formation of producer cooperatives and fewer intermediaries has improved benefit penetration. This finding is consistent with those from other successful NTFP supply chains supported by institutions that enable investment and improved marketing and profit distribution [57,159–161]. The other value chain was that of the bush mango (*Irvingia gabonensis*) in Cameroon, where Ofundem et al. (2017) [109] report that the sustained demand and organised local as well as cross-border trade has led to farming of the species.

3.3.3. Policy

Access to NTFPs is an important determinant of NTFP use, and their contribution to the household economy and food security [13,62]. Some speculate that open access renders NTFPs vulnerable to overexploitation and less commercially viable due to dissipation of profits [9,18], while secure land tenure has been linked to sustainable use and trade of some NTFPs [162–165]. Devolved management rights usually foster sustainable practices [155,165–167], as well as improved synergy and interinstitutional collaboration [141,168]. Dedicated stewardship and secure access of resources encourages users to consider long-term impacts and investments in sustainability [73,127]. Further, traditional ownership and management regimes have sustained extraction of some NTFPs over decades in biodiverse landscapes [15,146,169,170]. Although riddled with gray areas over tenure and access, NTFP collection is increasingly observed in urban landscapes [171–173]. Land use planning in both rural and urban areas needs to take into account NTFP collection as an active land use contributing to provisioning [172,174] and cultural [15,175,176] services, and consider local land tenure allocation.

Institutional failure to regulate use and trade of NTFPs is manifested in corrupt politics in resource allocation and lack of monitoring [151,155,177,178]. In some countries, the national legislation leaves harvesters with no option but to trade through intermediaries, either due to logistic reasons [160] or legal requirements [152]. In one of the only two studies found to engage primarily with governance and policy related to wild edible fruits, Ball and Brancalion (2016) [179] corroborate these drawbacks. In the other study, Foundjem-Tita et al. (2014) [180] find that lack of awareness and aversion to enforcement amongst stakeholders hinder policies promoting uptake of indigenous fruit trees in agroforestry. Lack of knowledge communication can also result in the over- or underutilization of wild edible plants [9,181] and NTFPs [182]. The application of traditional ecological knowledge is often linked to sustainable harvest [81,84,98,100,122,146], although relatively few studies [54,79,183] assess or quantify this relationship. Failure to recognize and communicate this knowledge can result in misappropriation of benefits from commercialization of wild medicinal plants [184,185], and teas [186]. Rist et al. (2016) [187] advocate improvements in knowledge sharing between harvesting communities, land managers, and scientists and researchers in order to attain sustainable social, economic, and ecological outcomes.

3.4. Conservation

3.4.1. Harvest Practices

In the literature reviewed, 30 articles described and critiqued mechanisms used to conserve NTFPs, but only 16 of these were related specifically to WEFs. With respect to species, domestication is an oft-recommended and discussed option for commercial production of NTFPs, especially WEFs, but it is not considered in this review (Section 1). The reproductive strategies of a species and its response to disturbance and extraction (Section 3.2.1) need careful consideration in designing sustainable harvest practices and regimes. In some cases, chemical indices can be developed to determine optimal fruit harvest conditions for a species [188]. In others, sustainability can be ensured by slightly modifying existing harvest practices [189–191] to minimize damage to the plant. However, many favor short-term profits over long-term benefits [73], and may be averse to investing in acquiring capacity and infrastructure for sustainable harvesting practices [127]. Recent years have seen development of products from fruits of South American palms in an effort to curb leaf harvest by felling, but destructive practices continue to be used for fruit harvest in some regions [56,190,192–194]. WEF species that share habitats with other charismatic species may benefit mutually, as well as serve to protect their habitats, by promoting uptake of sustainable use practices leveraged by conservation incentives (see also Section 3.4.2). Examples of such species include *Schisandra* berries and giant pandas [195], *Garcinia* fruits and lion-tailed macaques [196], *Theobroma cacao* and gorillas [197], and *Terminalia* fruits and hornbills [198].

3.4.2. Management Strategies

As concerns the broader landscape, interactions between harvested species and their ecosystem, as well as land uses co-occurring in the extraction landscape (Section 3.2.2), influence the magnitude of the socioecological impacts of harvesting. Co-management strategies, such as community-based conservation/natural resource management (CBC/NRM) and community/joint forest management (C/JFM), commonly involve NTFPs as an incentive for conservation. Co-management regimes can improve household food security [16] and increase income [199] from NTFPs, bring about voluntary cessation of unsustainable NTFP harvest [200], and integrate sociocultural connotations to promote sustainable NTFP harvest [201]. Social monitoring of NTFP resources is recommended as a conservation strategy by Ortega-Martinez and Martinez-Pena (2008) [202] and Pacheco-Cobos et al. (2015) [203] in their studies on involving harvesters in inventorying and monitoring forest mushroom diversity. Community engagement in forest restoration and NTFP management can evoke a sense of empowerment and stewardship [165]. However, these mechanisms may also be ridden with corruption in resource allocation [204] and could fail to reduce deforestation [108,199]. With reference to WEFs, three studies found in this review focused on effects of co-management on NTFPs (including WEFs) in the Brazilian Amazon. Guariguata et al. (2008) [169] find that logging regulations overriding traditional management of Brazil nut harvests can render co-management ineffective. However, Menton et al. (2009) [170] show that communities involved in co-management contracts had higher income and lower fruit harvests than those not involved, and Shanley et al. (2012) [146] find that logging reduces access to NTFPs. Agroforestry is found to be a particularly effective conservation strategy, especially in the case of WEFs [180,205,206], diversifying farmer income and augmenting food security and economic benefits.

3.4.3. Ecosystem Services

From a landscape perspective, use of NTFPs has been proposed to incentivize conservation of forests [207], in turn fostering ecosystem services and climate change resilience [3,90,208], as well as strengthening food security [209,210]. Enrichment planting of WEFs has been proposed as an effective means of restoring degraded forests [128,211]. WEF species, such as *Berchemia discolor* [39] and *Ziziphus spina-christi* L. Willd. [38], have been recommended for agroforestry and restoration due to their adaptation to hot dry conditions and resilience to climate extremes. Silvicultural management has the potential to foster diversification in the plantation understory using mushroom and berry species [212–214]. Haglund et al. (2011) [205] report increased household income and indigenous fruit tree species diversity and density from agroecological landscapes using WEF species in restoration. Birch et al. (2010) [215] found that ecosystem services from NTFPs consistently increased the cost-effectiveness of landscape restoration (compared to ecosystem services from land use for timber, pasture, and tourism). As an example from a WEF-specific study, Brazil nut (*Bertholletia excelsa*) stands in relatively disturbed forests show greater intact ecosystem functions, such as pollination and interactions with wildlife, buffers between logging areas [121]. Explicit quantification of the ecosystem services associated with NTFPs and specifically WEFs can help formulate conservation policy and incentives for more beneficial, efficient, and wider reaching outcomes.

3.4.4. Economic Incentives for Conservation

Economic incentives have been used to influence people's behavior toward conservation of biodiversity resources. Examples of direct incentives include payment for ecosystem services (PES) schemes, such as the reducing emissions from deforestation and forest degradation (REDD+) [216] and trade of natural resources (such as NTFPs and game meat) and their non-use values (e.g., ecotourism, carbon offsets). Schemes like REDD+ can augment household food security and income [199], albeit as long-term benefits [16], but may not reduce forest dependency or deforestation [108]. Further, the implementation of programs such as REDD+ are found to be problematic, partly due to perceived imposition of 'western' ideals and their inability to target high-risk areas due to their comparatively weak incentives [217,218]. The literature on payments specific to WEF use is scarce and is restricted to mushroom harvest [219,220]. Newton (2008) [71] notes that local trade alone as an economic incentive for NTFP conservation may not be sufficiently large to address complex threats (Section 3.2). Certification is another form of direct incentivization promoting sustainable harvest practices and fair and ethical trade [221]. Certification can improve socioeconomic conditions for harvesters and forest communities [222] and can aid monitoring of forests and their ecosystem services [223], but it is also associated with high investments and problematic economies of scale [224,225]. Usually, NTFP value chains are certified by standards developed for agriculture, forestry, product quality, and trade [224] and FairWild is a relatively new certification developed specifically for NTFP value chains [226]. Although ecological outcomes of plantation and agroforest certification are emerging [227,228], the literature on NTFP certification is sparse.

4. Discussion

Although WEFs are a widely distributed and used subset of NTFPs and wild edible plants, they display remarkable multifunctionality (Section 3.1), be it the fruit itself, other plant parts, or as part of their landscape-level ecosystems (Section 3.2, Section 3.4.3). Although NTFPs, in general, have been studied in relation to livelihoods, markets, and policy, there is less information specific to WEFs (Section 3). We suggest that a focus on WEFs is necessary due to (1) their versatility and ubiquity even in the absence of forests [94,99], (2) co-occurrence with various other land uses [25,52,84,121,127,146], (3) their significant contribution to nutrition, income, health, and culture of rural and urban peoples around the globe, and (4) their importance as a food source for many frugivorous species, including insects, birds, reptiles, and mammals, some of which are obligate frugivores [123,229]. We make specific recommendations for research and policy, and emphasize the role of communication between research, policy, and WEF users for effective management of WEF resources and associated ecosystems as well as livelihoods.

4.1. Avenues for Research

With respect to species ecology, development and dissemination of methods to optimize sustainable WEF harvest [72,188] is a priority. Suitable conditions and quantities of harvest vary by species and context, and therefore, it is important to identify the diversity and extent of used WEF species and the context they are used in (such as shock, subsistence, trade, etc.). Species-landscape interactions also influence the quantity and sustainability of WEF harvest [69,124]. As an example, the relationship between WEFs and frugivores remains understudied for most WEF species [86,230], despite frugivores being important seed dispersers [231] and sometimes also providing bushmeat [123,146]. Research should be undertaken to ascertain how WEF harvesting interacts with ecosystem composition, functions, and flows to determine species and landscape resilience and responses to WEF extraction. Further, NTFP and WEF extraction are usually part of larger, often diverse bundles of ecosystem services [25,39,215,216,223]. These bundles and services need to be explicitly defined to inform and facilitate planning and management decisions, and to incentivize conservation. Stakeholder consultations [180,232] and valuation [233] are some means through which research could achieve this. WEFs are of relevance to a number of domains in addition to agroecology and ethnobotany (Figure 1), and the human dimensions of WEF use need to be further integrated with ecological knowledge to ensure their perpetuity.

As regards determinants and drivers of WEF use and trade, both household and landscape level trends need to be identified. Access to NTFPs and WEFs changes across different land uses [91,146,147], and implicitly, with tenure. Although tenure is recognized as an important foundation for sustainable extraction in many settings [162–167], there is little evidence testing this hypothesis. A comparison between protected areas, communal lands, and private properties (both rural and urban) is likely to yield valuable insights on the socioecological outcomes of NTFP and WEF harvest under varying degrees of secure access. Access to WEFs may also be influenced by ecosystem characteristics, such as biodiversity, rainfall, soil, and temperature [28,143,234], but articles in our review found limited evidence. This reiterates the need for generation and dissemination of knowledge (Section 3.2.3) of WEFs and other wild edible plants to encourage food security through sustainable use [79,181,183,187]. Such knowledge is key to identifying target areas and species for commercialization, as well as conservation, and informing resource governance and policy [61]. Lastly, research can aid development of innovative value-added products [193,194], supply chains [196,198], and optimal production systems to promote sustainable use and trade of WEFs. In terms of production systems, there is much literature on the benefits of agroforestry, but too often it involves introduced tree species. A greater integration of multifunctional, indigenous WEFs into agricultural and residential spaces offers numerous social, ecological, and economic benefits [235]. However, the nonuse values of WEFs should not be neglected, such as their contributions to local cultures, traditions, products, and ceremonies, which need to be respected by planners and development agencies whose primary focus is usually on economics, incomes and value chains.

4.2. Recommendations for Policy

For ecological sustainability, policy related to WEF resource use has to be informed by research on species ecology, determinants of use and trade, and sustainable harvest practices, while research on landscape ecology and ecosystem services can inform sustainable management strategies. Including NTFP and WEF users in stakeholder assessments [236] of prospects and risks associated with land use policy and change can guide sustainable harvest, and in some cases, help achieve multiple conservation objectives [193,198]. On a larger scale, land use planning should consider local traditional knowledge and governance in decision and policy making. Recognizing that natural resource users are often involved in landscape and resource stewardship [15,165,217] will help policies and institutions to achieve synergized devolved governance [161,198]. Urban green spaces are crucial intersections of tenure and food security [171,173,237], making it a priority for urban planning to incorporate WEFs and wild edible plants in policies on green space management and urban foraging.

Ecological considerations and tenure safeguards can bolster sustainable use of WEFs. However, economic instruments are needed to reduce the risks of benefit capture, over-extraction, and undervaluation associated with WEF trade (Section 3.3.2). Product diversification and infrastructure such as machinery are key to ensuring supply chain resilience and efficiency [40,193,238]. Further, supply chains can be strengthened through capacity building of personnel in terms of sustainable harvest practices, use of efficient infrastructure, and market price determination [40,109,198]. The integrity and transparency of supply chains can be enhanced by certification of practices and processes [224,226]. Economic incentives such as subsidies, premiums, and performance payments can be employed by governments and policymakers to encourage sustainable use and trade of WEFs [216]. The quanta of these incentives can be based on research on determinants (Section 3.3.1) and ecosystem services (Section 3.4.3).

5. Conclusions

The literature on WEFs is dominated by ethnobotanical and taxonomic descriptions and studies on species level ecology. Different WEF species respond differently to harvesting, as well as other environmental pressures, such as fire and herbivory. Many WEF species occur in landscapes ranging from forests to highly disturbed ecosystems, and sometimes support pollinators, seed dispersers, and other keystone species. Although fruit removal may potentially yield optimal product with minimal damage, poor harvest practices and lack of knowledge can result in unsustainable offtake.

The motivations behind WEF use and trade remain unclear, and the literature highlights the need for more information on WEF supply chains and for more transparent policies that account for traditional tenure and management practices that emphasize sustainable resource use. WEF species are ideal candidates around which landscape conservation and management incentives could be designed. WEF species are versatile, resilient, and often highly productive, offering a promising prospect for climate change adaptation, ecosystem restoration, and food security.

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