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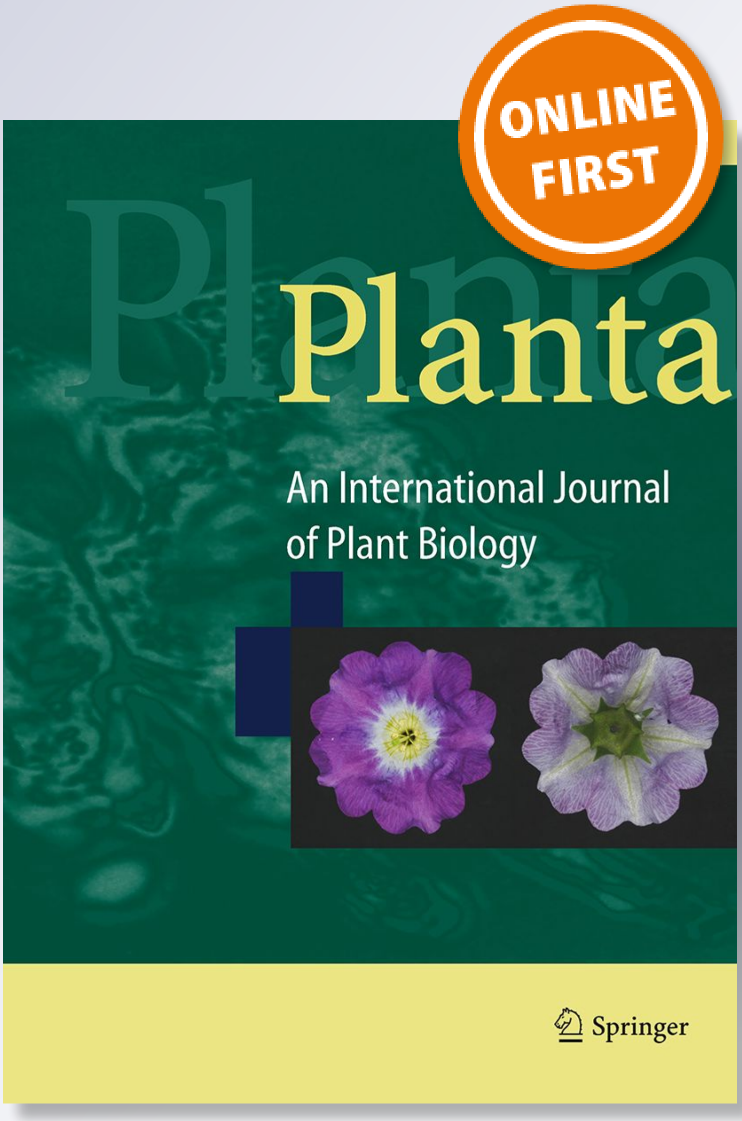

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REVIEW

From ethnobotany to mainstream agriculture: socially modified Cinderella species capturing 'trade-ons' for 'land maxing'

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Abstract

Main conclusion **Over the last 25 years, the process of domesticating culturally-important, highly-nutritious, indigenous food-tree species. Integrating these over-looked 'Cinderella' species into conventional farming systems as new crops is playing a critical role in raising the productivity of staple food crops and improving the livelihoods of poor smallholder farmers. This experience has important policy implications for the sustainability of tropical/sub-tropical agriculture, the rural economy and the global environment.**

A participatory domestication process has been implemented in local communities using appropriate horticultural technologies to characterize genetic variation in non-timber forest products and produce putative cultivars by the vegetative propagation of elite trees in rural resource centers. When integrated into mainstream agriculture, these new crops diversify farmers' fields and generate income. Together, these outcomes address land degradation and social deprivation—two of the main constraints to staple food production—through beneficial effects on soil fertility, agroecosystem functions, community livelihoods, local trade and employment. Thus, the cultivation of these 'socially modified crops' offers a new strategy for the sustainable intensification of tropical agriculture based on the maximization of total factor productivity with minimal environmental and social trade-offs.

Keywords Agroforestry tree products · Domestication · Multifunctional agriculture · Socially modified crops · Trade-offs · Vegetative propagation

Introduction

There is nothing unusual about the progression of locally useful wild plants into cultivation. Most, if not all, crop domestication has originated from ethnobotanic knowledge. However, this flow seems to have been stagnated by the green revolution which focussed on a small number of staple food crops (Tribe 1994), while a few others are cultivated as cash crops. Overall, the number of widely used crop species is only 0.5% of the thousands of potentially useful wild plants with edible products (Leakey and Tomich 1999). Consequently, food species generally fall into four categories: (i) internationally important and widely cultivated staple foods for the provision of calories; (ii) widely cultivated cash crops like tea, coffee and cocoa for beverages and citrus, apples, etc. for fresh fruits; (iii) locally domesticated and cultivated species or 'orphan crops' which have wider potential; and (iv) a wide range of culturally important species, little known outside their natural range, whose products have traditionally been gathered from wild plants. Those in this fourth category, many of them trees, have been called 'Cinderella' species as they have been overlooked by science (Leakey and Newton 1994a; Leakey 1999a). In the 1980s, the idea was proposed that deforestation could be addressed by promoting the use and cultivation of these Cinderella species (Leakey et al. 1982). This idea rapidly gathered momentum triggered by a conference in 1992 (Leakey and Newton 1994b) and its uptake by ICRAF as a "farmer-driven" and "market-led" tree domestication program (Leakey and Simons 1998) to meet the needs of millions of potential stakeholders—typically smallholder farmers on the brink of subsistence (Franzel et al. 1996, 2008). The current African orphan crops consortium (AOCC) has included many Cinderella species in

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its program, despite the fact that typically they are not yet crops, and that including them in OACC is very unlikely to deliver the social and economic benefits flowing from their 'social modification', as described in this review.

While the species in the first three categories have made the transition from ethnobotany to agriculture hundreds if not 1000 of years ago, it is the Cinderella species that are currently making that step into cultivation following recent research to determine their potential as new crops (Leakey 2012a, 2017a). Over the second and third decades of this process, this research has increased in the number of candidate species, their geographic distribution and in the range of research topics being investigated (Leakey et al. 2012; Leakey 2017c). Now well over 50 of these locally important wild species basically known only to local people are being domesticated for agroforestry systems as a source of vitamins, minerals, amino and fatty acids, protein, fiber, etc. to combat malnutrition (Table 1). They are also traditionally important in local culture and are locally traded as an important source of much-needed local income (Leakey et al. 2012). In parallel with these developments, there has been an increase in the number of ethnobotanical surveys seeking candidate species for domestication (e.g., Goenster et al. 2011; Fandohan et al. 2017; Leßmeister et al. 2018; Jeruto et al. 2010; Iponga et al. 2018; Roshetko et al. 2017; Shomkegh et al. 2013) and an increase in analytical studies to add scientific data to ethnobotanic knowledge to identify traits of value and importance (e.g.; Tauchen et al. 2016; Ngadze et al. 2017; Fapohunda et al. 2017; Yirankinyuki et al. 2018; Aguiar et al. 2018; Bassey et al. 2018; Bai et al. 2018; Mohamed et al. 2018).

Domestication of Cinderella species

The domestication process for Cinderella trees was initially hindered by a serious lack of information about the genetic diversity of these species, although this was offset by the strong traditional knowledge of local people regarding those with desirable characteristics important for local livelihoods (Schreckenberg et al. 2006; Degrande et al. 2006; Jamnadass et al. 2011). Products from the best trees have typically been gathered for home consumption and/or local marketing, while those of the least desirable trees have been rejected and the trees sometimes felled to make space for other crops. This local knowledge provides farmers with essential information regarding the trees with potential for domestication. The desirability of these trees is easily verified by simple measurements of tree-to-tree variation (Atangana et al. 2001, 2002; Anegbeh et al. 2003, 2005; Waruhiu et al. 2004). This research has led to the development of a domestication strategy based on the combination of a decentralized, farmer-driven approach supplemented by research implemented in wild populations of candidate species and market studies (Simons and Leakey 2004; Leakey and Page 2006; Leakey 2012b). In this way, the domestication process aims to meet the many needs of subsistence farmers through the consumption and marketing of a wide range of tree products across a diverse range of agricultural environments (Simons and Leakey 2004).

Genetic characterization

Field studies initially used a simple analysis of tree-to-tree variation in a wide range of morphological traits (Leakey et al. 2000) and this led to the recognition that the intraspecific variation within a single village population of trees typically ranges from three- to tenfold (Leakey 2012a). Furthermore, it was found that this variation was recognized in local informal retail markets, but not by local wholesalers who traded bulk samples from many trees (Leakey et al. 2002). It also became clear that there was continuous variation in any given trait contrary to earlier suggestions that there were recognizable "varieties" in these wild populations (Okafor 1983). This continuous variation is not an unexpected finding as it is a typical outcome following the random mating between outbreeding individuals. Many desirable traits were also found to be uncorrelated. These findings indicate a great opportunity for tree domestication based on the selection of those with rare combinations of superior traits. Such traits can be captured clonally as a putative 'cultivar' by vegetative propagation. This has opened doors to the development of new crops with substantial superiority well above the average of a wild population. Later, these field studies were supplemented by laboratory studies investigating both the nature and yield of ingredients and their genetic structure (Leakey et al. 2012). A "take-home" message from this research has been that the mean value for out-breeding species like trees conceals very important information about the range of variation available for use in domestication. Thus, it is clear that studies aimed at identifying the potential for domestication should evaluate the tree-to-tree intraspecific variation.

These studies with Cinderella species (Table 1) have typically involved the characterization of many desirable traits—e.g., fruit size, skin color, flavor, etc. and have found that some desirable traits are closely related, while others are not. This is especially important regarding chemical traits like nutritional or medicinal value; or traits of importance in industrial processing. Indeed, the magnitude of all these intraspecific variations in the fruits, nuts and other products of these species has illustrated the opportunity to identify specific multi-trait combinations. Based on this research, there is clear potential to capture ideal trait combinations—or 'ideotypes'—for different end-products or markets (Leakey and Page 2006). These ideotypes typically combine traits, such as high harvest index and high quality, that are only seldom found together. Furthermore, many different ideotypes can be identified even within a single species;

Table 1 Some of the Cinderella species being domesticated as new crops producing food and non-food products (excluding timber trees) for diversified mixed cropping

Species	Locations	Some citations
Adansonia digitata	Malawi, Benin, Mali, Burkina Faso, Sudan, Kenya	Soloviev et al. (2004), Assogbadjo et al. (2005, 2006, 2009), de Smedt et al. (2011), Cuni Sanchez et al. (2011), Simbo et al. (2013), Muthai et al. (2017), Gurashi et al. (2017), Anjarwalla et al. (2017)
Aegle marmelos	Bangladesh	Kabir et al. (2018)
Allanblackia floribunda, Allanblackia parviflora, Allanblackia stuhmannii,	Ghana, Tanzania, Cameroon	Ofori et al. (2008), Peprah et al. (2009), Jamnadass et al. (2010), Atangana et al. (2011), Asaah et al. (2011b), Tsobeng et al. (2016, 2017, 2018)
Annona cherimoya	Equador, Bolivia, Peru	Vanhove and van Damme (2013)
Argania spinosa	Morocco	Bani-Aameur et al. (2001), Benbya et al. (2018)
Artocarpus altilis	Hawaii	Ragone (1997)
Bactris gasipaes	Brazil	Clement (1988), Adin et al. (2004), Cornelius et al. (2010)
Balanites aegyptiaca	Niger, Mali	Soloviev et al. (2004), Sotelo Montes and Weber (2009), Weber et al. (2008), Abasse et al. (2011), Weber and Sotelo Montes (2010)
Barringtonia procera	Solomon Islands	Pauku (2005), Pauku et al. (2010)
Baillonella toxisperma,	Cameroon	Fungo et al. (2015)
Calocophyllum spruceanum	Peru	Weber et al. (2001), Sotelo Montes et al. (2006, 2008), Weber et al. (2009), Cornelius et al. (2018), Weber and Sotelo Montes (2005)
Canarium indicum	Papua New Guinea	Nevenimo et al. (2008), Leakey et al. (2008)
Carapa procera	Burkina Faso	Lankoande et al. (2015)
Chrysophyllum caimito	Panama	Parker et al. (2010)
Cola acuminata	Benin	Egbe Enow et al. (2013), Dah-Nouvlessounon et al. (2016)
Cola nitida	Benin	Dah-Nouvlessounon et al. (2016), Savi et al. (2018)
Cola anomala	Cameroon	Kanmegne et al. (2017)
Cornus mas	Iran	Alijanpour (2017)
Cyclopia subternata	South Africa	Mabizela et al. (2017)
Dacryodes edulis	Cameroon, Nigeria, Congo	Okafor (1983), Silou et al. (2002), Kengni et al. (2001), Tchoundjeu et al. (2002b), Kengue et al. (2002), Waruhiu et al. (2004), Anegbeh et al. (2005), Asaah et al. (2010, 2012), Mialoundama et al. (2002), Agwu et al. (2017), Dossou et al. (2018)
Detarium microcarpum	Sahel	Agbo et al. (2018)
Dyera polyphylla	Indonesia	Tata et al. (2016)
Garcinia kola	Cameroon, Benin	Dosunmu and Johnson (1995), Ayuk et al. (1999), Dah-Nouvlessounon et al. (2016)
Gnetum africanum, Gnetum buchholzianum	Cameroon, Congo, Gabon	Shiembo et al. (1996b), Ndam et al. (2001), Biye et al. (2017), Doungous et al. (2018)
Guazuma crinita	Peru	Weber et al. (2008, 2011), Cornelius et al. (2018), Weber and Sotelo Montes (2008)
Inocarpus fagifer	Solomon Islands	Pauku (2005)
Irvingia gabonensis	Cameroon, Nigeria, Benin	Shiembo et al. (1996a), Tchoundjeu et al. (1998, 2010b), Atangana et al. (2001, 2002), Anegbeh et al. (2003), Leakey et al. (2005d), Padonou et al. (2017), Fasogbon et al. (2017), Kengni et al. (2017)
Irvingia wombolu	Cameroon, Benin, Nigeria	Asaah et al. (2003), Dolor et al. (2009)
Pausinystalia johimbe	Cameroon	Ngo Mpeck et al. (2003a), Tchoundjeu et al. (1996)
Pentaclethra macrophylla	Cameroon	Tsobeng et al. (2015), Fungo et al. (2015)
Pourouma cecropiifolia	Amazonia	Pedrosa et al. (2018)
Prosopis africana	Sahel	Tchoundjeu et al. (1996), Weber et al. (2008), Sotelo Montes and Weber (2009), Sotelo Montes et al. (2011)
Prunus africana	Cameroon, Kenya	Muchugi et al. (2006), Tchoundjeu et al. (2002a)

Table 1 (continued)

Species	Locations	Some citations
Pseudospondias microcarpa	Gabon	Ndoutoumou et al. (2013)
Ricinodendron heudelotii	Cameroon	Shiembo et al. (1997), Ngo Mpeck et al. (2003b)
Santalum austrocaledonica, Santalum lanceolata	Vanuatu, Australia	Page et al. (2010a, b), Tate and Page (2018)
Sclerocarya birrea	South Africa, Namibia, Botswana, Kenya, Burkina Faso	Holtzhausen et al. (1990), Thiong'o et al. (2002), Shackleton et al. (2003), Shackleton and Shackleton (2005), Leakey et al. (2005b, c), Leakey (2005), Bationo-Kando et al. (2016)
Strychnos cocculoides	Zambia	Mkonda et al. (2003)
Tamarindus indica	Sahel	Soloviev et al. (2004), Fandohan et al. (2011), van den Bilcke et al. (2014)
Uapaca kirkiana	Malawi, Zambia	Mwamba (1995), Ngulube et al. (1995), Akinnifesi et al. (2004, 2009), Kadzere et al. (2006), Mwase et al. (2006a, b), Mng'omba et al. (2007, 2015), Mwang'ingo and Lulandala (2011)
Vitellaria paradoxa	Benin	Maranz and Wiesman (2003), Sanou et al. (2006), Diarrasouba et al. (2007), Aleza et al. (2018)
Vitex payos	Kenya	Kimondo et al. (2012)
Warburgia ugandenssis	Kenya, Uganda	Muchugi et al. (2008), Ochieng et al. (2013)
Ziziphus mauritiana	Sahel	Kalinganire et al. (2012)

each for a different product. For example, fresh fruit and nut/kernel ideotypes have been identified in *Irvingia gabonensis* (Atangana et al. 2002); while in *Sclerocarya birrea,* a range of different kernel ideotypes (Leakey 2005; Leakey and Page 2006) can be identified for edible oils, as well as oils for cosmetic products or medicinals. These ideotypes, thus, form a hierarchy creating new value chains for a range of markets or industries even within a single species (Leakey and Page 2006). Building on this ideotype approach, we can, therefore, see that it is possible to create cultivars that are as different as the breeds of dogs derived from the wolf (von Holdt et al. 2012; Leakey 2017d). Furthermore, the geographically decentralized participatory approach to this domestication means that the risks of seriously narrowing the genetic base of the species are minimized (Leakey and Akinnifesi 2008).

One unexpected outcome of the above characterization studies of morphological variation in Cinderella species has been the ability to use the frequency distribution of tree-to-tree variation in different traits to assess their domestication status in farmers' fields (Leakey et al. 2004). This has shown that by selecting the best trees, farmers have initiated the slow process of tree breeding in ways that improve the progeny—in *D. edulis*, *I. gabonensis* and *S. birrea* (Leakey et al. 2005b; Leakey et al. 2005c; Leakey 2005), *Tamarindus indica* (van den Bilcke et al. 2014), *B. procera* (Pauku 2005) and *C. caimito* (Parker et al. 2010). This emphasizes the previously unrecognized local importance of these species in peoples' livelihoods, and hence the potential for their greater role in agricultural systems.

Over the last 25 years, agroforestry tree domestication programs like that started in Cameroon have been initiated in many countries (Table 1; Leakey et al. 2012) and so, a new wave of crop domestication for the diversification of farming systems with selected putative cultivars of agroforestry trees has begun (Leakey 2010; Leakey and Asaah 2013). It is also being realized in some industrial countries that many of these species have nutritional and medicinal properties of importance in industrialized countries; as well as potential uses in the cosmetics and perfume industries (Leakey 2012a; Leakey and van Damme 2014).

In addition to the morphological and biochemical traits discussed above, trees vary in growth, yield and other physiological and ecological traits. These are typically the result of multiple gene interactions, often affected by the environment. This makes it difficult to accurately select individual trees with rapid growth or high yield for cultivar development; at least in the first phase of domestication. To capture desirable 'genotype x environment' interactions, it is generally better to establish growth and yield trials of putative cultivars already selected for the qualitative traits and to test them at a range of specific sites. Interestingly, variation in seasonal phenology can also be captured by vegetative propagation (Leakey 2012a). However, to effectively combine phenology with desirable morphological and quality traits, it may be necessary to undertake a breeding program between cultivars as a second phase of domestication. Cultivars formed in this way should allow producers to take advantage of higher prices of out-of-season fruits. In *D. edulis,* the market price for out-of-season fruits can be up to tenfold greater that fruits marketed in main season.

Modern molecular techniques have also been used to characterize and explain the genetic variation in several Cinderella species (Leakey et al. 2012; Jamnadass et al. 2009). One important outcome of this approach has been the finding that in *Barringtonia procera,* around 80% of the genetic variation is found at the village level (Pauku et al. 2010). This confirms the importance of the village level tree-to-tree morphological variation found in many species, for example *Adansonia digitata* (de Smedt et al. 2011) and *Sclerocarya birrea* (Leakey et al. 2005b; Leakey et al. 2005c; Leakey 2005), and consequently illustrates the strategic benefit of implementing numerous decentralized village-level domestication programs as a means to minimize the risk of narrowing the genetic base of a cultivated species.

Vegetative propagation

Vegetative propagation is the most efficient and rapid technique to harness and create new crops, especially in long-lived, out-breeding species like trees with large amounts of intraspecific variation (Leakey and Akinnifesi 2008). Thus, individuals with superior traits can be cloned as putative 'cultivars' and so replicated in large numbers as exact copies of the selected tree (Leakey 2014c). In remote rural communities, this can be done using single-node leafy cuttings set in a simple, low-technology, non-mist propagator that does not require piped water or electricity (Leakey et al. 1990). Made from simple locally available materials, the propagators have many practical advantages and are now found across the globe—from Africa, the Amazon, the high Andes, Central America, Southeast Asia, Far East and Oceania as well as Australia, Europe, and the United States.

Following some 20–25 years of vegetative propagation research, it has been possible to identify key principles for the successful and long-term rooting of stem cuttings from managed stockplants (Leakey 2014c). These principles have now been successfully used to propagate many species that have not been previously propagated vegetatively (e.g., Tsobeng et al. 2017, 2018); as well as to resolve the problems of rooting leafy cuttings from sexually mature trees (Dick and Leakey 2006). This allows the capture of traits associated with the sexually mature tree crown. This is important for the creation of fruit and nut cultivars that are productive without the long (typically 5–15 years) unproductive juvenile phase associated with sexual reproduction. The clonal approach also avoids the inherent intraspecific heterogeneity found in the progeny of outbreeding species arising from the segregation of parental genes during meiosis. This intraspecific diversity is the reason that the genetic gains achieved by tree breeding are both slow and small.

Intellectual property rights

To minimize the risk of unscrupulous entrepreneurs undermining the achievements of small-scale tropical farmers producing new tree crops by participatory domestication, there is an urgent need to develop appropriate Intellectual Property instruments. In the short term, Lombard and Leakey (2010) have offered some informal interim steps, but a more formal global solution is required. To this end, Santilli (2015) has examined the current situation and concluded that none of the existing instruments meets the needs of smallholder farmers. She has then proposed the development of new international protocols to ensure that farmers get protection for their innovations.

Biotechnology

Some Cinderella species have been included with Orphan Crops in genomic studies as part of the Africa orphan crops consortium (AOCC). While these upstream, cutting-edge studies will raise the profile of these Cinderella species, it seems unlikely that this research will deliver rapid benefits in the lives of poor subsistence farmers still without access to the key Green Revolution technologies—inorganic fertilizers, pesticides and mechanization—on account of their poverty. This contrasts with the very rapid impacts flowing from the participatory domestication of Cinderella species as 'socially modified crops' which are already transforming the lives of participating farmers, as explained below (Sect. 5).

Implementation of participatory domestication

To facilitate the dissemination and up-scaling of the participatory domestication of agroforestry trees, a decentralized, bottom–up community approach has been utilized. It is called "participatory domestication" (Leakey 2012a; Leakey 2014a; Tchoundjeu et al. 2010a; Asaah et al. 2011a, b) and has focused on the species identified by local communities that meet many of their everyday needs. This approach to socially modifying ethnobotanically important species as new crops has been found to deliver many social and economic benefits (Lombard and Leakey 2010) arising from linkages with the value chain (Leakey and Izac 1996; Leakey and van Damme 2014; Leakey 2017b, 2018, 2019b). Much remains to be done as few studies have quantified the achievements of participatory domestication and the delivery and impact of its potential benefits beyond recording the outcomes mentioned by farmers (Leakey 2014a).

Principles

As mentioned above, some of the key principles of the participatory domestication of Cinderella species: are:

- Capture of the desirable traits found in elite trees in wild populations, both determined by local knowledge and by supporting research.
- The use of simple techniques to characterize tree-to-tree variation at the village level.
- The use of simple, low-technology, non-mist vegetative propagation techniques appropriate for remote locations without running water and electricity to capture the traits, sometimes in rare combinations, found in individual trees to create locally important superior crop putative cultivars. Field trials are then needed to affirm these as unique and stable cultivars. This approach is supported by research-based principles developed over the last 45 years.
- A decentralized, village-based domestication program, to minimize the risks of excessively narrowing the genetic base of useful species in parallel with retention of existing wild populations.
- Participatory rural appraisal implemented at the village level to ensure that the needs of local people are met by the domestication process.

This approach is embedded within a wider set of principles for sustainable development (Leakey 2014a) and strategy for the genetic improvement of trees (Leakey and Akinnifesi 2008).

Rural resource centers

A novel approach to bottom–up rural extension of participatory domestication has focused on the development of Rural Resource Centers (RRC) (Tchoundjeu et al. 2006, 2010a; Degrande et al. 2014, 2015; Takoutsing et al. 2014). These RRCs follow up and advance the participatory rural appraisal principle and promote the dissemination of techniques, skills and strategies together with an understanding of the issues. They involve partnerships between researchers and local NGOs and CBOs to address the lack of knowledge about the fundamentals of tree biology/physiology essential for tree domestication. They also provide training in the techniques of vegetative propagation using non-mist propagators, tree selection and nursery management, as well as training and capacity building in the use of nitrogen-fixing trees and shrubs for soil fertility enhancement (Degrande et al. 2007; Cooper et al. 1996). Crucially, they also act as "diffusion hubs" for production and market information. This facilitates marketing by linking farmers and traders (Facheux et al. 2006, 2007, 2012; Degrande et al. 2007, 2014; Cosyns et al. 2011, 2013; Foundjem-Tita et al. 2011, 2012a; Foundjem-Tita et al. 2012b; Gyau et al. 2012, 2014; Asaah et al. 2011a; Mbosso et al. 2015). This farmer-to-farmer self-help philosophy to agricultural development has successfully resulted in the dissemination of simple skills and knowledge fundamental to address the expressed desires of farmers; led to the development of satellite tree nurseries in neighboring communities; promoted the local economy and had transforming outcomes for community well-being, social justice and value-chain developments (Asaah et al. 2011a; Degrande et al. 2012).

The concept of socially modified organisms/crops

The successful implementation of participatory domestication has resulted in extremely poor smallholder farmers developing horticultural clones as putative cultivars from indigenous trees with desirable characteristics in their own farms and villages. They then plant these trees in their own farms for domestic consumption and for sale in local markets. Thus, they are the beneficiaries of their efforts—both nutritionally and financially. In addition, the village nurseries produce other trees that can be sold to neighbors and, in this way, the financial benefits can rapidly be substantial. Thus, on average, community income has risen from almost zero to over $28,000 in 10 years (Asaah et al. 2011a). This income stream is important, as will be seen later ("Addressing the constraints to production" section), to further the development of community enterprises and to improve the production of staple food crops in ways that promote agrobiodiversity and agroecological functions. Consequently, in contrast to the development of genetically modified crops, this self-help participatory domestication of wild natural resources increases food and nutritional security, reduces poverty, enhances agroecological functions and empowers the community in many ways. For all these reasons, these community-developed putative cultivars have been described as 'socially modified organisms/crops' with a critical role to play in Steps 2 and 3 of closing the Yield Gap in staple food crops ("Addressing the constraints to production" and "Impacts of Cinderella species as crops in agriculture" section; Leakey 2017b, 2018, 2019b).

Processing of agroforestry tree products—value addition and commercialization

The products of agroforestry trees, especially those of the indigenous trees that provide products generally described as non-timber forest products (NTFPs), have been described as Agroforestry Tree Products (AFTPs). This is because as common property resources from natural forests and woodlands, the harvesting and trade of NTFPs are often subject to legal restrictions, while AFTPs are products from cultivated resources on private land (Simons and Leakey 2004). As such, the term AFTPs is useful to avoid policy misconceptions (Foundjem-Tita et al. 2012b) and to clarify the origins of marketed produce.

The products of ethnobotanically important Cinderella trees have been gathered from forests and woodlands by local people for thousands of years and are part of the Traditional Knowledge associated with many culturally significant uses. As already described, the domestication of these trees has beneficial livelihood impacts at the household level, but poverty is a severe constraint to everyday life in many rural communities of the tropics and sub-tropics, especially in Africa. Thus, many social and economic benefits can be expected to flow if income can be further generated by expanding trade of these locally and regionally important resources.

It is well known in the trade of agricultural commodities that the value is greatly enhanced if the quality, uniformity and reliability of supply are improved by genetic selection and domestication. Evidence from Cameroon indicates that retail markets of *D. edulis* fruits recognize the superiority of fruits from certain trees, and that the bulk samples of the wholesale trade do not (Leakey et al. 2002). Therefore, it seems reasonable to expect that farmers would receive higher market prices, if they could supply bulk samples of superior tested and named cultivars. This indicates that it is important for domestication and commercialization to go hand-in-hand. Ideally, this involves partnerships between the domestication program and commerce to identify appropriate ideotypes to shape the genetic selection program (Leakey 1999a). Thus, promoting an effective "value chain" that maximizes the benefits of both processes, incentives are created for farmers to adopt the technologies, and so to drive changes in rural development policy (Leakey 2017e; Leakey and Prabhu 2017). To achieve this, value-chain activities must be set in their social context understanding the needs of producers and consumers across the domestication–commercialization continuum from local to international trade (Leakey and van Damme 2014), recognizing that improved product quality, uniformity, and reliability of supply become increasingly important as the scale of trade expands. To date, however, the potential for postharvest transformation of some of the AFTP products has still not been widely recognized and this is hindering the creation of novel foods for global industries. For example, there has been almost no work on processing to extend shelf-life for increased local and regional trade; or to examine the potential for entirely new products for new or existing international markets, either with or without sophisticated post-harvest treatments. Nevertheless, over recent years, there have been hundreds of processed products developed from the fruits/nuts/leaves of Cinderella species entering international markets (see for example 'Aduna' from baobab fruit and 'Flora Ekologisk' and 'Becel Gold' from *Allanblackia* species). In this connection, ideotype selection could be an essential pre-requisite when developing new markets for novel foods/commodities. The importance of post-harvest processing in the market place is illustrated by the fermentation of coffee and cocoa which are unpalatable in the raw state.

Integration of Cinderella species into mainstream agricultural systems

So far in this review, we have examined ethnobotanical importance of AFTPs as products in their own right. Now, we will investigate their role in the resolution of the land degradation and the socio-economic constraints to agricultural production in smallholder farming communities. In many tropical/sub-tropical countries, these communities are often living on the brink of the cash economy and suffering from food and nutritional insecurity. First, however, we should reflect on the relatively recent history of agriculture and a few stark outcomes that need to be addressed if we are to avoid the foreseen Global Food Crisis (Cribb 2010):-

1. The Green Revolution introduced globally the concept of high-input monocultures of exotic staple food crops and mechanization. Thus, today, the conventional model for intensive agriculture is the use of "high inputs for high outputs" based on improved crop varieties and livestock breeds, mechanization, artificial fertilizers, irrigation, etc. The result of this large-scale, capital-intensive approach to agriculture has been very impressive in industrialized countries of temperate latitudes, but it is much less appropriate for small-scale subsistence farms without access to the essential technical inputs. Failure to recognize this difference has trapped about 1.3 billion poor, developing country farmers in hunger and poverty on degraded agricultural land (UNCCD 2017).
2. Many of the trees which are the source of traditionally and culturally important food and non-food products are cleared from farm land. The products of these trees are greatly appreciated by local peoples. Furthermore, these trees are keystones in environmental sustainability.
3. The overseas regulation of the markets for commodity cash crops like cocoa, coffee, tea, and rubber undervalues their production by smallholders.

The Green Revolution has greatly increased the production of food in industrialized, and some transitional, countries, and has also boosted agricultural industries—being described as an 'engine of economic growth' (Gemmell et al. 2000; Tiffin and Irz 2006). Unfortunately, in contrast, in the least developed countries, the opposite has occurred, and intensive agriculture has led to declining productivity and farmers trapped in poverty, malnutrition and hunger. Consequently, we live in an economically and socially divided world of rich and ultra-poor exacerbated by the disparity between farming systems in temperate and tropical economies. On top of this, there is growing evidence that planetary functions are in decline due to climate change and pollution.

Addressing the constraints to production

Following from the above overview of agriculture, it is clear that we need to better understand the issues and causes behind the failure of smallholder agriculture in the tropics and sub-tropics, and especially in Africa. Leakey (2010, 2012a) has described a 'Cycle of land degradation and social deprivation' that leads to declining productivity of staple food crops, loss of biodiversity and increasing greenhouse gas emissions. Understanding this cycle which is responsible for yield gaps (the differences between potential yield and actual yield) commonly found in smallholder farming (Leakey 2013) has to be a prerequisite to finding ways to maximize the productivity of agricultural land in the tropics and sub-tropics. In Africa, the yield gap in maize, for example, is the difference between a potential yield of 7.5 tons ha^{-1} and a continent-wide average maize yield of 1.5 tons ha^{-1} (Sebastian 2014). This Cycle involves a complex set of interacting social economic and environmental factors (Leakey 2013). In essence, the desire to survive and to feed a family when lacking the resources to sustain crops results in a decline in soil fertility and agroecosystem health, loss of the essential biodiversity to drive ecological functions, and so to declining crop yields. The resultant hunger, poor health, and lack of marketable crops leads to declining livelihoods, social marginalization, disempowerment, poverty and an inability to support a family. At the macro-level, we find that the median income of all the countries of Africa is below $7 per person per day (Gallup 2014; Diofasi and Birdsall 2016). To turn this around, reversing this downward spiral of land degradation and social deprivation first requires the closure of the yield gap by better land use practices.

To reverse the cycle of land degradation and social deprivation means institutionalizing improved crop husbandry and the generation of new income streams. To achieve this, a tried and tested generic 3-step model for multifunctional agriculture has been presented (Leakey 2013). It combines results from some 40 years of agroforestry research into the use of leguminous trees and shrubs (e.g., *Calliandra calothyrsus*, *Gliricidia sepium*, *Sesbania sesban*) to fix atmospheric nitrogen in the soil (Step 1) with the agroecological benefits and income generation derived from the domestication and cultivation of Cinderella tree species (Step 2) and the commercialization of their products (Step 3) presented in this review. Thus, the three steps are:

Step 1 Combines the partial restoration of soil fertility by leguminous nitrogen-fixing 'fertilizer' trees and shrubs (Sanchez 2002; Sileshi et al. 2008, 2014) which restore soil nitrogen fertility and initiate the process of rebuilding the agroecological functions associated with deforestation and the consequent loss of above- and below-ground biodiversity. This step is easily achievable by extremely poor smallholder farmers and greatly increases food security without the need for expensive inputs. Typically, it reduces the Yield Gap by about 50%.

Step 2 Further improves agroecological functions by diversifying the farming system with a range of indigenous and exotic tree species that produce useful and marketable tree food and non-food products for income generation (Leakey 2012a). The resultant planned biodiversity of different agroforestry practices and their structural diversity creates niches for colonization by wildlife (the unplanned biodiversity) that enrich and multiply the ecological benefits—these can be especially important when cultivated with shade-loving cash crops such as cocoa and coffee (Leakey and Tchoundjeu 2001; Leakey 2014b). Many of the indigenous species are of great social and cultural importance due to their linkages with traditional knowledge especially that relating to their nutritional and medicinal properties. As large, long-lived perennial species, they are central to the re-establishment of an agroecological succession that will provide the natural checks and balances to lower the risks of pests and diseases (Leakey 2014b). As we have already seen earlier, these are the same indigenous species that farmers wished to domesticate as new socially modified crops (Leakey 2017b) using participatory processes in village-level nurseries to empower the community and deliver numerous social benefits. These tree nurseries have also been an important source of income from the sale of tree seedlings and new putative cultivars to neighboring communities. The creation of genetically superior cultivars with substantially improved quality traits should enhance the market and domestic value derived from any of the many agroforestry practices and opens up the opportunities for value-adding in new rural industries.

Step 3 Multiplies the social and economic benefits from the farming system by expanding the market opportunities for the tree products from selected clones (putative cultivars) by value-adding and product processing that extends the shelf-life of the products, so allowing them to be transported to more distant markets, sold when fresh products are out-of-season, and meet the more stringent quality requirements of foreign trade. These are all steps towards an enhanced value chain (Leakey and van Damme 2014) and should benefit farmers by increasing the size of the market, increasing farm-gate prices for quality products, increasing the opportunities for bulk sales of specific named cultivars, and creating off-farm business and employment opportunities. These opportunities offer some members of the community a chance to move out of subsistence agriculture and into the cash economy. Furthermore, these new businesses need tools and equipment, thus creating urban jobs in neighboring towns. Taken together, it is encouraging that young people in the community are now saying that they do not need to migrate to the towns and cities in search of employment, as they can see a viable future within their home environment (Leakey 2012a; Leakey and Prabhu 2017). Expanding the value-chain needs a partnership between agroforestry scientists and industry to ensure that the outcomes meet market needs (Leakey 1999b); this would also assist in the crossover from Globalization to Localization.

It is important to be clear here that there are a wide range of other locally important 'orphan crops' that can also play a vital role within the above generic model, adding further diversity to the farming systems and to the diets and lives of local people (see other papers in this Special Issue for further details). These orphan crops contribute to the 'niche-filling principle' for agroforestry (Leakey 1996; Leakey 1999b; Leakey 2017a) whereby useful and marketable species are cultivated adding to the species mix in ways that both make diversified farming system more sustainable and more productive. While this review is focused on plant species, livestock and fish are likewise important components of diversified farming systems.

To date, the efforts to implement this 3-step generic model have most effectively been achieved in Cameroon (Leakey 2012a) in parallel projects at different sites. To date, data from a single integrated study do not yet exist. However, its wider dissemination into other parts of Africa is in progress based on the establishment of rural resource centers (Degrande, personal communication). Further work is obviously needed to determine how farmers living in very different socio-economic and environmental situations need to adapt the model to meet their specific needs. Importantly, throughout Africa (and indeed the world), there is ethnobotanical knowledge about a wide range of local traditionally important species that are appropriate candidates for participatory domestication as socially modified crops (Table 1).

The above model conforms to the report by Sanchez et al. (1997) which emphasized that agroforestry systems need to evolve in both diversity and intensity to relevantly and effectively meet the needs of Africa. The challenge we face is to resolve the upscaling issues—mainly associated with policy-making—to address the slow progress in bringing about a new paradigm for tropical agriculture. I believe that the private sector has a key role to play in this but currently it seems it is blind to what could be achieved if they were to work with local entrepreneurs and grow truly tropical enterprises in-country in ways that meet the 2030 sustainable development goals (Leakey and Prabhu 2017; Leakey 2018, 2019b). The above model recognizes that commercial development in-country is an essential component of the restoration of agroecological functions in tropical agriculture as farmers need a good source of income, if they are to maximize production by reversing the Cycle of land degradation and social deprivation.

Impacts of Cinderella species as crops in agriculture

It is difficult to do rigorous impact studies on long-term, multidisciplinary research when it is typically done by different research teams at different sites. However, efforts have been made to draw such studies together, examine outcomes and to propose what appear to be realistic impacts (Table 2) from the combination of agroforestry soil improvement studies with leguminous trees and shrubs (Sileshi et al. 2008, 2014) and studies of the domestication and commercialization of Cinderella trees (Leakey 2014a; Leakey and Prabhu 2017).

Impacts on the environment

As with soil fertility in the previous section, the environmental baseline is typically very low on smallholder farm in tropics and sub-tropics. Soils have been 'mined' of their nutrients and organic matter, and vegetation cover has been reduced from mature forest and woodland to pioneer species—many of them described as weeds. This deforestation and land degradation changes the physical structure of the vegetation and the microclimate depriving plants and animals of niches to colonize; exposes soils to erosion and has knock-on effects on water catchments; and the siltation of rivers and lakes with consequent damage to freshwater and marine life. These losses in biodiversity have negative impacts on the functions that maintain the health of natural and man-made ecosystems, arresting ecological succession. Importantly, these impacts combine leading to decreased carbon sequestration in soils and in standing biomass, and so to greenhouse gas emissions that are changing the world's atmosphere and climate. To circumvent some of the local-scale outcomes, as an alternative to natural functions, conventional agriculture involves the use of pesticides to regulate invasive weeds and pests and diseases. Now, there is growing interest in developing alternative and more natural ways to regulate the dynamic interactions of organisms in agroecosytems (Garbach et al. 2014; Lavelle et al. 2014; Perfecto et al. 2014; Bennett et al. 2015) and in landscapes (Scherr et al. 2014), but much further work is needed to unravel the complex interactions of different food webs (Leakey 2014b). Likewise, studies are well advanced to find ways to mitigate climate change by planting trees in farming systems (van Noordwijk et al. 2011; Toensmeier 2016). One very specific way in which tree domestication seems to be having potential impact on climate change is the finding that clones of indigenous fruit trees sequester more carbon in their roots than seedlings (Asaah et al. 2012).

Table 2 The local-level cascade of expected outputs and outcomes from implementing agroforestry to deliver Multifunctional Agriculture. Thirty-two of these outputs have been reported elsewhere (Tchoundjeu et al. 2010a, b; Asaah et al. 2011a, b; Degrande et al. 2014; Leakey 2014c)

Intervention	Results	Outputs	Expected outcomes	Expected impact
Step 1—Harness Biological Nitrogen Fixation by planting leguminous trees	Replenishment of soil nitrogen	Crop yield increased	Partial closure of Yield Gap	Enhanced food security
	Enhanced agro-biodiversity in soils	Improved agroecological function below ground	Improved soil health—reduced risk of crop failure	Enhanced food security
		Increased organic matter	Carbon sequestration	Some mitigation of climate change
		Reduced erosion	Reduced soil run-off	Enhanced soil protection
		Enhanced water infiltration	Groundwater recharge	Water-table replenished
	Production of tree fodder	Increased livestock production	Increased consumption of meat, dairy products, etc.	Better dietary health and income generation
	Production of bee fodder	Enhanced pollination	Bee keeping for honey production	Income generation and improved dietary health
	Production of fuel wood	Reduced labor on fuel collection	Improved energy self-sufficiency and income	Enhanced well-being
	Business opportunity	Establish tree nurseries	Sale of tree seedlings	Income generation
Step 2—Domestication of indigenous food/medicinal trees	Tree planting and replenishment of depleted and threatened resource	Enhanced agro-biodiversity in soils	Improved agroecological function below ground and greater soil health	Reduced risk of crop failure and enhanced food security
	Production of useful tree products	Domestic consumption	Improved diet and nutrition	Better household health
		Marketing opportunity	Local trade	Income generation
			Post-harvest processing for wider trade year-round	Income generation
	Establish participatory domestication process	Community engagement in Rural Resource Centers	Acquire skills and understanding	Community empowerment and self-sufficiency
		Self-help process	Better self-image	Improved self-esteem
			Satisfaction	Enhanced well-being
		Involvement of women and youth	Gender and youth equity	Healthy rural communities
	Selection of elite trees	Production of superior planting stock	Farm diversification	Improved agroecological function below ground
		Multiplication of superior varieties	Greater uniformity of product quality	Reach more regulated markets
			Opportunity to match products to industrial market needs using ‘ideotypes’	Reach more specialist or niche markets (even export markets)
			Opportunity to market further up the value chain	Regional trade and income generation
		Farm intensification	Greater total productivity	Enhanced social and economic lifestyle
				Opportunities to purchase farm inputs and develop farm infrastructure

Table 2 (continued)

Intervention	Results	Outputs	Expected outcomes	Expected impact
Step 3—Commercialization of tree products	Post-harvest processing and packaging	Longer shelf life	Opportunity to market outside production 'season'	Increased income generation
			Opportunity to expand trade geographically	Increased income generation
		Creation of local business enterprises	New entrepreneurism and job opportunities	Increased income generation
			Create opportunity for local equipment fabricators	Local employment and income generation
			Opportunity for microfinance	Greater income generation
			Opportunity for women and youth	Greater social equity
			Enterprise diversification	Diversified and healthy rural economy
			Enhanced wealth	Opportunities to purchase education and health care
				Opportunities to develop local infrastructure

The ways in which agroforestry, as applied agroecology, helps to re-establish perennial vegetation and its associated ecological functions has been reported elsewhere in detail (Leakey 2014b; 2017a). In the next sections, we see this also benefits the farming communities by meeting their social and economic needs, so in effect making sure that agroecology includes the top predator and ecosystem manipulator—*Homo sapiens*. The ethnobotanically important species that are being domesticated are an important part of this re-building process as they provide social and economic incentives for farmers to diversify their farms—something they probably would not do just for the benefits to biodiversity. These fruit trees also increase the range of agroforestry systems that together form landscape mosaics. It is important to understand that the environmental benefits from agroforestry are enhanced by these mosaics and that patches of conventional monocultures are part of these enriched and beneficial landscapes. Orphan crops too can be important components of these diversified agroecosystems.

Social impacts on livelihoods and social justice

A recent study of modern agricultural intensification in Cameroon has found evidence that the development of modern conventional agriculture has had negative impacts on nutritional security and health in the rural population due to the reduction of indigenous fruits in the diet (Tata Ngome 2015; Tata Ngome et al. 2017). To counter this, it has been predicted since it's advent in 1990s that the domestication of these indigenous fruits and nuts in the tropics would have important social and economic outcomes (Leakey and Newton 1994a; Leakey and Tomich 1999) and so to contribute to the achievement of sustainable development goals by reducing hunger, malnutrition, poverty, inequity and injustice (Leakey et al. 2005a; Leakey and Prabhu 2017). Counter-arguments have suggested that the Cinderella species are just 'famine foods' and will not be adopted as new crops due to a social stigma associated with hunter-gathering. However, interestingly, the study by Tata Ngome (2015) in Cameroon has found that, even in peri-urban areas, local people have a strong affinity for indigenous fruits without any feelings of shame attached to their consumption. Indeed, they recognize the nutritional and health benefits and consider them as preferred foods to diversify their otherwise dull and repetitive diet. Further support for the nutritional benefits of indigenous foods has also arisen from studies of the gut microbiome (Schnorr et al. 2014).

The Cameroon case study presented here which has implemented appropriate technology to meet the stated desires of local farmers has validated the above predictions of impact (Franzel et al. 1996; Asaah et al. 2011a; Degrande et al. 2006; Leakey and Asaah 2013; Leakey 2014a; Leakey and Prabhu 2017), albeit on only a small scale (500 villages). In particular, by cultivating highly nutritious local fruits, nuts and leafy vegetables, households have reported improved diets, better health and improved living standards (Asaah et al. 2011a). These benefits have been enhanced by a steady source of income (see "Impacts on staple food production" section) to purchase livestock and to enhance local infrastructure (wells, piped water, storerooms, bridges and roads), and to give access to child education and health services. Access to income has also been improved by the creation of cottage industries creating new businesses and employment off-farm (see "Impacts on staple food production" section). As mentioned earlier, the lack of intellectual property rights to protect the innovations of the participating farmers poses a threat to the sustainability of these outcomes (Lombard and Leakey 2010) as unscrupulous business enterprises could destroy the incentive for communities to engage in the widespread adoption of participatory domestication.

Perhaps, the most important outcome from the Cameroon case study has been reports by participating communities that through the self-help approach, they feel empowered to address their own problems and that they can now see a way to a 'better life' (Leakey and Asaah 2013). Some youths in these communities have reported that they can see a future in their villages and so do not need to migrate to towns and cities looking for employment. This heartening outcome perhaps offers a way to reduce the social problems of urban areas where crime, drugs and violence are common and feelings of jealousy and resentment against the Developed Economies of the world perhaps lie behind the issues of illegal immigration and terrorism. Again, as mentioned in (see "Social impacts on livelihoods and social justice" section), we see here that *Homo sapiens* has to be recognized as part of the agroecosystem.

Impacts on economic growth

With poverty being one of the major constraints to productive agriculture in Developing Countries, it is clear that income generation is an important requirement for any attempt to boost agricultural production. In particular, the need in Africa is illustrated by the median *per capita* income per year for all the countries of Africa falls below the overall global median which is reported to be between US$850 and $2630 or US$2-7 per day (Gallup 2014).

Income from domesticated Cinderella species comes from the sale of plants from village nurseries, from the marketed products of agroforestry trees and from associated businesses engaged in value addition, processing and wider trade across the value chain from local to international (Leakey and van Damme 2014; Degrande et al. 2014). Again, the Cameroon case study has illustrated that the average annual community income from Rural Resource Centers has risen from almost zero to about $28,000 over 10 years from the combined sales of 'fertilizer' tree seedlings and clonal plants of putative cultivars (Asaah et al. 2011a; Leakey and Asaah 2013), while local processing and fabrication enterprises in nearby towns is around $3000–4000 per person. Some socially modified organisms, in addition, have the potential for new international industries with international markets in processed foods and beverages, pharmaceuticals and cosmetics (Jamnadass et al. 2014)—an area with great potential for economic growth. Thus, we see that ultimately tree domestication and the commercialization of their products are important steps that come together in Step 3 of the generic model to close the Yield Gap and reverse the cycle of land degradation and social deprivation.

Impacts on staple food production

As explained above in "Addressing the constraints to production" section, actual staple food production in the tropics and sub-tropics is well below its potential, especially in Africa; thus, there is great potential for significant impact. Taken together, the environmental, social and economic impacts of Cinderella species presented above combine to have important indirect impacts on staple crop yields. Firstly, the income from the commercialization of their products allows farmers to purchase fertilizers; enhancing the effects of 'fertilizer' trees on soil fertility—see meta-analyses by Sileshi et al. (2008, 2014). This, and evidence from Cameroon (Degrande et al. 2007) clearly indicates that the use of fertilizer trees to partially close the Yield Gap, and artificial fertilizers to provide P and K (Sileshi et al. 2014) can fully close the Yield Gap. Thus, implementing the 3-step model proposed above ("Addressing the constraints to production" section) can boost productivity by four- to sixfold. Consequently, impacts on food production really depend on evidence of income generation from new trade, employment and entrepreneurism (see "Social impacts on livelihoods and social justice" and "Impacts on economic growth" sections) and evidence that farmers spend their income on these inputs. It is obvious that ultra-poor farmers have many demands on their very minimal income ($1–2 per day) and thus that the cash to purchase fertilizers is in competition with the need to buy medicines, school clothes and to pay for transport to markets, school fees, funerals, energy, piped water supply, and a multitude of other day-to-day needs. Thus, although high on the list, buying fertilizers for improved crop growth may not be the highest priority, especially when there is the no cost option of using 'fertilizer' trees to make a substantial short-term difference to food production. Therefore, the identification of impacts on production arising from income generation is complex and it is highly likely that these will only become obvious when competition from other uses is reduced. Evidence from farmer interviews, however, indicates that farmers expect to reach this point as their regular income rises (Asaah et al. 2011a). All the above suggest that real progress at the farm level depends on achieving the combination of environmental sustainability linked with social and economic livelihood factors.

Strategies for sustainable intensification

There have been many calls for more sustainable approaches to agriculture over the last 10–20 years (e.g., MEA 2005; IAASTD 2009; Royal Society 2009) to address the numerous worrying outcomes of population growth and industrial expansion, recognizing that 'business as usual' is not an option. Likewise, many alternative approaches (e.g., Organic agriculture, Conservation agriculture, Agroecology, Permaculture, Doubly Green Revolution, EcoAgriculture, EverGreen Agriculture) have been proposed. However, no consensus has emerged. Leakey (2010, 2012a, 2013, 2014d, 2017a, 2018) has argued that a solution has to address the complex set of social, economic and environmental factors driving the 'Cycle of land degradation and social deprivation' and so reverse the cycle by implementing a highly adaptable 3-step generic model (see "Addressing the constraints to production" section) for Multifunctional Agriculture delivered by agroforestry (Leakey and Prabhu 2017). The current review now examines how to scale up this approach to agricultural intensification in ways that are appropriate to the needs and aspirations of millions of people, while restoring local and global environmental functions. In this connection, the impacts above ("Impacts of Cinderella species as crops in agriculture") resonate well with recent discussion about ecological intensification (Tittonell and Giller 2013; Tittonell 2014); sustainable intensification (Pretty et al. 2011; Garnett et al. 2013), and Total Factor Productivity—the efficiency with which all factors of production are utilized for overall output (Coelli and Prasada Rao 2005) and the needs of poor smallholder farmers. Likewise, the environmental and agroecological impacts relate to the current debate about agricultural land use *vis à vis* the conservation of biodiversity (Phalan et al. 2011)—land sparing *versus* land sharing.

Land sharing/land sparing

Environmental and social tradeoffs have typically been considered to be the inevitable outcomes of conventional farm intensification (Godfray and Garnett 2014). Concerns about these trade-offs have led to the global debate about 'land sparing' and 'land sharing' (Phalan et al. 2011)—a debate which has stagnated (Bennett 2017). Bennett (2017) has emphasized the need to focus on ways in which agriculture can improve human well-being rather than just food production *versus* biodiversity conservation and indicated that this will require science that considers food security together with ecosystem services and important social issues, such as governance, equity, poverty, human well-being for nations and individuals. In my view, this debate should be expanded to include the full spectrum from the serious underproduction of food—the Yield Gap—to the so far unattained maximum 'total factor production' (Coelli and Prasada Rao 2005): in other words, from 'land failing' to 'land maxing'. In this regard, the separation of production from wildlife conservation—the 'land sparing scenario—seems less relevant as in the tropics and sub-tropics because the loss of biodiversity, poverty and social deprivation lie at the heart of the failure of conventional agricultural intensification to resolve food insecurity (Leakey 2013). Land sharing, on the other hand, can initiate the re-building of agroecological functions (Leakey 2014b), but on its own does not resolve social and economic trade-offs that underpin food production by millions of poor smallholder producers in developing countries. In this review, I suggest the focus should be on reversing the complex Cycle of land degradation and social deprivation' and so move from 'land failing', via 'land sharing' to 'land maxing'?

'Land Maxing'—maximizing social, economic and environmental impacts of productive agriculture

Based on experience in Cameroon (Leakey 2012a, 2017a), we saw earlier ("Addressing the constraints to production" and "Impacts of Cinderella species as crops in agriculture") that a simple, 3-step generic approach to multifunctional agriculture can reverse the Cycle of land degradation and social deprivation closing the Yield Gap in staple food crops. This approach, delivered by agroforestry: (i) improves soil fertility, (ii) rebuilds above- and below-ground agroecosystems, and (iii) generates income through the combination of participatory domestication of indigenous tree species; and the processing, value adding and trade of their traditionally important and highly nutritious food and marketable non-food products (Leakey 2012a, 2017a, 2019b). In other words, the knub of this approach is that, without the need for purchased external inputs, it combines applied agroecology with income generation to increase total productivity, meet the dietary, social and economic needs of farming households, and minimize the undesirable trades-offs with a cascade of beneficial impacts (presented in: Leakey and Prabhu 2017; Leakey 2018). Mosaics of multi-species mixed cropping systems in a number of different configurations to suit the topography, farming system, domestic and production needs to maximize overall productivity while internalizing ‘trade-ons’. This is akin to the concept of ‘Maxiculture’ (McNamara 1991). The concept of land maxing, therefore, expands on that of land sharing by deliberately targeting the trade-ons (defined here as ‘positive impacts from management and policy interventions’) that flow from developing marketable socially modified organisms from neglected traditional food species. This fits Bennetts (2017) criteria for a new debate that combines wildlife- and farmer-friendly approaches with greater food production.

By scaling-up this approach to multifunctional agriculture actual yields of staple food crops could be increased three- to sixfold, making big advances toward food security with better nutrition and livelihoods for all. Thus, through the development of socially modified tree crops and multifunctional agriculture, it is perfectly possible to intensify tropical/sub-tropical agriculture in environmentally and socially appropriate ways that address the constraints to productive smallholder farming (Leakey and Prabhu 2017; Leakey 2018, 2019b). As this is based on traditionally important species improved by local communities, this adds a new facet to the concept of Ethno-agronomy through ‘ethnocropping’. However, when rising to these opportunities, it will be important to recognize that the cultures, the environment, soils, species and ecology of temperate and tropical regions affecting agriculture are extremely different.

From a global perspective, the domestication of new ethnobotanically derived crops for income generation opportunities has been neglected, leaving unutilized opportunities for in-country businesses and consequently employment for members of both the rural and urban population and for the economies of many tropical and subtropical countries, especially in Africa. Bringing billions of poor people into the cash economy and then helping them up the lower rungs of the economic ladder would have big positive impacts on the global economy, creating the ‘engine for economic growth’ (Gemmell et al. 2000; Tiffin and Irz 2006) not seen previously in Africa. This would, therefore, help to address the issues of imbalance in the global economy in our divided world—half rich and half poor—moving the agenda of new Sustainable Development Goals forward in a more holistic fashion, rather than one goal at a time.

Finally, to be clear, within this approach, there is great potential to expand the use of the orphan crops, to integrate livestock and fish farming, and to engage in the wise use of conventional Green Revolution technologies, such as inorganic fertilizers. By boosting the ‘actually achieved yields’ of staple food, this approach also greatly increases the economic returns on the substantial global investment in the Green Revolution.

To conclude and fully appreciate the scope of addressing the failings of farming systems in the tropics and sub-tropics, we can see that land maxing can address the ecological, social and economic dysfunctionalities of agricultural land. Thus, in theory, it is possible to raise farm land to about the same level of environmental sustainability as natural forests and woodlands, while also enriching the niches in these agroecosystems with genetically superior socially modified crops in ways that raise the total output/yield and profitability of the farming system to levels considerably in excess of those from natural woodlands and forests, in other words, sustainably maximizing the total factor productivity of the land.

Policy

Within the context of many calls for more sustainable agriculture (International Assessment of Agriculture, Science, Knowledge and Technology for Development 2009; Millennium Ecological Assessment (MEA 2005), The Royal Society’s Reaping the Benefits: Science and the Sustainable Intensification of Global Agriculture (Royal Society 2009), the Sustainable Development Goals and the current ‘Call to Heal Planet Earth’ through the African Union’s AFR100 Initiative (Gueye and Ndeso-Atanga 2018), there is an urgent need for a new mindset to making tropical and sub-tropical agriculture more productive, better for the livelihoods of farming communities and less damaging to the environment. The concepts presented in this paper have important policy implications for agriculture, the global environment, and the creation of a world without the current big social and economic divide between extreme poverty and great wealth. Addressing the issues facing our dysfunctional world will be impossible, if we continue to ignore the needs of disadvantaged people in areas where agriculture is failing (Leakey and Prabhu 2017; Leakey 2018, 2019a). Ethnobotany has much to offer in finding a solution that deliberately internalizes ‘trade-ons’ rather than accepting ‘trade-offs’ as inevitable.

Conclusion

The development of socially modified crops from ethnobotanically important wild food species overlooked by science has important policy implications for the future productivity and sustainability of tropical and sub-tropical agriculture as the ‘Cycle of land degradation and social deprivation’ can be reversed. In this way, Yield Gaps can be closed, and the environmental, social and economic impacts of intensification conventionally thought to be inevitable ‘trade-offs’, can instead be deliberately targeted and converted as ‘trade-ons’. This transformation of farming systems, which has been tested in Cameroon, also has important implications for the global economy. It is based on a generic, but highly adaptable, 3-step approach to the delivery of Multifunctional Agriculture as delivered by agroforestry.

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