POLICY, ECONOMICS AND WAY FORWARD

22 TWELVE PRINCIPLES FOR BETTER FOOD AND MORE FOOD FROM MATURE PERENNIAL AGROECOSYSTEMS

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ABSTRACT

An analysis of the factors leading to unsustainable agriculture and its associated problems of food insecurity, malnutrition and poverty, identifies a downward spiral of land degradation and social deprivation which is associated with lower crop yields, loss of biodiversity and agro-ecological function, and declining farmer livelihoods. This spiral is responsible for the Yield Gaps (the difference between the potential yield of a modern crop varieties and the yield actually achieved by farmers) found in many modern farming systems. To reverse this complex downward cycle and close the Yield Gap requires simultaneous crop and soil husbandry, ecological and socio-economic interventions at several different 'pressure-points' within this spiral. This paper advocates 12 important principles for the achievement of food security, which including the adoption of a simple, yet highly adaptable, three-step generic model involving perennial crops to kick-start the reversal of the spiral and so the closure of the Yield Gap. This agroforestry approach involves both the use of biological nitrogen fixation from trees and shrubs, as well as the participatory domestication and marketing of new highly nutritious cash crops derived from the indigenous tree species that provide poor people with the traditionally and culturally important foods, medicines and other products of day-to-day importance. Closing the Yield Gap improves food security by improving the yields of staple crops, but also has beneficial social, economic and environmental impacts. Agroforestry involving the combination of many annual and perennial crop species is, therefore, not an alternative to current agricultural systems, but is a way to diversify and enrich them, making them more sustainable. It does this by increasing food and nutrition security, increasing social and environmental sustainability, generating income, creating business and employment opportunities in rural communities and mitigating climate change. Agricultural policy currently tends not to appreciate these outcomes delivered by tropical and sub-tropical production systems which are based on perennial species and meet the requirements of 'sustainable intensification'.

Keywords: agroforestry, land degradation, tree domestication, poverty, sustainable intensification, yield gap

INTRODUCTION

Agriculture faces a very complex set of social and biophysical issues associated with the economic, social and environmental sustainability. This paper examines the role of perennial species, especially trees, in the attainment of improved staple crop yields; provision of nutritious traditional food; the reduction of poverty, hunger, malnutrition and environmental degradation; the improvement of rural livelihoods; as well as the mitigation of climate change - all with increased economic growth with a programme of Integrated Rural Development (Leakey, 2010; 2012a/b). It therefore provides a model, or policy roadmap, for the delivery of the sustainable intensification of productive tropical and sub-tropical agriculture which is pro-poor and multifunctional – i.e. enhancing agriculture economically, socially and environmentally (Leakey, 2012a). This paper is based on 12 interconnected Principles (Box 1).

BOX 1. TWELVE PRINCIPLES FOR IMPROVED FOOD SECURITY WITHIN MULTIFUNCTIONAL AGRICULTURE AND ENHANCED RURAL DEVELOPMENT

	PRINCIPLES
1	Ask, do not tell
2	Do not throw money at farmers, but provide skills and understanding
3	Build on local culture, tradition and markets
4	Use appropriate technology, encourage diversity and indigenous perennial species
5	Encourage species and genetic diversity
6	Encourage gender/age equity
7	Encourage farmer-to-farmer dissemination
8	Promote new business and employment opportunities
9	Understand and solve underlying problems: The Big Picture
10	Rehabilitate degraded land and reverse social deprivation: Close the 'Yield Gap'
11	Promote 'Multi-functional Agriculture' for environmental/social/economic sustainability and relief of hunger, malnutrition, poverty and climate change
12	Encourage Integrated Rural Development

PRINCIPLES

PRINCIPLE 1. Ask farmers what they want, do not tell them what they should do.

As the human population has grown, shifting cultivation has become less and less sustainable as deforestation has made new productive land scarcer. One consequence of this has been that farmers have been forced to become more sedentary. With this their crop yields have declined and farmers have struggled to feed their families, let alone generate income from surplus production. These families have therefore becoming increasingly trapped in hunger, malnutrition and poverty and are in need of help and substantial policy reform to free them from the circumstances that they are in. The problem originates with the advent of colonialism and the industrial revolution, because there has been a tendency for leaders in developed countries to think that agricultural developments that have worked in the temperate zone must be applicable in the tropics; despite big differences in the climate, soils, ecology and socio-economic conditions. As a result agricultural policy in developing countries has often been based on a model that is not well adapted to local conditions.

Recognizing the above issue, the work reported here began with a participatory approach to priority setting (Franzel *et al.* 1996; 2008) that sought the ideas of farmers on what they needed. These farmers identified their desire to grow the forest species from which, as hunter gatherers and subsistence farmers, they had formerly gathered wild fruits, nuts and other products of everyday value (Leakey, 2012a). This has led to an unconventional approach to agricultural development that focuses on the domestication of indigenous fruit and nut trees using a participatory approach. From this initiative the following principles have emerged (Tchoundjeu *et al.* 2002; 2006; 2010; Leakey *et al.* 2003; Asaah *et al.* 2011; Degrande *et al.* 2006; Leakey and Asaah, 2013).

PRINCIPLE 2. **Provide appropriate skills and understanding, not unsustainable infrastructure.**

Many agricultural and other rural development projects provide funding for communities to implement new and 'improved' technologies – often ones based on concepts which are 'foreign' to the farmers. While the funds are flowing these projects can be successful, but very often when the project comes to an end the new approaches are not sustained. Typically this is because the stakeholders are still dependent on a continuing stream of finance, but this is often exacerbated by a lack of 'buy-in' to the new approach. To try to overcome these problems the work reported here first asked farmers what they wanted and then, once that was agreed, went on to assist by providing skills and understanding through training, but without direct financial assistance. Thus project funds were spent on training and mentoring the participating communities with only the provision of minimal facilities. Then, as the concepts were adopted and the programme grew, these facilities were improved by both donor funds and by community contributions. In this way, pilot village nurseries grew into Rural Resource Centres staffed by village members with support from local NGOs and Community Based Organizations (CBOs) (Tchoundjeu *et al.* 2006, 2010; Asaah *et al.* 2011). This has been found to be an effective strategy for the dissemination of agroforestry innovations (Degrande *et al.* 2012).

PRINCIPLE 3. **Build on local culture, tradition and markets.**

In the past, tree products were gathered from natural forests and woodlands to meet the everyday needs of people living a subsistence lifestyle. Non-timber forest products gathered from the wild in this way have played an important role in the lives and culture of local people, as is recognized by the study of local flora (e.g. Abbiw, 1990) and ethno botany (Cunningham, 2001) With the application of intensive modern farming systems this resource has declined. To rebuild and improve this useful resource the concept of tree domestication for agroforestry was proposed in 1992 (Leakey and Newton, 1994) and subsequently implemented by the World Agroforestry Centre (ICRAF) as a global initiative from 1994 (Simons, 1996). Great progress has been made in the first two decades of this initiative (Leakey *et al.* 2005; 2012) which have encouraged local entrepreneurism in the processing and marketing of agroforestry tree products. This has had beneficial impacts on farmers' livelihoods (Tchoundjeu *et al.* 2010; Leakey, in press a).

To capitalize on this tradition and culture, the domestication of indigenous fruit and nut trees for integration into farming systems through agroforestry is based on participatory processes involving local communities. The prime objective of the participatory approach is to involve the target communities in all aspects of the planning and implementation of the programme so that they have ownership of the programme, while also benefitting from the close involvement of researchers and NGOs as mentors in the domestication programme. By building on tradition and culture in this way, participatory tree domestication has stimulated rapid adoption by growers and has enhanced the livelihoods of the households and communities involved (Leakey *et al.* 2003; Simons and Leakey, 2004; Asaah *et al.* 2011).

In implementing this strategy it is of great importance to recognize the legal and socially-important communal rights of local people to their traditional knowledge and local germplasm (Lombard and Leakey, 2010) and to ensure that they benefit from their use and are rewarded for sharing them for the wider good. Because of the sensitivity arising from past commercial exploitation of these rights by individuals, companies, academics, international agencies and government, it is very clear that the partners in domestication programmes have to earn the trust of local communities. This is to ensure that benefits flow back to the farmers and communities, the recipients of traditional knowledge and germplasm should enter into formal 'Access and Benefit Sharing' agreements (ICRAF 2012) in which the rights of the holders of knowledge and genetic resources will be legally recognised.

With poverty alleviation as one of the objectives of the domestication of indigenous trees it is clear that incentives for, and approaches to income generation are important in the overall strategy. Consequently, improving and expanding the markets for agroforestry trees and their products are central to the strategy. The experience of the last 10-15 years indicates that this is transforming the lives of the participating farmers and helping them to break-into new business and employment opportunities (Leakey and Asaah, 2013).

In many countries land tenure systems are complex with a combination of community customary rights and individual legal rights based on land purchase. In addition, government attempts to regulate logging and deforestation make the sale of tree products illegal. These issues can affect farmers' decisions about the growth of tree crops. In Cameroon, a study of formal policies found that regulations do not clearly distinguish between products from trees found in the wild and those gathered from farmers' fields (Foundjem-Tita *et al.* 2012). This finding supports the need to distinguish between common-property wild forest resources (e.g. non-timber/wood forest products) and private domesticated tree resources (agroforestry tree products) growing in farmland (Simons and Leakey, 2004) and to recognise that the exploitation, transport, import and export of indigenous fruit crops from farmers' fields do not pose any threat to conservation (Schreckenberg *et al.* 2006b). Defining agroforestry tree products (timber and non-timber) as conventional farm products in this way should increase farmers' incentives to formally cultivate trees and harvest their products, with beneficial impacts on farmers' income, national revenues, rehabilitation of degraded land and the environment (Schreckenberg *et al.* 2006a).

A strategy to increase income generation from the sale of tree products in local markets is particularly important as local people are familiar with the use of these food and medicinal products and the demand typically exceeds supply. In the longer term, this trade often has potential to expand regionally and even internationally as the products become more widely known or better processed for global customers. However, as the commercialization process involves more players and becomes more complex, so the risks that producers will be exploited increases. To counter this risk, innovative approaches to ensure that farmers and local communities are rewarded for their marketing innovations have been developed by PhytoTrade Africa and are being extended to tree domestication (Lombard and Leakey, 2010; Leakey, in press a). Again, the approach involves working with indigenous communities and helping them to secure long-term access to markets in ways which reward them and protect their intellectual property rights.

PRINCIPLE 4. **Use appropriate technology and indigenous perennial species.**

Principles 1 and 3 mentioned the relevance of indigenous trees and their products to tropical and sub-tropical farmers. To capture, harness and improve the flow of benefits from these trees recent approaches to their domestication have focussed on the large opportunity for genetic selection and clonal propagation as horticultural cultivars. This is based on the capacity of vegetative propagation to capture and fix desirable traits, or combinations of traits, found in individual trees (Leakey and Simons, 2000). This approach to clonal propagation also has the benefit that selected trees can be propagated from mature tissues so that the cultivar has a lower physical stature and early fruiting - making early returns on effort and the harvesting of fruits easier.

The simplest technique for mass clonal propagation is the rooting of leafy stem cuttings. Studies over the last 50 years have greatly enhanced the understanding of basic principles for robust and efficient techniques (Leakey, 2004; in press b), as well as the development of simple, low-cost propagation systems for implementation in remote village nurseries without access to running water and electricity (Leakey *et al.* 1990). With only a little training, these propagators made from locally available materials have been widely and successfully adopted around the tropics by unskilled and illiterate farmers and have opened up the opportunity to develop improved clones/cultivars of over 50 tree species for local planting, as well as for sale to others. Without this appropriate technology participatory tree domestication would probably not have been possible.

To decide which trees have potential for cultivar development it is necessary to have an understanding of the tree-to-tree variation within wild populations. Fortunately farmers who have gathered products from the wild trees in their area are generally well aware which trees have particular traits, such as large fruit or nut size, good taste, or particular elements of seasonality – all desirable traits that attract a good market price (Figure 1). To assist this process of farmer selection, appropriate quantitative techniques have also been developed for the selection of superior trees that meet the needs of local markets and industries. The tree-to-tree variation in hundreds of morphological traits of importance to the development of food, cosmetic, pharmaceutical and other products have been assessed in the field and used to identify appropriate multi-trait combinations that can be easily understood by local farmers. Scientific studies of chemical and physical traits have been done in parallel and the results of these are used to assist farmers to understand the potential for the development of new commercial products. The above scientific inputs to the understanding of genetic variation can then inform the process of farmer selection and help to provide guidance of how best to meet the needs of different market opportunities. Based on the concept of 'ideotypes' for tree selection (Leakey and Page, 2006) cultivars can be developed that have the ideal combination of traits for a product to meet the needs of a particular market. So, for example an ideotype for a fresh fruit would have a lot of flesh (and small seeds/nuts/kernels), be sweet, juicy, tasty, nutritious and look attractive. On the other hand, a nut ideotype would have a large kernel(s) (and probably little flesh), have a thin shell so that it is easily cracked, be rich in edible oil with an appropriate fatty acid profile or have other characteristics meeting the needs of the cosmetic or pharmaceutical industries. In both instances, these quality traits are ideally associated with a high yield of fruits or nuts, so that the cultivar can be said to have a high 'harvest index' – a large amount of 'ideal' harvestable product.

FIGURE 1. FRUITS OF SAFOU (*DACRYODES EDULIS*) FROM A MARKET IN YAOUNDÉ IN CAMEROON, WITH THEIR ASSOCIATED PRICE WHICH RECOGNIZES BOTH SIZE AND FLAVOUR

***c.f.* three fruits selling for 250CFA *versus* 22 fruits selling for 50CFA.**

To assist the marketing of tree products (especially nuts), simple, low-technology tools are being developed for nut cracking and the pressing of oil from nut kernels (e.g. Mbosso *et al.* in press). These are labour saving, better for large scale processing and safer than many tradition methods, such as the use of a machete to extract kernels.

PRINCIPLE 5. **Encourage species and genetic diversity.**

Of the 20 000 plant species producing edible products only about 0.5 percent have been domesticated as food crops, yet many have the potential to become new crops through the implementation of participatory domestication; indeed research is already in progress in over 50 tree species (Leakey *et al.* 2012). Adding new crops to small farms reduces risks from crop and market failures, as well as playing an important role in the re-building of agro-ecological functions on degraded farm land (Leakey, 1999b; 2012a). In environmental terms, the diversification with long-lived perennial plants is important because it is the way to rebuild the ecological functions of agro-ecosystems and landscapes.

Some people are rightly concerned that the domestication of new food crops will result in the loss of their genetic diversity by narrowing the genetic base. This can certainly happen if the domestication process is not based on a wise strategy that is correctly implemented. In the case of agroforestry trees being domesticated by participatory processes implemented at the village level, there is good evidence that both the strategy (Leakey and Akinnifesi, 2008) and the implementation (Pauku *et al.* 2010) are not creating any serious concerns. About 70-80 percent of the tree-to-tree variation is found at the village level and selected trees with morphologically desirable traits have been found by DNA analysis to be unrelated. Consequently, development of different sets of unrelated cultivars in different villages ensures that the narrowing of the genetic base is minimal. In other words "decentralized domestication" seems to be a means of ensuring genetic diversity is retained.

Furthermore, by gaining an understanding of the tree-to-tree variation and developing different sets of cultivars based on ideotypes formulated to meet the needs of different markets it should be possible to repackage genetic diversity and develop cultivars which are as different from each other as breeds of dogs are different from each other (Leakey, 2012a), without destroying the wild species.

In the scientific approach to selection, modern laboratory techniques are being increasingly used to examine traits which are not visible to the naked eye. For example, to quantify genetic variation in the chemical and physical composition of marketable products such as polysaccharide food thickening agents, nutritional content (protein, carbohydrate, oils, fibre, vitamins and minerals, etc.) by proximate analysis, medicinal factors like anti-inflammatory properties, the composition of essential oils and fatty acids, the determination of wood density, strength, shrinkage, colour, calorific value and other important wood properties correlated with tree growth (Leakey *et al.* 2012). Molecular DNA analysis is increasingly being used to gain understanding of genetic variation and relatedness (Jamnadass *et al.* 2009).

PRINCIPLE 6. Encourage gender and age equity.

In many rural communities around the world, women in particular have been engaged in gathering, using and marketing tree products. One of the purposes of a participatory tree domestication strategy is to ensure that all members of the community, whether male or female, are empowered by the programme and the beneficiaries of the outputs of their own initiatives and labour. This has been found to enhance the livelihoods of the community members in general and promote social and gender equity (Kiptot and Franzel, 2012), with exciting long-term benefits for youths (Leakey and Asaah, 2013; Degrande *et al.* 2012).

PRINCIPLE 7. Encourage farmer-to-farmer dissemination.

Through the development of Rural Resource Centres as the hubs of participatory tree domestication there has been a steady growth in the number of communities (from two to over 450) and number of people (from 20 to over 10 000) becoming engaged in participatory tree domestication as satellite nurseries have been developed in the areas around the Rural Resource Centres (Tchoundjeu *et al.* 2006) - a process which in continually expanding (Asaah *et al.* 2011). Much of this has been word-of-mouth neighbour-to-neighbour dissemination, but in addition efforts have been made for longer distance dissemination by community-to-community visits, fairs and competitions, as well as stories in the national media.

Evidence from Cameroon (Degrande *et al.* 2012) suggests that the involvement of grassroots organizations in the extension of agroforestry through the Rural Resource Centres has led to a relatively high level of satisfied farmers and been successful in reaching the women and youths often excluded by other extension systems.

PRINCIPLE 8. Promote new business and employment opportunities.

As mentioned earlier, local markets often exist for traditionally important food and non-food products from trees. Thus local knowledge and acceptance of the products is good. Again as mentioned, through the application of the 'ideotype' concept (Leakey and Page, 2006), tree domestication enhances the quality, uniformity and marketability of these products as clonal cultivars, selected for commercially desirable traits, stimulate a quantum leap in the marketability of the products. This means that traders and wholesalers can purchase a large volume of uniform, high quality product from a recognized and named cultivar. In return, hopefully the producer will receive a higher price, as it is clear that consumers are willing to pay more for the more desirable varieties. To ensure that these price benefits are passed back to the small-scale community producers, the development of trade associations, business partnerships and agreements are essential (Lombard and Leakey, 2010). Interestingly the benefits from tree domestication become increasingly important as the value chain progresses from local to global (Leakey and van Damme, in press). In the case of marketing Njangsang (*Ricinodendron heudelottii*) kernels in Cameroon more kernels were traded, with faster integration and greater financial benefits when interventions to enhance commercialization were implemented (Cosyns *et al.* 2011). Other relevant evidence from Cameroon suggests that the adoption of collective action in kola nut production is influenced by its ease of use, absence of entry barriers and emphasis on social activities which serve as an intrinsic motivator for farmers (Gyau *et al.* 2012).

Much work remains to be done to select cultivars for year-round production and to develop post-harvest technologies for the extension of the shelf life of agroforestry tree products and processing for added value. Interestingly, there are a growing number of processed tree products on regional and international markets – for example there are over 410 Baobab products (PhytoTrade Africa, www.phytotradeafrica.org). Many of these products rely on wild harvesting for their supply; this supply can be of very variable (non-uniform) and of mixed quality, as well as irregular across seasons and producers.

With the increasing importance of market acceptability, exclusivity and distinctiveness the use of ideotypes for the identification of the specific trait combinations become more and more critical. To meet this demand increasingly sophisticated research to determine the genetic variation in the chemical, physical and medicinal properties of the raw products is underway (Leakey *et al.* 2012). This also leads to the need for stronger linkages between agroforestry researchers and partners in industry (Leakey, 1999a), as can be seen in the case of Allanblackia oil (Jamnadass *et al.* 2010).

PRINCIPLE 9. **Understand and solve underlying problems – the Big Picture.**

Over the last 60 years, agricultural intensification has resulted in substantial gains in crop and livestock production. These are due to advances in breeding (e.g. genetic gain, stress resistance), husbandry (e.g. fertilizer, irrigation, mechanization), policy (e.g. Intellectual Property Rights, variety release processes), microfinance (e.g. credit, provision of inputs), education and communication (e.g. farmer-field schools), and market and trade (e.g. demand, incentives). World cereal production, for example, has more than doubled since 1961, with average yields per hectare also increasing around 150 percent (with the notable exception of sub-Saharan Africa). Likewise, modern agriculture has led to great improvements in the economic growth of many developed countries, with concomitant improvement in the livelihoods of many farmers. In real terms, food has become cheaper (although currently prices are increasing) and calorie and protein consumption have increased. Thus, on a global scale, the proportion of people living in countries with an average per capita intake of less than 2200 kcal per day has dropped from 57 percent in the mid-1960s to 10 percent by the late 1990s.

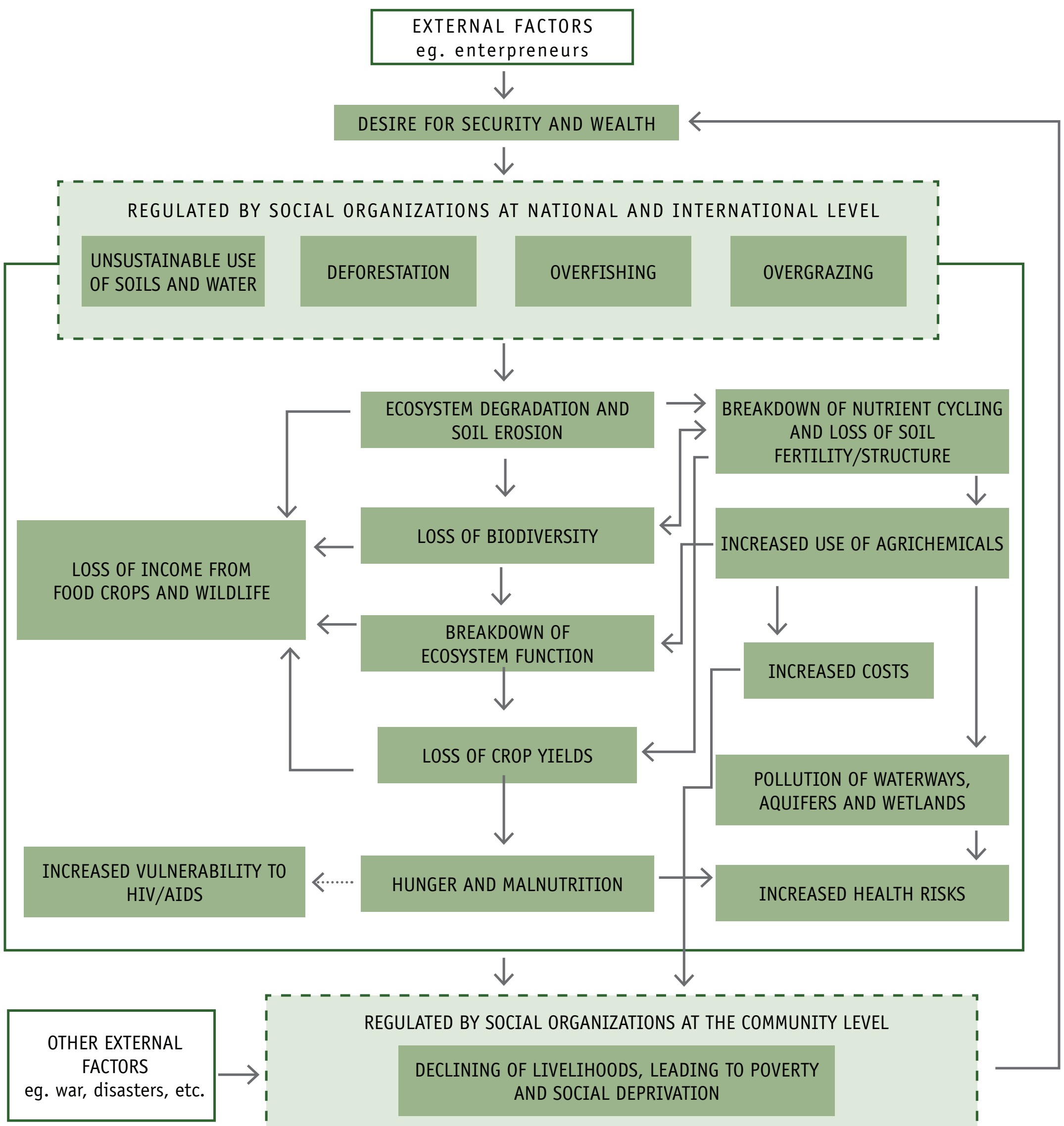
However, these benefits have come with a high environmental cost and only marginal improvements in reduced poverty, malnutrition and hunger in developing countries. Some of the major issues affecting global agriculture are:

- The scale of natural resource degradation (affecting 2.6 billion people and 2 billion ha of farm land), the depletion of soil fertility (nitrogen, phosphorus, and potassium deficiencies affecting 59, 85 and 90 percent of crop land, respectively), loss of biodiversity (valued at US$1 542 billion/yr), depletion of water resources (2 664 km^3/yr) and agro-ecosystem function, against a background in which new land for agriculture is increasingly scarce. This situation, which has arisen from the over-exploitation of natural capital, makes the rehabilitation of farm land, and its associated natural assets, an imperative.
- The incidence of poverty (3.2 billion people with an income of less than US$2/day), malnutrition, and nutrient deficiency (2 billion people) and hunger (0.9 billion people) remain at unacceptable levels, despite the very significant improvements in agricultural production. In addition, 1 billion people are affected by obesity due to poor diet.
- There are numerous organizational and conceptual “disconnects” between agricultural disciplines and organizations, especially those responsible for environmental services and sustainable development. Agricultural production and governance have focused on producing individual agricultural commodities rather than seeking synergies and the optimum use of limited resources through technologies promoting integrated natural resources management and multifunctional agriculture.
- Modern public-funded agricultural knowledge, science, and technology research and development has largely ignored the improvement of traditional production systems based on “wild” resources which, traditionally, have played an important role in peoples’ livelihoods.
- Agriculture is responsible for 15 percent of greenhouse gas emissions.
- Since the mid-20th Century, the Globalization pathway has dominated agricultural research and development as well as international trade, at the expense of the “Localization” benefits of many existing small-scale activities of farmers and traders that are aimed at meeting the needs of poor people at the community level.

Together, these issues contribute to the formation of a downward cycle of land degradation and associated social deprivation (Figure 2) that drive down crop yields and suppress farmers’ livelihoods, which together are responsible for a Yield Gap (Figure 3) between the biological potential of modern crop varieties and the yield that poor farmers typically manage to produce in the field (Leakey, 2010, 2012a).

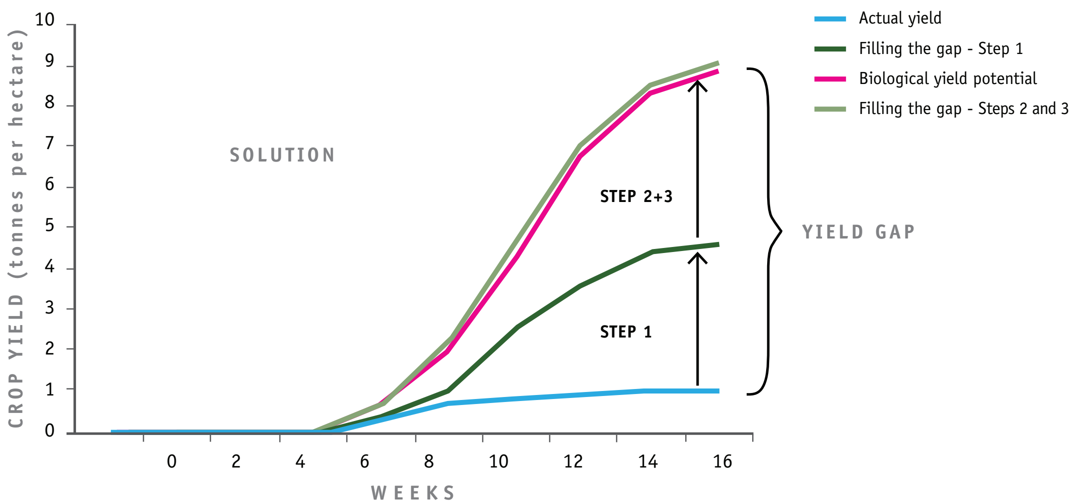
An analysis of the cycle of land degradation and associated social deprivation recognizes that the cycle is driven by a desire for security and wealth, which in turn drives deforestation, overgrazing and unsustainable use of soils and water: all of which cause agro-ecosystem degradation (Leakey, 2010, 2012a). In farmers’ fields this is seen as soil erosion, breakdown of nutrient cycling and the loss of soil fertility and structure. The consequence of this degradation is the loss of biodiversity, the breakdown of ecosystem functions and the loss of crop yield. Low crop yields result in hunger, malnutrition, increased health risks and a loss of income, all of which are manifest as declining livelihoods and so return the cycle to a desire for security and wealth. It is recognized that at all of the steps within this conceptual diagram, there are a range of socio-economic and biophysical influences which will determine the speed of the downward progress at any particular site. Such factors include: access to markets, land tenure and local governance - not to mention external factors such as natural disasters, conflict and war, and economic drivers such as international policy and trade agreements.

FIGURE 2. DIAGRAMMATIC REPRESENTATION OF THE CYCLE OF LAND DEGRADATION AND ASSOCIATED SOCIAL DEPRIVATION



Source: Leakey, 2012a.

FIGURE 3. DIAGRAMMATIC REPRESENTATION OF THE YIELD GAP AND THE STEPS REQUIRED TO CLOSE THE GAP



Source: Leakey, 2012a.

PRINCIPLE 10. Rehabilitate degraded land and reverse social deprivation: Close the Yield Gap.

To be productive, conventional approaches to modern agriculture typically require large inputs of fertilizers, pesticides, mechanization and, in dry areas, irrigation. However, the dependence of this type of agriculture on income and financial capital makes it inaccessible to hundreds of millions of poor farmers due to their high cost and local availability. As it is clear that cutting more forest down for agriculture is not an acceptable option, it is crucial to find ways of making degraded land productive again. Unfortunately, agricultural research and development has focused more on increasing potential yield than on addressed the cycle of land degradation and social deprivation that creates the Yield Gap.

To close the Yield Gap, Leakey (2010, 2012a) has suggested the following three-step approach as a way forward, using example of maize (*Zea mays L.*) production in eastern and southern Africa. The approach is based on the use of agroforestry fallows, perennial crops, tree domestication, and the marketing of agroforestry tree products as a way deliver multifunctional agriculture:-

- **Step 1.** Adopt agroforestry technologies such as two year improved fallows or relay cropping with nitrogen-fixing shrubs that improve food security by raising maize yields four-fold from around 1 Mg ha-1 (Buresh and Cooper, 1999; Sileshi *et al.* 2008). Likewise, stands of *Faidherbia albida* (Del.) A. Chev. trees play a similar role in the so-called Evergreen Agriculture (Garrity, 2012; Swaminathan, 2012). This allows the farmers to reduce the area of their holdings planted with maize and so make space for other crops, perhaps cash crops which would generate income. This diversification could also include the establishment of perennial grains. An additional benefit arising from improved fallows with leguminous shrubs like *Sesbania sesban* (L.) Merr. and *Desmodium* spp. is the reduction of parasitic weeds like *Striga hermonteca Benth*., and the reduced incidence of insects pests like the stem borers of maize (Cook *et al.* 2007).

- **Step 2.** Adopt the Participatory Domestication of indigenous trees producing marketable products, so that new, locally important and nutrient-rich cash crops are rapidly developed as a source of income and products of day-to-day domestic importance, and help empower women and maintain culture and traditions (Cooper *et al.* 1996; Sanchez and Leakey, 1997). Sale of these products would allow the purchase of fertilizers and so, potentially, the increase of maize yields up to 10 Mg ha-1. Consequently, the area under maize could be reduced further to allow more cash cropping. Filling the Yield Gap will also maximize returns on past investments in food crop breeding.
- **Step 3.** Promote entrepreneurism and develop value-adding and processing technologies for the new tree crop products, so increasing availability of the products throughout the year, expanding trade and creating employment opportunities – outputs which should help to reduce the incidence of poverty.

This approach, which is based on good land husbandry to rebuild natural soil fertility and health, therefore increases food security by improving crop yields. However, it does more than that. The inclusion of trees and other perennial crops within farming systems increases the number of niches in the agro-ecosystem. These are filled by a wide range of organisms (the unplanned biodiversity) in ways that improve nutrient, carbon and hydrological cycles; enrich food chains and meet the needs of more complex food cycles, and reduce the risks of pest and disease outbreaks. As the trees increase in size and the ecosystem progresses towards maturity, the numbers of niches for further ecosystem diversity continues to increase further enhancing agro-ecosystem function and services. This diversification makes these farming systems less damaging and more sustainable. The high species diversity of moist and dry tropical forests and woodlands means that there are many species available to play these important ecological roles in a developing agro-ecological succession (Leakey, 1996). The domestication of indigenous trees as new crop plants offer opportunities to increase the numbers of cultivated plants (the 'planned biodiversity') in these systems in ways that increase the wild organisms (the 'unplanned biodiversity') that fills the niches in the diversified farming system. The new crops of course also provide products to meet the social and economic needs of poor farmers (70 percent of the 3.2 billion people living on less than US$2 per day) for food self-sufficiency, micronutrients, medicines and all their other day-to-day needs not provided by modern monocultures. An important part of this approach is therefore to 'hedge' against environmental and ecological risk and provide the livelihood needs of the local communities.

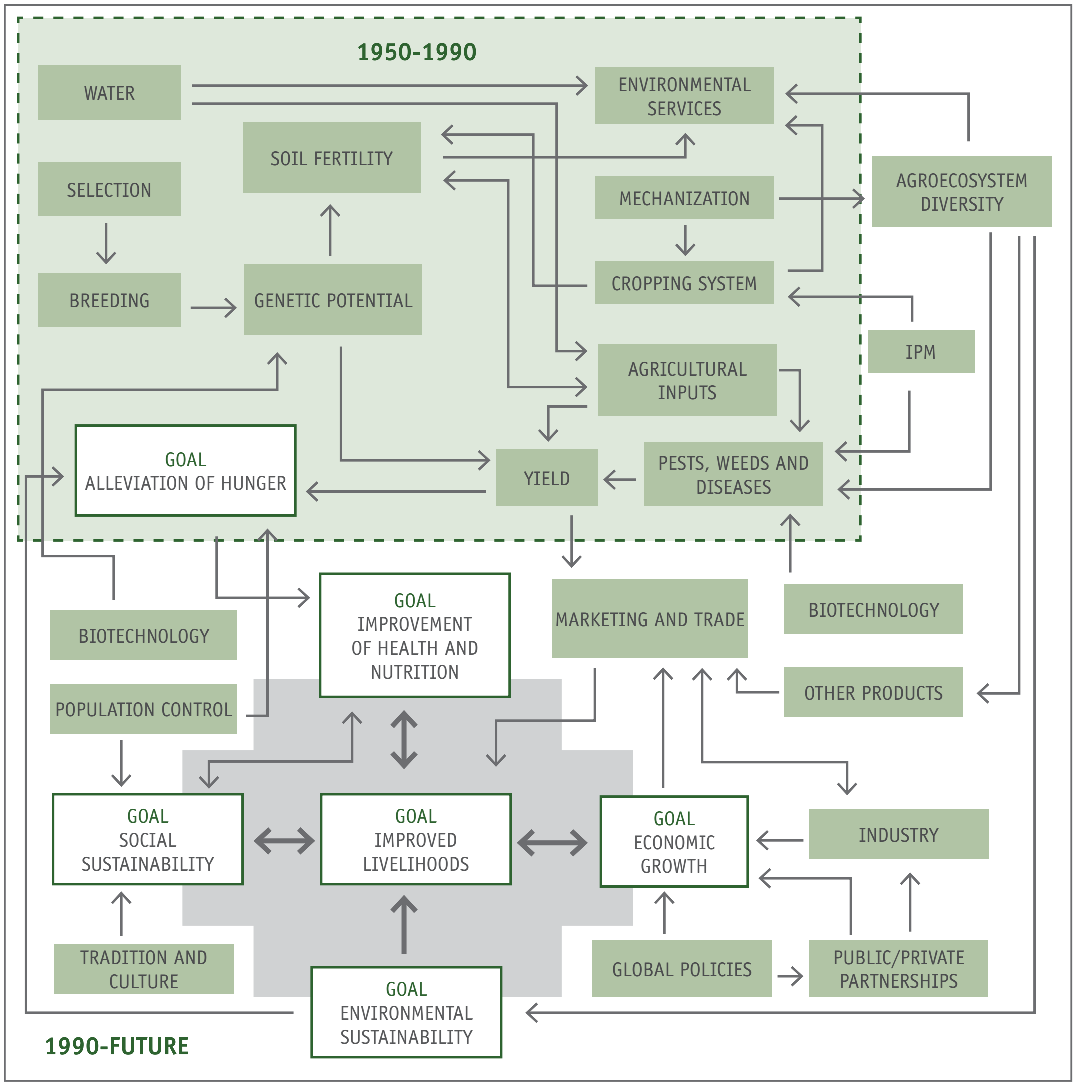
By including the domestication of traditional food species and the marketing of their products, this approach also meets the needs of the community for micronutrients that mitigate malnutrition and boost immunity to diseases (Leakey *et al*. 2012; Leakey, 2012a/b). Concomitantly, the commercialization of the tree products matches the product value chain to the needs of traders for more uniform and higher quality products with improved shelf life. This emphasis on enhanced trade is then being found to open up a pathway out of poverty based on new sources of employment and new local business opportunities (Leakey 2012a). So, as a package, this combination of social- and economic advancement with the environmental restoration creates a generic model for closing the Yield Gap – a model which is highly adaptable to a very wide range of climatic and edaphic environments and to numerous socio-economic situations, on account of the very large numbers of candidate tree species appropriate to all environments (Leakey, 2010; Leakey, 2012a,b).

PRINCIPLE 11. Promote 'Multi-functional Agriculture' for environmental/social/economic sustainability and relief of hunger, malnutrition, poverty and climate change.

Multifunctional agriculture, as described by International Assessment of Agricultural Science and Technology for Development (IAASTD) (McIntyre *et al*. 2008), has the objective of simultaneously promoting the social, economic and environmental benefits of farming systems. In other words, agriculture is very much more than just the production of food (Figure 4).

Agroforestry is particularly relevant to the delivery of multi-functional agriculture as it addresses: (i) environmental issues: (a) soil fertility management, (b) the rehabilitation of degraded farming systems, (c) loss of biodiversity above and below ground, (d) soil and watershed protection, (e) carbon sequestration and (f) energy needs through the provision of wood fuel; (ii) Economic issues: (a) income generation through trade in useful and marketable tree products, (b) the creation of business and employment opportunities in trade and value-adding through the processing of tree and non-tree products and (c) the creation of new cottage industries for diversification and enrichment of the rural economy; (iii) Social issues: (a) lack of gender equity and the need for community empowerment, (b) urban migration, (c) poverty and health related problems, (d) loss of cultural identity and of Traditional Knowledge, (e) loss of food sovereignty, (f) the lack of income for better education and training, provision of essential skills, and (g) the lack of income for community projects such as the supply of potable water, community infrastructure developments, transport, etc.

FIGURE 4. DIAGRAMMATIC REPRESENTATION OF MULTIFUNCTIONAL AGRICULTURE AND ITS GOALS.



Together, the above benefits help to resolve the higher level livelihood issues of: (i) a lack of food and nutritional security - and associated poor health, (ii) extreme and widespread poverty, (iii) the loss of self-esteem arising from the marginalization of poor communities by the social elite and the consequent vulnerability to exploitation arising from a lack of self-sufficiency, (iv) deforestation and over-exploitation of natural resources, (v) the lack of available productive land due to the degradation of complex mature and functioning agro-ecosystems and the fragmentation of agricultural landscapes (Perfecto and Vandermeer, 2010; Leakey, 2010; van Noordwijk *et al.* 2012).

With the increasing recognition of the need to address climate change the integration of trees in farming systems is being recognized as crucial for the reduction of greenhouse gas emissions and climate smart agriculture (Nair, 2012; van Noordwijk *et al.* 2011). Large perennial trees have a high volume of standing biomass and through litter fall and root turnover they also enrich the soil with carbon (Minang *et al.* 2012). Studies suggest that the conversion of degraded farm land to mature agroforest could increase carbon per hectare from 2.2 to 150 mg over a potential area of 900 million ha worldwide (World Agroforestry Centre, 2007).

So, we see that by using agroforestry to resolve the production, food and nutritional security and poverty issues causing the Yield Gap we simultaneously move farming systems towards the objectives of multifunctional agriculture and create an approach to tropical agriculture which both builds on the positive outcomes of the last 60 years of the Green Revolution, and addresses some of its negative outcomes. As a consequence, tropical agriculture becomes more productive – a process of intensification - yet environmentally, socially and economically more sustainable that the current conventional approach to modern agriculture (Leakey, 2012c).

PRINCIPLE 12. Encourage Integrated Rural Development.

So far, we have seen that agroforestry has two important roles in the development process relating to agriculture and the rural economy: i) it provides techniques for the implementation of a highly adaptable set of three steps for the closure of the Yield Gap that includes value-adding within the marketing of a wide range of indigenous tree products from mixed farming systems, and ii) it is a delivery mechanism for intensified multifunctional agriculture. While these are big steps towards more sustainable rural development, they need to be set within an even wider context in which agroforestry and multifunctional agriculture are part of a regional programme of integrated rural development.

To pull the above 11 principles together into a single project, the World Agroforestry Centre in Cameroon initiated a development programme in 1998 centred around the provision of training in agroforestry for the rehabilitation of degraded land and the domestication/commercialization of fruits and nuts from indigenous trees. This was implemented in a participatory manner through Rural Resource Centres which in addition provided training in nursery management, entrepreneurism and the use of microfinance, community organization and infrastructure development, fabrication of simple tools and equipment for value-adding tree and non-tree food products and the expansion of the value chain for traditional food products.

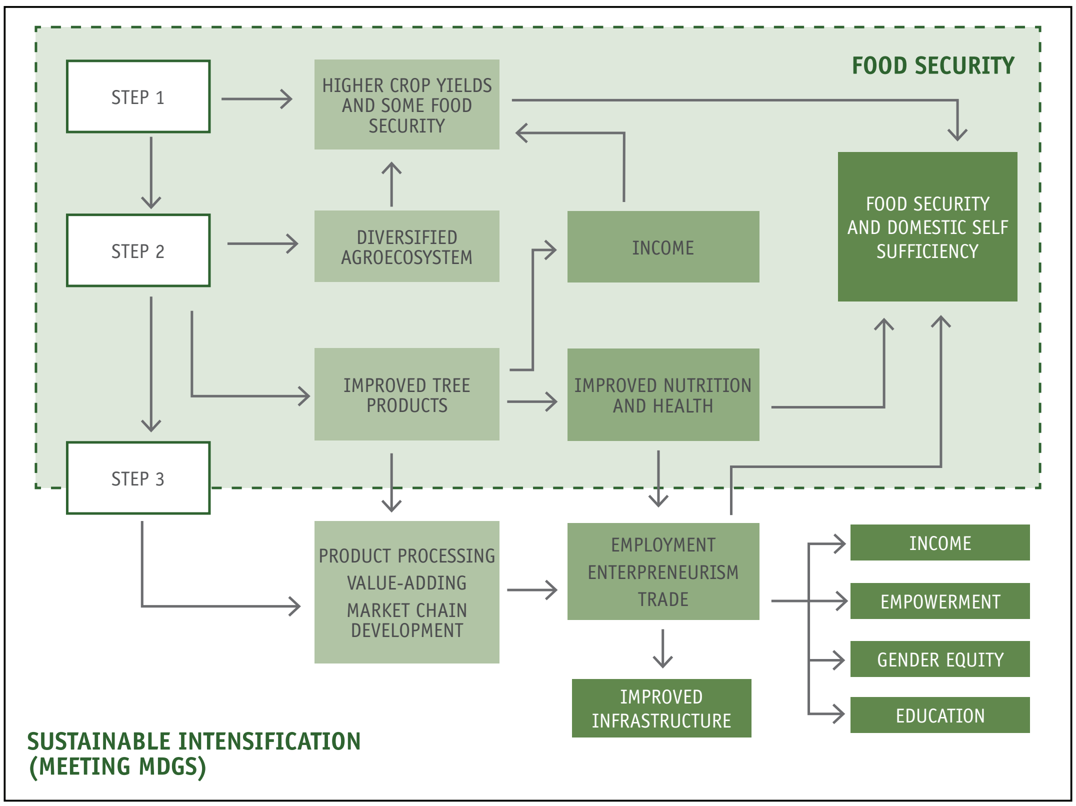
In this longest-running example of participatory domestication in agroforestry trees the researchers fed their outputs to NGO partners through training-of-trainers courses and by acting as mentors to the NGO-managed Rural Resource Centres established in pilot villages (Tchoundjeu *et al.* 2002, 2006, 2010; Asaah *et al.* 2011). The farmers in this partnership contributed their knowledge about the use and importance of local species, the range of variation in different traits of relevance to genetic selection and their Traditional Knowledge about the role of these species in local culture and tradition. They have also contributed their time and labour. Furthermore and crucially, they also made available some of their trees for research and for training in domestication techniques.

This case study - a winner of the prestigious Equator Prize – now involves more than 10 000 farmers and over 200 communities in the West and North-west regions of Cameroon, as well as entrepreneurs in local towns. The project is centred on five Rural Resource Centres which are providing a wide range of training to farmers through the growth of more than 120 satellite tree nurseries in surrounding communities supported by Relay Organizations (NGOs, CBOs, etc.) in the villages. The experience of the last 15 years indicates that the first income stream from agroforestry projects is derived from the sales of plants from village nurseries to neighbouring communities; and especially the sale of seedlings of nitrogen-fixing or the so-called 'fertilizer' trees (Asaah *et al.* 2011; Leakey and Asaah, 2013). In terms of soil fertility replenishment, the benefit flows from these trees are obtained relatively quickly (crop yield up two to three-fold in 2-3 years). On the other hand, it generally takes longer (>4 years) to obtain returns from the production and sale of the tree products. On average, results to date indicate that farmers' income from the sale of plants from village nurseries has risen dramatically as the project gathers momentum (US$145, US$16 000 and US$28 350 after 2, 5, and 10 years, respectively).

In addition, to overcome one of the constraints to better food processing local metal workers in nearby towns have been supported to develop appropriate equipment for drying, chopping, and grinding a range of foodstuffs, including tree products not previously processed. The tree products are selling at higher than usual prices and in a few cases are being sent abroad. This component of the programme has created employment for metal workers and allowed local entrepreneurs to extend the shelf life and the quality of the produce they sell in local markets. For example, the fabrication of about 150 discharge mills and 50 dryers has generated income in excess of US$120 000 (Asaah *et al.* 2011; Leakey and Asaah, 2013). In parallel, women in nearby towns have set up businesses for grinding crops like cassava (*Manihot esculenta*) have also increased their income substantially. The largest of these groups was run by ten women who employed eight workers and processed about sixty-six 180kg-bags of dried cassava flour per day throughout the year. Profits from bags selling at US$40-US$54 per bag, depending on the season, were said to be more than US$2.5 per bag. When integrated with developments across in the agricultural sector, small business developments such as these benefit from linkages with microfinance, business training and better access to simple equipment for the processing and packaging of raw products.

From the above it is clear that the commercialization of sustainably grown products delivers really important impacts from agroforestry and multifunctional agriculture (Figure 5). However, we have to recognize that commercialization that can also pose great risks affecting the success or failure of the overall initiative. One study has found that bottom-up community initiatives like those described here have the greatest chance of being 'winners', although if the companies involved recognize the importance of buying raw products from local smallholder producers, top-down commercialization can also be effective (Wynberg *et al.* 2003).

FIGURE 5. DIAGRAMMATIC REPRESENTATION OF HOW THE THREE STEPS TO CLOSE THE YIELD GAP IMPACT ON FOOD SECURITY, POVERTY AND LIVELIHOODS (SUSTAINABLE INTENSIFICATION)



One important and exciting thing about the Cameroon project has been the wide range of positive livelihood impacts that the farmers are saying have truly transformed their lives (Leakey and Asaah, 2013). These require further quantification and verification, but include: substantially increased income, new employment opportunities, improved nutrition, improved health from potable water and better diets, and the ability to spend money on children's schooling, home improvements, wells, etc. Significantly, one of the outcomes mentioned by young people in the participating communities is that this now means that they can see a future for themselves if they remain in the village rather than feeling that they have to migrate to towns and cities for a better life. In addition, women have indicated that improved infrastructure (wells, roads, etc.) has reduced the drudgery in their lives as a result of not having to collect water from rivers and carry farm produce from remote farms. These benefits, like the mechanical processing of food crops, have meant that they had more time to look after their families and engage in farming or other income generating activities.

It is encouraging that the levels of income generation achieved in Cameroon, albeit on a very small scale, exceed those proposed in the Millennium Development Goals. This and the other impacts presented here strongly suggest that by promoting self-sufficiency through the empowerment of individuals and community groups through the provision of new skills in agroforestry, tree domestication, food production and processing, community development, and microfinance, it is possible for communities to climb the entrepreneurial ladder out of poverty, malnutrition, and hunger. What is needed now is to disseminate this approach to millions of other poor people in Africa and other tropical countries.

To conclude, through the integration of rural development activities, farmers in Cameroon are intensifying their farming systems in ways that are environmentally, socially and economically more sustainable, while people in local villages and small towns are developing cottage industries and engaging more in marketing and trade. The consequence of this has been the start of the climb out of poverty and entry into the cash economy. This relationship between enhanced farm production and urban life is important for the rural economy as it is an example of farm production being the 'engine of growth'. This is perhaps the start of a new approach to rural development in the tropics – one that perhaps replicates what happened thousands of years ago in the Near East and Europe as cereals and other staple food crops were domesticated and brought into cultivation. Interestingly, Diamond (1997) has credited the domestication of food crops with the advance of western civilization. Recognizing this power of crop domestication, Leakey (2012a/d) has called for a 'new wave of domestication' to benefit people in developing countries who did not greatly benefit from the first wave. In this regard, one interesting development in recent years has been the involvement of a few multinational companies in Public-Private Partnerships with rural communities engaged in production of agroforestry products in tropical countries (Jamnadass *et al.* 2011; Leakey, 2012a). Although associated with risks, this also offers great opportunities for the future development of agroforestry tree crops if the strategies and practices can be developed appropriately.

SUSTAINABLE INTENSIFICATION

Currently, there is great interest internationally in seeking 'sustainable intensification' (Garnett and Godfray, 2012; Garnett *et al.* 2013). This paper presenting 12 principles for achieving both better and more food from mature perennial agro-ecosystems seeks to contribute to this debate and illustrate how the domestication of indigenous trees producing high value products, such as traditional foods and medicines, can be a catalyst for sustainable and integrated rural development. This paper also emphasises that an important strategy within this approach to sustainable intensification is the implementation of steps to restore productivity to degraded land and close the Yield Gap and meet the needs of a growing human population without the need for further deforestation (Figure 5; Leakey, 2012a). Clearly, the challenge for the future is to scale up the application of the principles outlined here to have meaningful impact on national, regional and global scales. A key to achieving this will be the attainment of political will. Towards this end, the IAASTD (McIntyre *et al.* 2009) placed a need for greater emphasis on:-

- Integrated approaches to land use management involving participatory approaches to planning and implementation
- Less exploitative approach to natural resources, especially soils and water, and a lower dependence on inorganic inputs and fossil energy
- Good husbandry to support agro-ecosystem health, restoration of degraded land and the reduction of the 'Yield Gap'.
- Increased involvement of local user groups in actions to improve natural resources management.
- Diversification of agriculture for improved soil amelioration, pest and disease control, and new marketable products.
- The domestication of new nutritious and marketable crops from local species, especially trees, to diversify diets and the local economy.
- Enhancement of rural livelihoods by meeting the needs of local people and supporting culture and tradition.
- Better integration of agricultural sectors, government departments and institutions, communities, and stakeholders to overcome "disconnects" in policy and practice.
- Public–private partnerships involving diverse stakeholder groups at the local level to support sustainable production, and in-country processing and value-adding.
- There is strong accord between these pointers to a better future for agriculture from IAASTD and the principles outlined in this paper.

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PERENNIAL CROPS AND TREES: TARGETING THE OPPORTUNITIES WITHIN A FARMING SYSTEMS CONTEXT

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INTRODUCTION: THE SEARCH FOR SUSTAINABILITY

Sustainable and resilient intensification of farming systems during the coming decades is a central challenge of our times. Almost half the world — over 3 billion people — live on less than US$2.50 per day; and approximately 1.3 billion, or about 22 percent of the population, consume less than US$1.25 per day (Chen and Ravallion, 2012). The immediate imperative is improving the household food security, incomes and livelihoods of the 1.3 billion poor: and the future challenge is to expand food production in order to feed the forecasted 9 billion consumers in 2050.

Economic growth is necessary to reduce poverty and food insecurity, but it is not sufficient (FAO, 2012). The majority of extremely poor households depend on agriculture for a significant part of their livelihoods, so it is not surprising that agricultural development is particularly effective in stimulating economic growth and reducing hunger and malnutrition (World Bank, 2008). Smallholder-based agricultural growth increases returns to labour and generates employment, especially for poor women. Dixon *et al.* (2001) identified five pathways by which farm households increase income and escape poverty: intensification (of existing patterns of production), diversification (sometimes bundled with intensification), expansion of operated farm size, increased off-farm income and exit from agriculture. Some recent improvement in household food security is reflected in the Global Hunger Index (IFPRI, 2013), but the progress is uneven and natural resources which underpin future agricultural productivity and food production are under increasing pressure.

Sustainability is a major concern given the pressure on land, water and energy resources (Lee and Barrett, 2001). Alongside the competition from other sectors for land, water and energy resources, the land frontier is approaching closure (Deininger and Byerlee, 2011). The pressure on land, water, energy and food is reflected in increasing prices during the recent past, notably increased resource valuations, the food price spike of 2008 and the forecasts of higher and more volatile food prices in coming decades.

The roadmap to achieve sustainable intensification is much debated (GO-Science, 2009; Tillman *et al.* 2011). The historic doubling of food production over the last four decades in Asia, largely due to the Green Revolution, was achieved through yield increases with limited additional land and water inputs, stemming from improved varieties complemented by improved fertilizer and crop management and functioning institutions and policies (Evenson and Gollin, 2003). The intensification of cropping systems through the Green Revolution was initially concentrated in well-watered areas with good connections to markets; and thus the initial livelihood benefits tended to be local whereas the food security dividends were regional or national. The Green Revolution was just one example of technology-driven changes which underpinned the growing intensification and differentiation of farming systems.

In relation to food production, recent analysis show significant variation of growth in total factor productivity across and within countries (Fuglie and Wang, 2012). Other analyses show growing concentrations of food production in a small number of annual commodities. For example, maize, wheat and rice production expanded relative to coarse grains and tubers; and chicken and pig production grew relative to cattle, sheep and goats (Tillman *et al.* 2011). However, even the growth in yield of the preferred cereal grains (roughly 40 kg/ha/y for wheat, 52 kg/ha/y for rice and 64 kg/ha/y for maize) lags behind growth in demand. Furthermore, there is evidence of some slowdown of annual cereal yield growth (Cassman, 2011). Moreover, in most food crop improvement programmes, the characteristic of perenniality has been neglected or removed through selection for yield. Over time, the role of perennials in food production has progressively diminished.

Quite apart from the core goals of global food security and economic growth, there are a spectrum of ecosystem services which are relevant to the search for inclusive sustainability – for example, biodiversity, water yield and purification and carbon sequestration (Asbjornsen *et al.* 2013). The authors are not aware of studies which compare the losses of annual and perennial species, but suspect that the former are more vulnerable to loss than the latter. Conversely, farmer re-vegetation initiatives show that the re-establishment of perennials is more challenging than for annuals. From the perspective of agro-ecosystem integrity and resilience, we argue that perennials tend to stabilize and enhance agro-ecosystem functions. This characteristic is critical for human outcomes, as the variability of productivity is a major source of the persistence of poverty, and also of 'new' poverty as households are stripped of assets and slide into poverty during (increasingly frequent) droughts. The important and well known ecosystem functions of perennials include increasing habitat niches for biodiversity (including crop pest predator habitats), reduced soil erosion and enhanced soil organic matter and moisture infiltration and storage, microclimate buffering, and greater above- and below-ground carbon sequestration.

As noted by other papers in this volume, perennial crops, pastures and trees potentially offer technical advantages for increased sustainable and resilient agricultural production (where agriculture is taken in the broad sense of crops, livestock, trees and fish). However, perennials must fit within farming systems which are shaped by agro-ecological and socio-economic factors. The following sections examine the added value from 'perenniality' (i.e., the functions potentially associated with perennial crops, pastures and trees) in eco-systems and farming systems, and identify a number of farming systems where perennials may have particular advantages. The adoption of perennials has implications for household livelihood improvement pathways. Because the future added-value of perennials depends very much on the evolution of farming systems, the main drivers of farming systems change are considered.

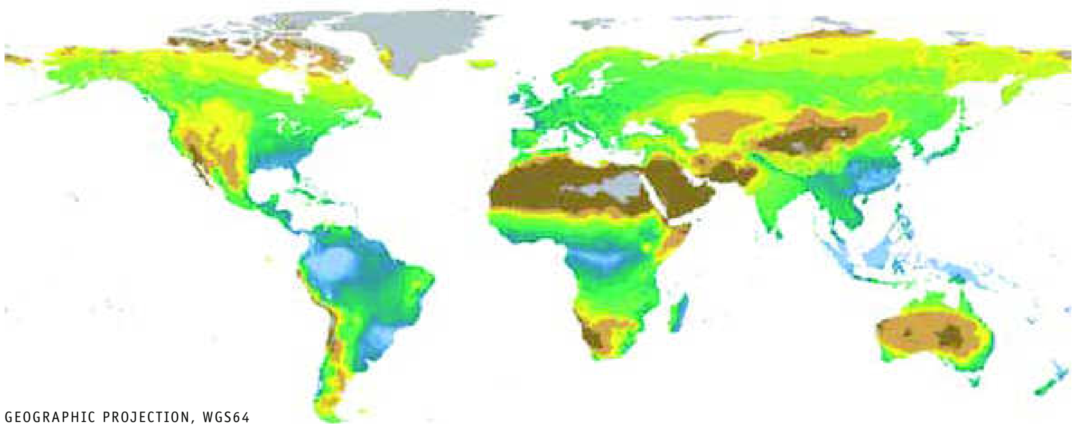
GEOGRAPHIC DISTRIBUTION OF FARMING SYSTEMS

Geography plays an important underlying role in the distribution of production and purchasing endowments. Except for irrigated areas, the average length of the growing period given precipitation, soils and temperatures is a major determinant of the potential productivity of rainfed crops, pastures and trees. Figure 1 illustrates the uneven distribution of lengh of the growing period across the surface of the globe. Moreover, the gaps between the achievable and actual yields of food crops are large in many environments especially in developing countries (Waddington *et al.* 2010).

FIGURE 1. GLOBAL DISTRIBUTION OF LENGTH OF GROWING PERIOD

GAEZ
Global Agro-Ecological Zones

REFERENCE LENGTH OF GROWING PERIOD ZONES (BASELINE 1961-1990)



GEOGRAPHIC PROJECTION, WGS64
resolution: 5arc-minute

0 3 900 7 800 15 600

DIMENSIONS

CROP	not applicable
WATER SUPPLY	not applicable
INPUT LEVEL	not applicable
YEAR	baseline period 1961-1990
SCENARIO	not applicable
CO2 FERTILIZATION	not applicable
VARIABLES	not applicable

LEGEND

0.0: background	9.0: 210–239 days
1.0: 0 days	10.0: 240–269 days
2.0: 1–29 days	11.0: 270–299 days
3.0: 30–59 days	12.0: 300–329 days
4.0: 60–89 days	13.0: 330–364 days
5.0: 90–119 days	14.0: 0–365 -days
6.0: 120–149 days	15.0: 0–365 days
7.0: 150–179 days	16.0: 0–365 +days
8.0: 180–209 days	

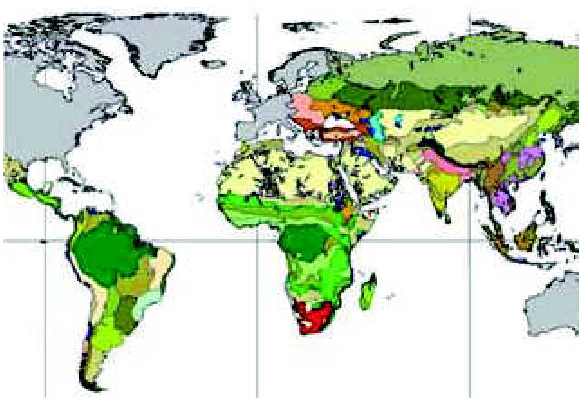
The various agro-ecologies are overlain by a mosaic of human settlement patterns that creates a multitude of diverse farming systems. Combining length of growing period and market access creates a pair of criteria which shape the land use, farming systems and livelihoods patterns of farmers in all countries. Following Dixon *et al.* (2001), a farming systems is defined as: 'a population of individual farm systems that have broadly similar resource bases, enterprise patterns, household livelihoods and constraints, and for which similar development strategies and interventions would be appropriate. Depending on the scale of the analysis, a farming system can encompass a few dozen or many millions of households.'

At different scales, the concept would be applied in different ways – and heterogeneity would be apparent in different ways. Dixon *et al.* (2001) defined five dozen or so broad farming systems across six developing regions. Following the above concept, agro-ecology and socioeconomics shape crop, livestock and other farming system characteristics. Labour is an important household resource, and so off-farm employment is considered alongside crop and livestock production on the farm, and also domestic labour requirements, for example in the farm household. Each farming system has its own structure and function (Allan, 1965; Ruthenberg, 1971). There is remarkable diversity of farming systems in all regions of the world – ranging from productive banana-maize-coffee systems in the east African highlands to nomadic pastoralism of Central Asia to the maize soybean systems of the great plains of the United States. Figure 2 illustrates the five dozen most important farming systems across six developing regions of the world; much of the diversity of OECD agricultures can be captured in another couple of dozen farming systems.

FIGURE 2. DISTRIBUTION OF MAJOR FARMING SYSTEMS ACROSS DEVELOPING REGIONS

See Dixon *et al.* 2001 for a full description.

FARMING SYSTEMS IN DEVELOPING REGIONS



DRIVERS OF THE CHANGE
- Population
- Resources, climate
- Energy
- Science, technology
- Markets
- Institutions, policies
- Information

Source: Dixon et al., 2001, www.fao.org/farming systems/

These farming systems can be grouped into the following eight classes in both developing and developed countries:

- Irrigated farming systems, embracing a broad range of food and cash crop production, often for sale;
- Wetland rice based farming systems, dependent upon monsoon rains supplemented by irrigation;
- Rainfed farming systems in humid areas of high resource potential, characterised by a crop activity (notably root crops, cereals, industrial tree crops – both small scale and plantation – and commercial horticulture) or mixed crop-livestock systems;
- Rainfed farming systems in steep and highland areas, which are often mixed crop-livestock systems;
- Rainfed farming systems in dry or cold low potential areas, with mixed crop-livestock-tree and pastoral systems merging into sparse and often dispersed systems with very low current productivity or potential because of extreme aridity or cold;
- Dualistic (mixed large commercial and smallholder) farming systems, across a variety of ecologies and with diverse production patterns;
- Coastal artisanal fishing, often with mixed farming systems; and
- Urban-based agriculture

Perennials offer different advantages within each of these system categories, as examined in the next section.

FITTING PERENNIALS INTO FARMING SYSTEMS

In farming systems, many perennials foster nutrient cycling, reduce wind effects, curtail soil erosion, and improve the micro-climate. Trees represent a class of farm asset that can be liquidated for capital (a 'bank') in times of need – which parallels the narrative around livestock as another easily saleable class of asset. Such asset accumulation is extremely critical to smallholders because many lack access to formal financial markets. Also, the inclusion/expansion of perennial grains or woody perennials in farming systems is a form of income and asset diversification that enhances livelihood resilience and reduces risk. Diversification of farm household activities is a very effective aspect of poverty escape strategies for farm households in many different farming systems, and is often more effective and dependable than intensification. Many perennials offer multiple products, which is an aspect that is particularly attractive to smallholders. For example, perennial rice could produce grain, forage and ecosystem services (e.g. carbon, reduced water erosion). Similarly, agroforestry trees may simultaneously provide fodder, fuelwood energy for the household and/or for sale, construction material, and ecosystem services in addition to high-value products that are produced for consumption and sale.

The production constraints and opportunities in farming systems are rapidly changing, with urbanizing markets, climatic variability and labour shortages growing in importance. Perennials are critical for both capturing new opportunities and for overcoming these constraints. Market constraints are generally declining for smallholder farming populations as infrastructure gradually improves and national, regional and global markets grow. This plays to the advantage of tree products. Perennial grains will reduce field labour requirements, and thus reduce women's labour burden.

We will now examine the present and future role of perennials in the generic classes of global farming systems, as summarized in Table 1.

TABLE 1. PRESENT AND POTENTIAL ROLES OF PERENNIALS IN DIFFERENT FARMING SYSTEMS CLASSES

CLASS OF FARMING SYSTEM	ROLES OF PERENNIAL GRAINS	ROLES OF PERENNIAL PASTURES	ROLES OF WOODY PERENNIALS
Irrigated farming systems, embracing a broad range of food and cash crop production, often for sale.	Limited role until perennial grains' agronomic performance is equivalent to annuals.	Role as a break crop or where livestock (especially dairy) is profitable.	Major role as high-value irrigated vines and fruits; significant roles along bunds, canals and access tracks; major role as intercrops (e.g. wheat-poplar systems), potential role as fertilizer trees and green manures, e.g. Faidherbia, Tephrosia.
Wetland rice based farming systems, dependent upon monsoon rains supplemented by irrigation.	Limited role until perennial grains' agronomic performance is equivalent to annuals.	Limited role for perennial pastures – but significant role for annual forages.	Significant role along bunds, canals and access tracks; high-value trees on mounds within fields (e.g. fruit crops), potential as fertilizer trees and green manures, e.g. *Faidherbia, sesbania*.
Rainfed farming systems in humid areas of high resource potential, characterised by a crop activity (notably root crops, cereals, industrial tree crops – both small scale and plantation – and commercial horticulture), or mixed crop-livestock systems.	Potential role for dual purpose grain/grazing, or as intercrop in tree crops.	Major role for pastures in livestock and crop-livestock systems.	Major role as a diverse range of agroforestry systems for production of fruits, medicinals and neutraceuticals, export commodities (e.g. coffee), high-quality fodder, timber and pole production, fertilizer tree integration.
Rainfed farming systems in steep and highland areas, which are often mixed crop-livestock systems.	Major role for triple purpose erosion control, grazing and grain especially on steep slopes where annual crop establishment would not be sustainable, e.g. p-rice, p-sorghum.	Major role for pastures in livestock and crop-livestock systems in order to control erosion.	Major role for high value trees, timber, and forage trees and shrubs in livestock and crop-livestock systems, for sustainable production systems on steep land evolving out of unsustainable annual cropping, controlling soil erosion and degradation.

CLASS OF FARMING SYSTEM	ROLES OF PERENNIAL GRAINS	ROLES OF PERENNIAL PASTURES	ROLES OF WOODY PERENNIALS
Rainfed farming systems in dry or cold low potential areas, with mixed crop-livestock and pastoral systems merging into sparse and often dispersed systems with low productivity or potential because of extreme aridity or cold.	Potential role for double purpose salinity management and grain production, e.g. p-wheat.	Major role for pastures in livestock and agropastoral systems in order to make best use of available moisture.	Fundamental role as evergreen agriculture in dryland crop-livestock systems to enhance fodder production, improve crop yields through improved nutrient cycling, water holding capacity and buffering microclimate, reducing production vulnerability and increasing resilience. Diversification with high-value fruits, gums, etc. Special role of farmer-managed natural regeneration of Faidherbia and similar trees.
Dualistic (mixed large commercial and smallholder) farming systems, across a variety of ecologies and with diverse production patterns.	As above, depending on the agro-ecology and economic environment.	As above.	As above.
Coastal artisanal fishing, often mixed farming systems.	Potential role in harsh sandy environments where well established roots enable perennials to exploit deeper water.	Limited role because of frequently harsh agro-ecologies and prevalence of fish as an alternative protein source.	Major role for diverse home garden and agroforest systems of fruit, nut and forest species in coastal fishing-based environments.
Urban based, including peri-urban agriculture.	Limited role.	Limited role because of high value of land – thus other feeds used for livestock.	Major role for fruits for cash sales.

IRRIGATED FARMING SYSTEMS, EMBRACING A BROAD RANGE OF FOOD AND CASH CROP PRODUCTION, OFTEN FOR SALE

Farmers in the world's large-scale irrigated systems have generally been pursuing a strategy of crop intensification to maximize crop production through deploying the most advanced genetics, fertilization, pest management, and water management practices available. In areas where these technologies have been exploited to their fullest, the yield gap has been largely closed and only incremental gains are foreseen from intensification. Thus, their attention has been turning to reducing labour costs and to exploring ways to diversify production of enterprises that can provide new and more lucrative opportunities for income gains and income stability. The introduction of perennial varieties of their annual crops (rice, wheat, maize, etc.) could potentially help them achieve reduced labour and other production costs, when and if, agronomically superior varieties become available. With the possible exception of rice, these possibilities appear to be decades away.

Perennial forages play a niche role in some irrigated systems, often underpinning dairy farming and occasionally the fattening of ruminants. For example, berseem clover is a common irrigated forage in the Nile Delta or Wadi Haramout in Yemen. Irrigated grasses and alfalfa are grown for similar purposes in the United States and Australia, but are not yet widespread in irrigated systems in developing countries.

In the meantime, many irrigated farmers, particularly small-scale producers in the tropics, are avidly exploring enterprises that will diversify their income streams, and reduce their current levels of risk dependency on one or very few irrigated crops. This has led to the integration of higher-value crops in their irrigated systems, including fruit trees, vegetables and the like, often partially replacing their irrigated food crops with these alternatives. There has also been a trend toward growing trees for lumber, roundwood for veneer, construction poles, and other wood products.

One example of this has been the trend toward producing tree enterprises on irrigated land in northern India, where considerable areas of irrigated land has now been shifted into wood production. In some systems, timber trees such as poplar have been integrated in irrigated wheat production, improving the land equivalent ratios on the farm, and the overall annual income generated from the land. And in many other areas of the tropics, irrigated land has been shifted into high-value fruit tree production, particularly in countries where the local demand for fruits has increased and/or export markets have opened up, such as in the Sahel. These trends are accelerating in some countries.

Another opportunity that farmers have is to make better use of the non-irrigated portions of their land in the surroundings of irrigated fields. Increasingly, these portions of the farm (roadways, dikes, pathways, and unirrigated corners) are being planted with trees for asset-building, fruit production, environmental amenity, and windbreak microclimate functions to reduce crop water stress. The latter is a particularly important adaptation to the increased temperatures and longer and more severe drought events that are being observed in many areas. The role of perennials in micro-climate buffering will become a major area of interest in climate change adaptation in the future.

WETLAND RICE-BASED FARMING SYSTEMS, DEPENDENT UPON MONSOON RAINS SUPPLEMENTED BY IRRIGATION

Wetland rice systems are a class of irrigated systems where the land is waterlogged and/or under shallow flooding for a portion of the year; such agro-ecosystems are eminently suitable for wetland rice cultivation which has great cultural value in much of Asia. As noted above, the introduction of perennial rice might reduce labour and other production costs, but agronomically superior varieties are not yet available and so we do not anticipate widespread use of perennial rice in wetland rice systems in the near future. The availability of markets for milk and meat have provided incentives for the limited adoption of annual forages in some locations, but there seem to be weaker incentives for the adoption of perennial grasses or leguminous forages.

Naturally, such ecological conditions present farmers with considerable challenges in introducing and managing perennials directly in their rice fields. Nevertheless, opportunities abound. For example, innovative rice farmers in Indonesia, Thailand and Viet Nam are introducing high-value fruit trees directly into their irrigated fields by constructing mounds of soil in a grid pattern that enable them to culture fruit trees and avoid waterlogging the trees while providing them with a highly favourable rooting environment for fast and vigorous growth. This is a variation of the traditional bed and ditch system of rice-growing that became popular in Bangladesh and Indonesia as a means to use waterlogged rice soils for crop and tree diversification.

Many tree species have an inherent genetic degree of waterlogging tolerance. This has provided the basis for the selection of species, particularly timber, fodder and fuelwood-bearing trees that can be produced very successfully in rice fields, particularly in systems where the land is only waterlogged for less than half the year. Bangladesh has been a leader in the testing and incorporation of such species into rice production systems. Vigorous pruning of the trees during the rice-growing season yields fuelwood and fodder while minimizing competition for light, nutrients and water with the rice crops, thus achieving substantial overall income benefits.

Agroforestry trees are increasingly being deployed to reduce waterlogging and salinization of soils in the vicinity of irrigation canals with blocked drainage systems. Rice scientists are also observing that in many situations, excessive soil compaction limits the farmers' flexibility in the preparation of their rice fields for direct-seeding and limited irrigation regimes (Buresh, personal communication. 2013). This has stimulated interest in the possible role of trees in creating soil physical conditions that would enhance the success of these water-saving practices by enhancing field drainage conditions, particularly during land preparation. The choice of tree species with the appropriate rooting dynamics to provide this service role along with the provision of income-generating products could be a suitable approach to overcoming this drainage constraint. Further research in this area is anticipated.

Rainfed and partially irrigated rice-based systems are commonly prone to highly variable yields due to drought stress and flooding events. Thus, cash investments in inorganic fertilizer use, is a risky proposition for smallholder farmers facing these constraints over a huge proportion of the world's ricelands. Practices that would enhance the provision of biological fertilization with minimal labour inputs would be of substantive value in these situations.

On the rice-growing floodplains of the Senegal River, farmers have maintained a fairly dense population of the native tree species *Faidherbia albida*, which is indigenous to these environments. It is a highly tolerant to waterlogging, nitrogen-fixing species that displays reverse phenology, meaning that it is dormant during the rice-growing season, producing minimal shade. These observations have led to the hypothesis that such a compatible species might be the basis for a transformative type of rice-tree production system that would provide an abundant source of biofertilizer (particularly nitrogen) as it sheds its leaves at the beginning of the rain season, and would provide a source of fuelwood and fodder during the dry season, sustaining ruminant livestock in the system.

Rice production systems have always been particularly non-diverse crop production systems because of their unique hydrological situation. But clearly there is ample opportunity to foresee the diversification of these systems through the incorporation of a wide range of perennial options if researchers and extensionists were to pay more attention to the range of farmer innovations that have already pointed the way toward their future transformation.

RAINFED FARMING SYSTEMS IN HUMID AREAS OF HIGH RESOURCE POTENTIAL

Agricultural practices like agroforestry, introducing hedges, low and no tillage and cover crops have an important potential to increase carbon sequestration in rainfed farming systems. Aertsens *et al.* (2013) found that this would correspond to 37 percent of all CO_2-equivalent emissions in the EU in 2007. They found that the introduction of agroforestry was the measure with the highest potential to sequester carbon in European agriculture. Its potential was estimated to be 90 percent of the total sequestration potential of the various practices studied. Taking account only of the value for climate change mitigation, they found that the introduction of agroforestry is estimated to have a value of 282/ha in 2012, and that this will gradually increase to 1 007/ha in 2030. This implies that there is a very large potential benefit for society in general and for the agricultural sector in particular. At the European level, during the past few years, policy makers have recognized the important benefits of agroforestry, and rural development programmes some European countries now support farmers to introduce agroforestry. But the current level of support is still only a small fraction of the societal value. Aertsents *et al.* (2103) posited that if this value would be fully recognized by internalizing the positive externality, agroforestry will be introduced to a very large extent in the next decades, in Europe and the rest of the world, and that this will dramatically change rural landscapes.

In Africa, the Maize-Mixed Farming System is a dominant one, extending over much of eastern and southern Africa. It has a greater agricultural population and more poverty than any of the other farming systems in Africa, and serves as the food basket as well as driver of agricultural growth and food security in the region. Conservation agriculture (CA) is currently being promoted at a major scale in African maize-growing systems. CA involves minimum soil disturbance, crop residue retention, and crop rotation.

However, the uptake of CA in Africa, and in the rainfed upland areas of Asia, has been modest so far. The short-term advantages observed where CA is currently practiced are earlier planting to enable better use of seasonal rainfall, and increased rainwater conservation in the soil to better tide crops over during drought periods (Rockstrom *et al.* 2009). But there are a number of unique constraints to smallholder adoption of CA that are retarding its more rapid uptake. Most important among these are competing uses for crop residues where livestock production is common, inadequate biomass accumulation of cover crops in the off-season, increased labour demands for weeding when herbicides are not used, variable yield results across soil types, and the need for adequate application of organic and inorganic nutrients.

Recently, the CA and agroforestry research and development communities recognized the value of integrating fertilizer trees and shrubs into systems of 'conservation agriculture with trees' (CAWT). These enhance both fodder production and soil fertility (FAO, 2010, FAO, 2011). Practical systems for intercropping fertilizer trees in maize farming have been developed and are now being extended to hundreds of thousands of farmers in Malawi and Zambia (Ajayi *et al.* 2011; Garrity *et al.* 2010). The portfolio of options includes intercropping maize with *Gliricidia sepium*, *Tephrosia candida*, pigeon peas or forage legumes, or using trees such as *Sesbania sesban* as an improved fallow.

One particularly promising system is the integration of the *Faidherbia albida* in crop fields at a 10 m by 10 m spacing. *Faidherbia* is an indigenous African acacia that is widespread on millions of farmers' fields throughout the eastern, western, and southern regions of the continent. It is highly compatible with food crops because it is dormant during the rainy season, and it exhibits minimal competition, while enhancing yields and soil health (Barnes and Fagg, 2003). Several tonnes of additional biomass can be generated annually per hectare to accelerate soil fertility replenishment, provide additional livestock fodder. Numerous publications have recorded increases in maize grain yield when it grown in association with Faidherbia, ranging from 6 percent to more than 200 percent (Barnes and Fagg, 2003), depending on the age and density of trees, agronomic practices used, and the weather conditions. These CAWT systems are a type of Evergreen Agriculture in which trees are managed as an integral element of crop fields (Garrity *et al.* 2013).

Of course, commercial tree crops such cocoa, coffee, rubber and oilpalm are concentrated in humid rainfed farming systems such as in coastal West Africa, Malaysia of Kalimantan, Indonesia. Often the tree crop is grown as a monoculture, but increasingly farmers are realizing additional income by inter-cropping during establishment with annual food or high value crops (e.g. vegetables) or perennials pastures and ground cover during later years.

In general, incorporating trees into crop farming may confer sustainability benefits through ecological intensification. They may increase the resilience of the farm enterprise to climate change through greater drought resilience, and they sequester more carbon. Conventional CA systems tend to sequester a maximum of 0.2–0.4 tonnes C/ha/yr. CAWT systems may accumulate carbon both above and below-ground in the range of 2–4 tonnes C/ha/y, roughly an order of magnitude higher than with CA alone (Garrity *et al.* 2010). This is particularly true for systems incorporating fertilizer trees such as Faidherbia or Gliricidia (Makumba *et al.* 2007). Consequently, there is considerable interest in the development of reward systems to channel carbon offset payments from developed countries to stimulate more carbon sequestration in African food crop systems while simultaneously enhancing the livelihoods of smallholders and the environment. These investments will encourage development pathways resulting in higher carbon stocks at a whole landscape scale.

CAWT systems are now attracting considerable research and extension attention. Their success will depend on the use of a wider range of tree species for varied agro-ecologies, higher quality tree germplasm, better tree seed dissemination systems, and further improvements in tree propagation and establishment methods. The optimum tree densities for different CAWT systems have yet to be fully understood, and the best practices in exploiting the soil fertility synergies between organic and inorganic nutrient sources need to be elucidated. Targeting and scaling-up methodologies deserve particular attention. These need to be supported by work to reverse detrimental policy frameworks in some countries that may discourage farmers from cultivating trees on farms. Also, active farmer organizations have always been instrumental in the development and spread of CA. Thus, the growing interest in Landcare for grassroots mobilization in Africa and Asia can provide a particularly suitable approach for the engagement of farming communities in the refinement and spread of CAWT.

RAINFED FARMING SYSTEMS IN STEEP AND HIGHLAND AREAS

This farming system has the most to gain from increased perennialization, associated in large measure with the ability of perennials to provide surface cover and to drastically reduce erosion. Hill farming systems in southern China and the Mekong might become the first beneficiaries from perennial rice, producing both biomass and grain while stabilizing the ecosystem and reducing labour requirements in areas with strong market demand for ruminant products. In this role, perennial rice might compete with perennial forages which are increasingly being intensively managed in sloping land agriculture as in the Philippines and much of south-east Asia. Of course, similar roles might be identified in sub-tropical and sub-tropical and temperate zones.

Subsistence annual cropping systems have spread to many steeply sloping lands in the tropical developing countries as a consequence of poverty, unemployment, and the shortage of land. Continuous cropping on steep lands generally results in enormous rates of soil erosion and rapid land degradation. Perennial crop systems have proven to be a much more sustainable land use in these ecosystems. Tree crops such as rubber, oil palm, and cocoa have been expanding rapidly on these sloping lands during recent decades, particularly in Southeast Asia.

In eastern Africa the farming systems have also come to be dominated by perennial crops, particularly coffee, tea and cooking bananas (Garrity, 2012). These areas now support some of the highest rural population densities in sub-Saharan Africa. They also exhibit some of the highest agricultural potential. They have been a natural experiment in the interaction between population growth, declining farm sizes, and the intensification of farming systems., as sustainable intensification runs up against extreme limits to minimum farm sizes, and as well as the possibilities and limits of farming systems commercialization. They are now characterized as permanent systems and fallowing for soil regeneration is no longer possible (Carswell, 2002). The liberalization of markets in the late 1990's now offers a principal pathway for further intensification of these farming systems.

RAINFED FARMING SYSTEMS IN THE DRYLANDS

Because of the moisture limitations and climatic variability in semi-arid areas, perennial crops, pastures and trees have a natural advantage and often produce more biomass than annual plants (the converse can be true of arid zones). Sorghums and millets are common food grain crops in the tropical drylands, yet often fail because of establishment drought. Hence perennial sorghum (or millet) might be attractive to many risk-averse smallholder farmers. The farming systems of the drylands generally feature the integration of crops and livestock, with crop residues representing and important source of fodder for ruminants. In this context, dual purpose grain/graze cereal or legume crops would have advantages; and so too a stay-green trait for deep-rooted perennials which could maintain forage quality in the early part of the dry season.

Of course perennial natural pastures are the mainstay for livestock industries in most dryland areas. The ecosystem services from rangelands are often under-estimated, not least erosion control and carbon sequestration. However, the importance of small scale irrigation in the drylands is often overlooked. Such highly productive patches stabilize farm-household livelihoods, whether used for crop or forage production – and for the latter perennial grass and legume forages, mixed or as a monoculture, would have many advantages.

The retention of trees in dryland crop fields in the tropics has been a widespread traditional practice in semi-arid areas. In the Sahelian region these agroforestry parkland systems became common as agriculture gradually intensified (Boffa, 1999). The trees are an integral part of the agricultural system, providing food, fuel, fodder, medicinals, wood for buildings, cash commodities, as well as contributing to soil fertility, water conservation, and environmental protection. However, demographic, economic, environmental and social developments during the past 40 years have put pressure on traditional land-use systems, and concerns have intensified about the steady degradation of land health in the semi-arid dryland agricultural systems in the tropics. This has turned attention to the ways that trees and shrubs can be more successfully integrated into food crop systems on a larger scale, in order to regenerate the soil health, increase annual crop yields, and diversify livelihoods, building on the knowledge and practices of dryland farmers themselves.

A globally relevant model of positive action has evolved in Niger. Since 1985, more than a million rural households in Niger have protected and managed the natural regeneration of native trees, growing in farm fields across 5 million hectares. Nigerien farmers have added approximately 200 million additional trees across agricultural landscapes, which have directly contributed to the increased production of about 500 000 tonnes of grain per year, an amount sufficient to feed an additional 2.5 million people (Reij *et al.* 2009). The United States Geological Survey also recently mapped 450 000 hectares of newly created agroforestry parkland in the Seno Plains of Mali (Tappan, 2012). Farmers in Zambia and Malawi are also increasing the protection and management of trees on farms and increasing adoption of intercropping of nitrogen-fixing species, including the native tree *Faidherbia albida*. It is estimated that currently about 500 000 Malawian farmers have Faidherbia trees on their farms (Garrity *et al.* 2010). The majority of these trees grew through assisted natural regeneration of seedlings that emerged in farmers' fields.

POLICY CONSIDERATIONS

It is worthwhile considering the policy and institutional settings which will influence the spread of perennials and benefits therefrom. Of course, starting about 10 000 years ago annual crops began to progressively replace perennial food plants including grasses, tubers and fruit trees.

Much annual food crop production is supported, in principle or in practice, by public subsidies, e.g. seed, fertilizer and machinery subsidies. Thus, for widespread adoption of perennial food crops a 'level playing field' would be required – either through reduction of input subsidies or compensating subsidies to perennial crop, pasture and tree adoption. Of course, public support to perennials R&D would be important (and relatively easy to justify because perennials offer prospects of greater eco-system services than annuals). It should be recognized that many annual crops with high input levels provide incentives for private sector involvement, whereas perennial crops would generally require less management of seed/planting material and inputs.

Because of the complexity of farming systems incorporating perennials, research managers should support participatory research and development methods. Such methods might lead naturally to enrichment of farming systems rather than wholesale replacement of annual crops.

CONCLUSION

Perennials are increasingly appreciated as playing a major role in agricultural diversification, risk management and mitigation. This brief survey has highlighted some of the innovative ways that perennials are being deployed in major farming systems around the globe, and the rationale for this trend. Clearly, the potentials, resource pressures and intensification pathways vary across the different types of farming systems (Dixon *et al.* 2001). It is at the level of the farm system that the trade-offs between food security, livelihoods and adaptation to climate change become apparent. And the relative importance of poverty escape pathways varies across farming systems. For example intensification and enterprise diversification dominate poverty reduction in high potential pathways but off-farm income and exit from agriculture are important in low potential systems. These differences in pathways and tradeoffs should be reflected in the design of sustainable intensification research programmes and policies.

Growing concerns about how agriculture will adapt to climate change, how food security can be enhanced, extreme poverty eliminated, and how land degradation processes will be reversed, have accelerated efforts to advance the roles that woody perennials and perennial crops will play in the future of farming. Their role will be transformative over the medium to long term, but they represent opportunities that are often at odds with conventional path-dependent thinking. Research investments and agricultural policy continue to be overwhelmingly dominated by short-term interests. And the enormous opportunities that the perennialization of agriculture are opening up have yet to be translated into commensurate research and policy attention.

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24 PERENNIAL POLYCULTURES: HOW DO WE ASSEMBLE A TRULY SUSTAINABLE AGRICULTURAL SYSTEM?

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ABSTRACT

Population growth and demand for food continues to place pressure upon agriculture to provide for mankind. Primary staple production is currently from annual crop species. Herbaceous perennial species for grain and other food products have not been rigorously pursued. Current interest and research into the development of herbaceous perennial species for food is providing new options for food production systems. Development of perennial species will provide the cornerstones for perennial polyculture development. Production challenges including weed competition and fertility requirements may addressed by perennial polyculture. Utilization of multiple species has been demonstrated to provide greater DM productivity by utilizing the entire growing season. Issues concerning synchronization of production and harvest however may not be easily resolved. Historically selection of perennial grasses species for seed production has most often failed to translate into consistent enhanced productivity at the field scale. Current selection methodology and nursery design are most likely inadequate to address field level productivity issues. Competitive nurseries are suggested to provide field level gains at both the mono and polyculture levels. Landscape-wide utilization of narrow genetic cultivars will lead to divergent communities and reduce reliability of production. Initial development and deployment of perennial grains and oilseeds would be enhanced by the utilization of greater diversity within the crop species. Utilization of companion species will aid in many issues related to sustainability, e.g. N_2 fixation, weediness. Initial economic utilization of perennial grains and oilseeds and perennial polyculture are linked to animal production.

Keywords: perennial grain and oilseeds, selection, competition, diversity, companion species

Greater demands for food production, for efficiencies in food production and for sustainability of food production systems are required to meet the needs of an ever-growing population.

Herbaceous perennial species are only recently receiving favourable consideration for grain and oilseed production. Whether owing to the size of the seed, or the ease of establishment and combined with relatively quick production, annuals have been preferred and therefore have garnered almost all of the effort and resources for improvement. Breeding and selection of herbaceous perennials for their seed crops has also received very little effort over the millennia of agriculture. Where improvement in seed productivity has been attempted, seed yield improvement of herbaceous perennials has frequently not experienced great success.

NATURALIZED PRODUCTION

"Production agriculture with its ecosystems simplification, pesticide and fertilizer use, and emphasis on yield, often appears to be at odds with conservation biology." (Banks, 2004). Potential for perennial polyculture to bring agriculture and conservation biology closer may be demonstrated in the ecology of natural production systems such as prairies (Glover *et al.* 2010).

Inputs for controlling environmental factors such as water stress via irrigation have negative impacts at the landscape level (Pataki *et al.* 2011). Reduction in anthropogenic impacts of agriculture may be accomplished through the use of perennials for bioenergy (Georgescu *et al.* 2011) and therefore, by extension, herbaceous perennials as grain, oilseed and potentially as other types of crops. Perennial monocultures for bioenergy are still subject to yield fluctuations owing to environmental conditions, despite adequate agronomic practices (Tulbure *et al.* 2012). Grasslands, nature's polycultures, however are seen as important for carbon sequestration (O'Mara, 2012).

Monoculture seed production of herbaceous perennials, while allowing for many environmental benefits (depending upon inputs), has some shortcomings. Shortcomings include added fertility, weed control, insect control and a single, defined growth period. All of the above may be addressed through polyculture.

POLYCULTURE

Hunter-gatherer societies in North America had long been passive participants in natural polycultures with their infrequent harvests across wide areas (Kuhnlein and Turner, 1991). However no active polycultures of desirable species are reported, although some groups practiced monoculture agriculture (Kuhnlein and Turner, 1991). We currently practice polyculture in home vegetable, herb and ornamental gardens and in our production of forages for animal feed (e.g. Picasso *et al.* 2008; Wiltshire *et al.* 2010). Pastures and rangelands provide resource conservation, biodiversity enhancement and ecosystem preservation (Wiltshire *et al.* 2010). Polyculture establishment of herbaceous perennial species for large-scale food or feed production will be a new endeavour for humans. Perennial polycultures, where coupled with animal production, are envisioned to require little if any outside applications of nutrients or pest management materials (Glover *et al.* 2010) and the benefits to sustainability should surpass those which have been attributed to organic systems (Lammerts Van Bueren *et al.* 2002) owing to the potential to resist short- and long-term variations in the growth environment.

The Land Institute with its concept of natural systems agriculture has been the recent champion of perennial crop breeding (Jackson, 2002; DeHaan *et al.* 2005; Cox *et al.* 2006, 2010). Once perennial grain and oilseed crops have been developed, a logical next step will be polyculture. Polyculture proposes the annual harvest of potentially several crop species cropped together in each year (Jackson, 2002) and emphasizes sustainability. No single species predominates across the landscape (MacDougall *et al.* 2013) (Figure 1). Even areas predominated by invasive species allow niches for native species to persist (Gilbert and Levine, 2013).

Many herbaceous perennial forage crop species are produced under bi- or polyculture conditions. In experiments where up to sixteen and twenty-four species were seeded (Tilman *et al.* 2001, 1996, respectively), as the number of plant species seeded increased, higher above-ground biomass productivity was realized and soil nitrogen use by the plant community was more complete. DeHaan *et al.* (2009) however showed that if perennial biomass productivity is the sole aim, bi-cultures of a grass and legume are as productive. Seed productivity of perennials, where species maturity and reproductive productivity are major concerns was not addressed. Mixtures of grasses and legumes were found to provide increased DM production over a number of years (Sturludóttir *et al.* 2013). Similar efforts will be required for both bi- and polyculture for food.

Monoculture production of either annual or perennial species, is subject to appearance of non-intended plants (weeds) (Cattani *et al.* 2009; Sturludóttir *et al.* 2013) (Figure 2).

FIGURE 1. VARIABILITY IN STAND IN A HERBACEOUS PERENNIAL FORAGE SPECIES

FIGURE 2. COMPETITION IN AN HERBACEOUS PERENNIAL SEED PRODUCTION FIELD WITH UNSEEDED SPECIES OCCURRING

Picasso *et al.* (2008) found that as the number of seeded species increased above-ground DM production by weeds decreased. Weeds status however can be an arbitrary assignment to a species. Fletcher (1897) defines weed as: "There are many definitions of the word weed … from a farmer's standpoint …, 'any troublesome or unsightly plant that is at the same time useless or comparatively so'." This statement implies recognition that there are plants whose impacts are either neutral or beneficial, indicating that multispecies communities were known and accepted. Perennial polycultures with their growing- season long growth potential should lead to reduced weed growth and reduced potential yield loss due to reduced weed competition as seen in many annual crops (e.g. Zhao *et al.* 2006). In many perennial seed increase operations, manual removal of troublesome species is required owing to either the lack of an adequate control chemical and/or timing of appearance of the troublesome species with respect to reproductive growth of the desired crop species.

Weinberg's (1975) systems complexity theory hypothesizes that organized complexity (systems) are less random than unorganized complexity (aggregates). Extending Weinberg's (1975) systems complexity theory to monocultures versus polycultures, with the lack of system complexity in monocultures (e.g. relative genetic uniformity, single species), random events or factors entering the system and not under the control of the producer (e.g. climate, insects, weeds, disease) may have major impacts on the system (e.g. year to year variation in yields).

Human intervention in ecosystems may lead to the loss of redundancy in native species diversity (MacDougall *et al.* 2013). Polyculture systems should provide sufficient system plasticity to adapt to variability in growth environment and allow for adequate production. Components of total productivity will vary from year to year and from location to location (see Picasso *et al.* 2008). Included in this complexity and potential interactions, is the reduced ability to quantify effects of individuals due to the interactions (Weinberg, 1975). These interactions are the most critical components of multispecies (polyculture) systems (Chen and Welter, 2005; Dray *et al.* 2012).

Construction of a community that enhances the productive capacity of crop species or several crop species is possible. Companion species however, should not restrict crop production, or if a reduction occurs, the companion species contribution should be to a future year's productivity or to sustainability. Therefore, productivity must be evaluated over the life-span of plantings and include benefits accrued to the land unit (e.g. N_2 fixation, soil organic matter, weed control) and include ecosystem benefits and not be measured solely by crop yield and market value. Selection of proper species and selection potentially within of all component species will be required to ensure growing-season-long growth for greater sustainability and productivity. Selection within companion species may need to be against uniformity.

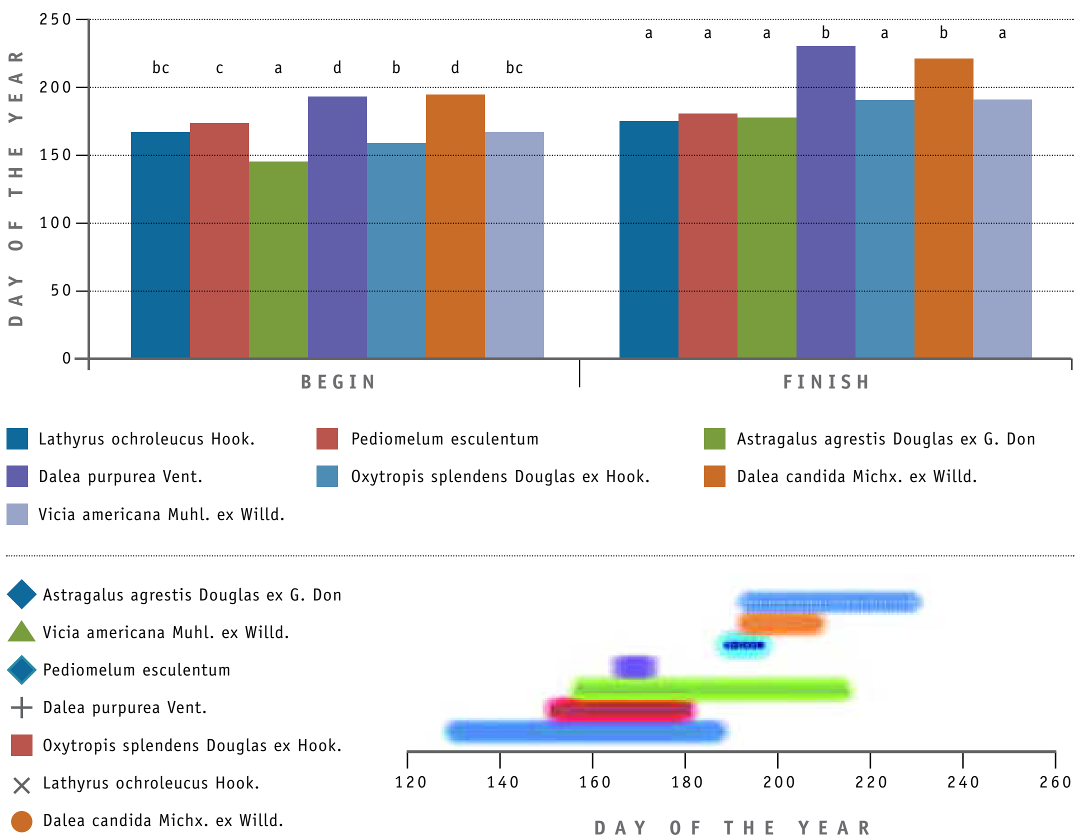
A properly designed perennial system should greatly reduce inputs demands, nutrient losses and the associated environmental impacts (Crews, 2005). Species coexistence depends in part upon temporal variation and therefore polyculture may also buffer impacts of climate volatility (Adler *et al.* 2006). For example, alfalfa (*Medicago sativa*) and stinkweed (*Thlapsi arvense*) are frequently found together in alfalfa seed production fields (perennial seed crop) in Manitoba, Canada (Cattani *et al.* 2009). Overlapping of the reproductive growth and development phases of these species does not occur whereas Canada thistle (*Cirsium arvense*) is relatively synchronized with alfalfa with respect to flowering (Cattani *et al.* 2009) (Figure 2). Canada thistle directly competes with alfalfa during its flowering and pod fill periods and is considered one of the major weed species in alfalfa seed production. The former may be an example of coexistence or concurrence while the latter exemplifies yield competition.

If Weinberg's (1975) theory holds, genetic diversity within a given species must also be broad (greater complexity) in order for that species to be able to appear across a wide swath of the landscape. Vellend (2006) predicts this and Picasso *et al.* (2008) found that the end result of polycultures in both different systems and locations can lead to different production communities. Picasso *et al.* (2008) however, used cultivars or composites for all of their seed sources which may have been too narrow genetically but only if the desired result was a similar species composition across diverse environments. Species diversity has been found in restored grasslands (Helsen *et al.* 2012) and this is most likely due to the occurrence of niches within an ecosystem (MacDougall *et al.* 2013). Selection should aid in the utility of crop and component species. Other factors that have the potential to impact plant biodiversity and persistence include herbivory (Chen and Welter, 2005; Dyer *et al.* 2010; Stein *et al.* 2010), foliar pathogens (Allan *et al.* 2010) and system management (MacDougall *et al.* 2013). Once established, plant recruitment is primarily from vegetative reproductive structures, with seedling establishment contributing very little (Jonsdottir, 1991; Benson and Hartnett, 2006).

Plant systems do not occur in isolation. An estimated 87.5 percent of angiosperms interact with pollinators (Ollerton *et al.* 2011). Cane (2006) reported that *Dalea purpurea* attracted a wide array of pollinating insects throughout its flowering period while Clement *et al.* (2006) list a number of species visiting *Astragalus* and *Onobrychis sp.* Facilitation by common species may allow for pollination success of rare species (Bizecki Robson, 2013). This indicates that selection of a few species that attract diverse pollinators and that have a somewhat overlapping flowering period may be used to provide adequate sustenance for pollinating species and to perpetuate pollinator species across years (Hajjar *et al.* 2008).

We have been monitoring flowering periods of native species for the past four growing seasons at sites around Manitoba. Looking at native legumes, flowering times are relatively consistent across years with respect to their order (Figure 3a). Selection of which species to include that would ensure an overlapping of flowering periods could result in dual purpose species, i.e. species that attract pollinators and are N_2 fixing. Other considerations such as potential toxicity to animals, if post-harvest biomass is to be grazed or fed, must also be considered (e.g. *Oxytropis splendens,* Macdonald, 1974).

FIGURE 3. A) MEAN BEGINNING AND FINISHING OF FLOWERING TIMES OF SEVEN NATIVE LEGUME SPECIES AT SETON, MB, FROM 2010-2013; B) MEAN OVERLAP OF FLOWERING PERIODS OF NATIVE LEGUMES AT SETON, MB, FOR 2010-2013



Breeding of perennial species for use in polyculture will be dependent upon the individual species involved as crop species. If, for example, *Helianthus maximiliani* is bred for uniculm production, yield will likely be dependent upon pollinator availability. Companion species' that can attract pollinators and flower near and/or across the period of *H. maximiliani* flowering will aid in productivity. Companion plant density will need to be weighed against crop plant density to determine the appropriate balance. Pollinators may be brought in from outside the area of production however sustainability is decreased in favour of profit and potentially at the expense of the surrounding ecosystem.

SELECTION

Selection for perennial herbaceous species has primarily been for forage production (Casler and Brummer, 2008). Cultivar development can often be outside of the country of use (e.g. Acharya *et al.* 2013).

Performance in agricultural settings is often very specific. Harlan and Martini (1938) found that few barley varieties were adapted across wide swaths of the landscape. Selection pressure with respect to the genetic uniformity of the crop species requires that it be determined prior to system development. Cultivar development dictates relative morphological uniformity within the resultant cultivar for identification purposes.

One approach for landscape-wide polyculture plantings requires multiple cultivars being developed to the current regulations only to utilize a number of cultivars in an individual planting to increase diversity of the crop species' with the aim of enhancing the crop's ability to withstand stresses (e.g. disease, moisture extremes) across the landscape. Limited selection within a species on important traits (e.g. seed yield and synchronous flowering) yet maintaining genetic diversity could benefit this system by providing adequate plasticity within each species (e.g. Ecovar™, Ducks Unlimited Canada). Utilization of the entire growing season could be achieved by selecting for maturity differences especially within the supporting species. Increasing diversity within component species should allow for greater adaptability, reducing the variation in the composition among communities established at different sites (Vellend, 2006).

How then should selections for perennial species be made? Will plant nursery type impact the utility of the end product in a different system (e.g. monoculture versus polyculture)? Can progress be made and maintained?

If productivity is to be realized from more than a single species, harvest timing must be such that (e.g. in a two crop species system) either one species is harvested prior to the reproductive growth of the second or both species mature simultaneously and/or are harvested simultaneously. Harvestable species may dictate the system utilized as inherent qualities of the species (e.g. shattering) could determine the approach taken. Companion species benefits must be quantified, possibly their contributions via N_2 fixation, attraction of pollinators (e.g.

Dalea purpurea (Cane, 2006)) or the ability to suppress other plant growth that would have a greater negative impact on the harvestable species. Ground cover provision in spring or autumn when the crop species may be relatively non-competitive may be beneficial. If a crop assembly is desired, testing will be required to identify ranges of reproductive effort of the potential member species and then combinations of complimentary maturation timings for sustainability of the system.

Elgersma *et al.* (1994) found that selection in space planted nurseries did not correlate to seed yield in progeny seed rows in perennial ryegrass (*Lolium perenne* L.) while Hayward and Vivero (1984) found similar results for forage yield in perennial ryegrass. Burton and DeVane (1953) inferred that advancement under selection under space planted conditions does not translate to similar increases in forage or seed yield in competitive stands. Genetic improvement for forage yield in perennial forage crops has been relatively poor (Casler and Brummer, 2008) due to the lack of a readily apparent traits and selection against 'quality' traits. Conversely, selection for harvest index in annual crops has allowed for genetic gain for yield, but possibly at the cost of overall fitness (Chen and Welter, 2005).

Seed yield component compensation may be impacting plant reproductive efforts under competitive conditions. Yield component compensation is likely environmental and not genetic and that the sequence of developing traits is important (Adams, 1967). Dofing and Knight (1992) based their proposed model for path coefficient analysis on this premise. Species ability to compensate for yield components (plasticity) will in part be dictated by the reproductive requirements of the species as well as reproductive morphology. For example, requirements for dual induction (Heide, 1994) may limit a plant's ability to recover from a poor autumn regrowth period in the spring if reproductive tiller number is fixed by autumn regrowth (e.g. Cattani *et al.* 1997) or by spikelets consisting of a single perfect floret (Cattani *et al.* 2004).

Stand duration prior to selection will also impact adaptation and persistence. Local adaptation is important and may take up to three years to become evident in a perennial species (Hufford and Mazer, 2012). Selection for harvest index in perennial species may decrease overall stand duration via allocation to sexual reproduction versus perenniating structures and tissues (parent-offspring conflict, e.g. Zhang and Jiang, 2000) given the importance of vegetative reproduction in perennial grasslands (Jonsdottir, 1991; Benson and Hartnett, 2006). A positive correlation between storage (corms) and seed production in *Amphibromus scabrivalvis* was reported indicating that increasing harvest index may not necessarily reduce long-term fitness and survival (Cheplick, 1995). In two *Geranium sp*. it was found that flowering had different effects on the following year's flower production (Ågren and Willson, 1994). Fitness reduction may increase with greater pollination success (Ågren and Willson, 1994) therefore selection for increased fertility and increased harvest index may negatively impact long-term survival of the crop in the field. Therefore, species differences may be such that seed yield progress under selection may impact life history in some species but not others.

"The potential seed yield of forage species is high, whereas realized seed yields are generally low and unpredictable." (Elgersma and van Wijk, 1997), due in part to the lack of importance placed upon seed versus forage production of these species and domestication traits such as shattering resistance. The Fecundity Allocation Premium hypothesis indicates that larger (by mass) species can have a greater range of variation of seed sizes (by mass), however species with larger seeds are more likely to have lower lifetime fecundity (Aarssen, 2005). Simply put larger but fewer seeds. Therefore, selection for larger seeds may reduce seed number per plant. In order to increase seed size and/or number for production purposes, selection for larger plant size should then be required. Or selection for greater allocation to seed mass or increased seed number may be at the expense of perenniating structures. The challenge, at least until adaptation to the growing environment is complete, will be to select for increased seed size and/or seed set and retain sufficient tolerance to "normally expected stress levels" and acknowledge the risk of extreme stresses adversely affecting stand longevity. Selection for increased seed productivity however may reduce the competitive ability of the individual within the community and enhance the diversity.

Schaaf and Rogler (1962) found seed weight highly heritable but not yield in crested wheatgrass. Christie and Kalton (1960) indicated that recurrent selection over inbreeding in *Bromus inermis* and seed weight selection on space plants was effective. Selections for seed yield in tall fescue based on clone materials were correlated to single cross progeny tests however, each parent was cloned 40 times (Thomas and Frakes, 1967). This methodology will greatly increase resources required for a selection programme. Knowles (1977) was successful using space-planted nurseries with intermediate wheatgrass, however the author noted that the moderate creep of the plants and the use of two and three year-old plant stands for selection purposes may have approximated production field conditions.

Selection in space planted nurseries therefore may be successful in perennial crops for both end use and seed production characteristics if related to identifiable characteristics. In creeping bentgrass selection for reduced plant spread resulted in greater tiller density in the intended end use, golf course turf (Cattani *et al.* 1996). These selections were also based upon higher reproductive tiller density for seed production purposes and resulted in higher harvest index values across production years in field studies (Cattani *et al.* 2004). Increased tillering was shown to be related to leaf appearance rates and reduced internode lengths (Cattani *et al.* 2002). Therefore improvements in perennial species for seed production can be made, however fitness traits may be reduced, (e.g. dwarf phenotypes). Three important caveats to the success of the above are: 1) the production region was identified prior to selection; 2) the product was for a monoculture seed production system; and 3) species plasticity may compensate for changes within the growth environment and reduce or nullify selection efficacy.

SELECTION NURSERIES

Plant competition can impact performance, and with polyculture the plant-to-plant interactions may be most important to overall stand performance. Weiner *et al.* (2010) argue for selection under high density and with group selection to increase characteristics for the good of the collective stand. The typical yield improvement approach is to improve an individual's fitness.

Annual species are better suited to the theory that individual fitness is what has been under natural selection, while perennial species have evolved other mechanisms of fitness (i.e. perenniating structures). Therefore selection for individual reproductive fitness may lead to increased productivity in perennials at the cost of perenniating vegetative structures. Care is then needed to balance reproductive methods to ensure long-term persistence of a plant within a stand.

A plant's performance may be dependent upon its neighbours and selection without this competition may impact not only the performance of the species in polyculture but also the overall performance of the polyculture. Selection in competitive nurseries should provide greater performance from all component species. Differences in access to resources as described by Smith *et al.* (2009) (Resource Pool Diversity Hypothesis) could account for differential performance under competitive versus non-competitive selection environments. Callaway and Aschehoug (2000) provide an example of differential impact of root exudates from *Centaurea diffusa* and competition for phosphorus on grasses dependent upon whether *C. diffusa* was from it its' area or origin versus its area of introduction. This is important in that competition for phosphorus was not reduced and may be explained by RPDH, and that selection for reducing allelopathic effects is possible.

A number of factors will impact a community including competition, facilitation and evolutionary processes (Brooker, 2006). The example of *C. diffusa* above illustrates evolutionary processes. *Helianthus maximiliani* (perennial sunflower) is a potential perennial oilseed crop and there are reports that it can be allelopathic (Leather, 1983). If true, selection in competition with *H. maximiliani* will be needed to provide maximization of reproductive effort for co-crop species and supporting species in polyculture.

Selection for monoculture cropping does not translate into optimum production in mixtures and selection under production environment conditions is needed (Wright, 1985). Similarly, Lammerts Van Bueren *et al.* (2002) argue that in order to make progress in developing adapted varieties for organic production selection and evaluation must take place under organic conditions, i.e. the conditions of production environments.

Perennial crop cultivars have lasted long after introduction, (e.g. Kentucky 31 tall fescue released in 1943, Climax timothy in 1947) are still in demand in 2013. Based on current regulations, intermediate wheatgrass (*Thinopyrum intermedium*) could therefore be produced for up to six years as a certified seed crop if seeded with foundation seed (CSGA, 2011). Additional years of seed production would then be considered common seed. Seed (grain) for human or animal consumption does not have to meet seed certification quality standards (for genetic make-up) but would be subject however to end-use quality parameters.

Adoption of new germplasm and the ability maintain desired seedstocks can be dependent upon socio-economic issues as well as agronomic performance (Sperling and Loevinsohn, 1993). Perennial crop species may reduce this through the need to only establish the crop once and make repeated harvests from the area, minimizing the risk of successive poor harvests reducing seedstocks. Additionally, land races may be developed over time, reducing the requirement for breeding for specific regions within the landscape.

CONCLUSIONS

Selection within herbaceous perennials for grain and oilseed production has historically not received great interest. Perennial grain and oilseed crops can be achieved however long-term resources must be available to allow for development. Once individual species have been developed, polyculture will be a logical next step. As development of individual species for enhanced forage production has not shown good correlation to production in bi- or polycultures for forage, breeding for polyculture production then will involve selection under different conditions than we currently employ for individual species improvement. Companion species will be required to contribute to sustainability of the system. Profitability of the crop stand will need to be measured by parameters other than simply crop market value to ensure fair comparison of systems and crops.

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AGRONOMIC MANAGEMENT OF PERENNIAL WHEAT DERIVATIVES: USING CASE STUDIES FROM AUSTRALIA TO IDENTIFY CHALLENGES

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ABSTRACT

The prospective development of viable perennial cereal crops is as much about developing novel farming systems as it is about developing novel germplasm. Unlike the development of other new crops such as triticale which could be quickly deployed into existing farming systems with only minimal adjustment, a perennial crop will require a substantial re-engineering of the farming system to take advantage of the production and ecosystem service benefits it potentially has to offer. Australia is a country in which pasture and crop production systems rely heavily on exotic species. Farming systems to utilize these species have therefore been developed over many decades and often differ markedly from production systems elsewhere around the world. The objective of this paper is to assess relevant case studies to identify likely challenges in the deployment of perennial cereal crops, with particular reference to perennial wheat. Perennial wheat crops are likely to be dual purpose crops used for grain and forage. They are likely to be for lower input systems that will require appropriate companion species for biological N_2 fixation and possibly to perform pest control functions in a perennial crop polyculture. Adequate nitrogen supply from biological sources will be a key challenge in viable perennial crop systems; the perennial forage grass experience in Australia highlights the chronic nitrogen deficiency that inhibits grass production in a conventional system that relies almost entirely on biologically-fixed sources of N. This paper provides examples of forage species which were developed in Australia that could present as useful templates in the development of a more biological production system based around perennial wheat. It also shows that different countries have different technologies and different perspectives that will potentially add value to the development of novel farming systems. The challenge to develop such novel farming systems will not be met easily and will likely require a multi-disciplinary, multi-institutional and probably global approach.

Keywords: farming systems, low input, monoculture, perennial grains

INTRODUCTION

A recent evaluation of available germplasm has established the feasibility of the concept of perennial wheat (Hayes *et al.* 2012). That study quantified longevity and grain yield for up to three years and demonstrated an association between the capacity to regrow post-harvest and the presence of at least one whole genome equivalent (14 chromosomes) from the perennial donor species. A subsequent study (Larkin and Newell, 2014) has gone on to explore the ramifications of this finding in the context of progressing perennial wheat germplasm development based on the synthesis of complete amphiploids. Larkin and Newell (2014) liken this approach to the development of triticale; the hybridisation of wheat (*Triticum* spp.) and cereal rye (*Secale cereale* L.), and therefore establish that the genetic improvement of perennial wheat germplasm using this approach has a precedent from which knowledge and experience can be drawn.

However, while the genetic improvement of perennial wheat might be able to draw upon the triticale experience, the integration of the novel perennial wheat technology into commercial farming systems has no such precedent upon which to draw. Few perennial cereal crops currently exist in commerce. triticale, once developed, was able to be incorporated into existing annual crop rotations reasonably seamlessly. The availability of perennial cereal crops will present a unique challenge to develop a farming system that is sufficiently flexible to utilize its grain (Cox *et al.* 2010; Hayes *et al.* 2012) and grazing potential (Jaikumar *et al.* 2012; Newell *et al.* 2013), while at the same time allowing the crop to undertake the essential ecosystem services that have ultimately spurred their development in the first place (Glover and Renagold, 2010; Glover *et al.* 2012; Culman *et al.* 2013). Perennial wheat development therefore not only requires refining the genetics of the germplasm but also the development of suitable farming systems.

This review paper uses examples from existing Australian production systems to identify likely similarities and differences between management strategies required for a commercial perennial cereal crop in the future compared with various existing production systems. The emphasis on Australian farming systems is due to: i) similarity in emphasis on 'mixed' livestock and cropping production systems which have been previously identified as key targets for perennial crop technologies (such as in parts of Africa, see Glover *et al.* 2012), ii) Australia's ancient and inherently infertile soils, again a key target for perennial crop technologies, and iii) Australia's long history of development of novel farming systems based on the need to adapt exotic species to agricultural production in a unique and variable landscape/soil/climate matrix (Bell *et al.* 2013). Using examples and with a particular emphasis on perennial wheat, this paper highlights the importance of considering the end use of novel perennial grain technologies to inform priorities in germplasm development programmes and the way in which the germplasm is evaluated along its pathway to market. We assume a perspective of developing perennial wheat for the Australian market, but suggest many examples cited will have a broader relevance beyond the Australian context.

THE AUSTRALIAN CONTEXT

Indigenous Australians were a hunter/gatherer civilization prior to European settlement in 1788. Agricultural production, in the European sense, is therefore relatively new to Australia. European livestock and cropping production systems needed to be adapted to Australian conditions due to the continent's inherently infertile soils (Hubble *et al.* 1983) and one of the most variable rainfall regimes on Earth (Love, 2004). As a result Australia's modern agricultural production systems are based predominantly on exotic species, notwithstanding a small number of exceptions – rangeland production systems being perhaps the most notable (Harrington *et al.* 1984).

Grain cropping in Australia is predominantly carried out in conjunction with grazing and livestock production – so called 'mixed farming' (Bell and Moore, 2012). Although it adds to the complexity of farm business management (Casburn *et al.* 2013) the mixed farming model offers a number of advantages over a single enterprise model. Firstly, a diversified business is more able to manage economic risk associated with inherently variable weather and commodity prices to which Australian farmers are routinely exposed (Hutchings and Nordblom, 2011). Secondly, a diversity of enterprises increases the capacity to utilize different soil types or landscapes that may exist within a given farm (Bell *et al.* 2013). Thirdly, there is the opportunity for synergistic effects between enterprises, such as fixed atmospheric nitrogen from a pasture phase becoming available during a subsequent cropping phase (Dear *et al.* 2004) thus reducing the need for fertilizer inputs. Notwithstanding, external factors such as reduced availability of labour relative to capital (Bell and Moore, 2012) exert significant pressure on Australian farmers to specialize, similar to their counterparts in other developed nations (Russelle *et al.* 2007; Wilkins, 2008).

The importance of pasture legumes to agricultural production on the infertile soils of Australia has been long recognised (Donald, 1965) and well described (e. g. Angus and Peoples, 2012; Peoples *et al.* 2012). However, very few herbaceous legumes native to Australia exist and many of those are toxic to livestock and unsuited to conventional production systems (Cocks, 2001). As a consequence and particularly post Second World War, Australian agriculture has embraced legume development perhaps more than any other country (Nichols *et al.* 2012) with programmes that have culminated in the release of many novel legume cultivars (Nichols *et al.* 2007). Nicholls *et al.* (2012) identify 30 different legume species that are all exotic to Australia but were first commercialised in Australia. Biological N_2 fixation from pasture legumes was the primary source of N for cereal crops prior to 1990 when the broadscale use of synthetic fertilizer N accelerated (Angus, 2001). Despite this management change, biological N_2 fixation remains important to contemporary Australian grain production systems (Angus and Peoples, 2012).

THE TRITICALE EXPERIENCE

Triticale (*Triticosecale* Wittm.) provides a model for the development of a viable cereal crop through wide hybridisation. This wheat × rye hybrid is the most successful synthetic crop species produced (Ammar *et al.* 2004). Compared with wheat, triticale demonstrates superior adaptation to acid soils, drought, cold, infertile soils and has improved disease resistance (Giunta *et al.* 2003; Erekul and Kohn, 2006; Motzo *et al.* 2011). The intergeneric hybrid between hexaploid wheat (*T. aestivum*) and rye (2n =14 = RR genome) produces octoploid triticale (2n =56 = AABBDDRR genome), while using tetraploid wheat (*T. durum*) as a parent produces hexaploid triticale (2n = 42= AABBRR genome). Although the aim of hybridisation in this case was not for perenniality, the same principles can be applied to develop perennial cereals (Larkin and Newell, 2014).

Since the synthesis of triticale, most breeding efforts and improvement programmes have focused on hexaploid types which dominate world utilisation, mainly in animal feeding, both as a forage and grain (Ammar *et al.* 2004). Triticale production in Australia is approximately 0.75 million tonnes annually (J. E. Roake, 2013, personal communication). By comparison the average wheat production is 25 (USDA, 2013), making triticale only a minor component of cereal grain production in this country. triticale fits seamlessly into current cropping rotations, as basic agronomic practices such as seeding, fertiliser management, pest control and harvesting are similar to other cereals. As a dual purpose cereal, triticale offers an alternative to other grains in mixed farming enterprises. The nutritional characteristics of triticale are superior to wheat in terms of amino acids (particularly lysine, Mergoum *et al.* 2004) which makes it a sought after grain in ruminant and monogastric animal industries. However, the higher ash content, lower milling yields and inferior loaf volume and texture are detrimental for use in commercial baking (Salehi and Arzani, 2013). Many of the gene loci responsible for bread making quality (glutenin-encoding genes) are located on the 1D chromosome, which is lacking in hexaploid triticale. However, techniques exist which can identify greater proportions of glutenin content in hexaploid triticale, which would allow selection for improved bread making quality (Salmanowicz and Dylewicz, 2007). A high proportion of alpha-amalayse activity is also common in triticale grain which further limits dough quality and predisposes triticale to preharvest sprouting (Martinek *et al.* 2008). Addressing these grain quality issues will be important for improving market access of triticale into the future. So too, end use capability and market access will be important attributes for the success of perennial cereal crops. Some attention must be given to grain quality and target area of adaptation when developing perennial cereals to prevent these crops becoming "just another" feed grain or forage species.

THE GRAZING CROP EXPERIENCE

Dual purpose crops (wheat, oats, barley, triticale and more recently canola) to produce both forage and grain, have been an integral part of mixed farming enterprises for many years, both in Australia and elsewhere (Dann *et al.* 1983; Virgona *et al.* 2006; Kirkegaard *et al.* 2012; Tian *et al.* 2012). The ability of annual crops to produce large quantities of herbage during autumn and winter offers an opportunity to rest pastures during this key period (McMullen and Virgona, 2009). The ability to graze dual purpose crops and produce harvestable grain, also improves the gross margin of the farming system and acts as insurance against harvest failure in a poor season and fluctuating commodity prices. This enables increased flexibility in decision making for the farm manager (Virgona *et al.* 2006; Moore, 2009).

Production from dual purpose crops requires a higher level of management as it requires earlier autumn sowing and then grazing in the winter. Earlier sowing takes advantage of warmer autumn temperatures for better crop establishment and crop vigour (Harrison *et al.* 2011). However, earlier sowing can predispose cereal crops to disease because of increased activity of fungal pathogens in warmer temperatures (Virgona *et al.* 2006). Effective break crops and resistant varieties are important to combat these issues, as are the use of pesticides. Similar issues are faced with canola as a grazing crop and the use of resistant varieties and careful grazing management are required to reduce disease incidence (Kirkegaard *et al.* 2012). While spring type cultivars can be used as dual purpose crops, winter types are favoured because of their longer period of vegetative growth. Grazing needs to be managed so that animals are removed before stem elongation. Once the crop matures to the reproductive stage, apical meristems rise quickly with stem elongation, increasing the possibility of removal by grazing and subsequent reduction in grain yield. Inputs of nitrogen (N) fertiliser are required following grazing to replace N removal by animals and to improve grain protein, especially in cultivars with higher grain quality (Virgona *et al.* 2006). While there are many factors that influence grain yield in dual purpose crops, grazing generally reduces grain yield (Harrison *et al.* 2011). However, with precise management grazing can have a positive effect on grain yield of grazed crops compared with their ungrazed counterparts. Grazing lengthens development and delays water use in crops (Virgona *et al.* 2006; McMullen and Virgona, 2009). This water can be conserved and used more effectively after anthesis, when assimilation is directed toward grain yield, thereby increasing water use efficiency. Earlier sowing also leads to deeper roots, increasing access to moisture in the soil profile. The delayed development can allow crops to respond to late season rain in favourable seasons and greater water use efficiency can improve yields under drier conditions.

Cereal forages are known to have extremely high nutritive value and to support high growth rates in sheep (Moore, 2009). However there is concern that the nutrient content of these forages may limit growth rates of grazing animals and lead to nutritive disorders (Berger, 1992; Dove and McMullen, 2009), particularly regarding the ratios of potassium (K), magnesium (Mg), sodium (Na) and calcium (Ca). All cereals contain sufficient Ca for ruminant dietary requirements but K contents can be up to ten times the required intake, while the Mg and Na content for wheat in particular, is generally below dietary requirements (Dove, 2007). Winter grazing of grass monocultures that have high levels of protein and K with relatively low quantities of Mg and Na causes reduced Mg adsorption in the rumen. This inhibits weight gain in animals and can lead to the hypomagnesaemia (grass tetany) disorder (Brightling, 1994). Mineral Supplements are required to correct these deficiencies. Indices of cation ratios can be helpful in deciding the supplement requirements from different forages. Cation ratios K/(Mg + Ca) exceeding 2.2 indicate the need to supplement diets with Mg. Cation ratios for wheat have been reported as high as 3.7 (Dove and McMullen, 2009). By comparison cation ratios for subterranean clover (*Trifolium subterraneum* L.) range from 0.9-1.3 (Dove, 2007). Indices for K:Na have not been quantified, however Na supplementation is also recommended when grazing winter wheats (Dove, 2007). These findings suggest that adverse animal health implications of grazing a perennial cereal crop could be reduced where the crop is grown as part of a polyculture in which grazing animals are exposed to different forages.

THE PERENNIAL FORAGE GRASS EXPERIENCE

Associated with Australia's extensive breeding, development and commercialisation of annual forage legumes from the Mediterranean Basin was the early realisation that these legumes had to be grown in a mixture with a productive companion species. This was necessary because pure annual legume swards tend to be prone to weed invasion and thus not very productive. Growing these legumes with a grass companion greatly increased overall productivity and because the N fixed by the legume would be used by the grass companion the botanical stability of the sward was also improved. The most common grass companion during the early stages of development of this pasture technology was annual ryegrass (*Lolium rigidum*; Oram, 1990). This species is rarely recommended now because of several disadvantages including (a) weed potential to cereal crops, (b) alternative host of several cereal diseases and (c) the annual habit may exacerbate soil problems including erosion, waterlogging and acidification. Perennial pasture grasses, such as phalaris (*Phalaris aquatica*), cocksfoot (*Dactylis glomerata*) and tall fescue (*Festuca arundinacea*) are broadly utilised in Australian farming systems because they do not have the disadvantages of ryegrass or other annual grasses and have been shown to enhance farming system sustainability (Dear *et al.* 2007).

The temperate perennial grasses that are important in the mixed farming zone of southern Australia, phalaris, cocksfoot and tall fescue all contain a wide degree of genetic variability associated with the fact that all their zones of origin encompass large tracts spreading from Eurasia, across the Mediterranean Basin to the verges of the Sahara in North Africa (Anderson, 1961; Borrill, 1972; Lumaret, 1988). Indeed, a key element of the development of appropriate adaptation in these grasses for Australia has involved germplasm discovery in Eurasian and north African isoclimes (Neal-Smith, 1955). Because the zones of adaptation of these species cover such large regions, the range of climates to which adaptation within any one of these species is found is also large. Thus populations from the cool to cold temperate, summer rainfall dominant zones in north-western Europe typically are summer active while those from arid Mediterranean climates of North Africa with summer dry periods of four months or more are winter active and summer dormant (Cooper, 1963). Indeed, some of the grass cultivars best adapted to Australia's drier mixed farming zones, e.g. Sirocco phalaris, Kasbah cocksfoot and Resolute tall fescue, trace their parentage back to populations collected during expeditions to Africa and the Near East. Ideally, perennial donor species for perennial cereal crops intended for Australian environments would also be sourced from Eurasian and/or north African environments, if no suitable native species could be identified.

Perennial grasses able to survive the hot, dry summers which are typical of southern Australia generally have to express one or a combination of traits including summer dormancy (Volaire and Norton, 2006), dehydration avoidance (Norton *et al.* 2012), or dehydration tolerance (Volaire and Conejero, 2001) to ensure survival. In addition lenient grazing over the summer may also be required because the joint stresses imposed by defoliation and drought, which threaten both plant carbohydrate reserves and water status, are important in reducing survival of perennial pasture grasses (Volaire, 1995; Hacker *et al.* 2006). In addition, some species, e.g. cocksfoot, typically shed many roots over dry summers and this may make them susceptible to being pulled out of the soil by livestock if grazing occurs before replacement roots have regrown sufficiently (Ridley and Simpson, 1994). It will be important to understand the nature of the perennial cereal crop rooting structure in order to develop a grazing system that maximises productivity but does not compromise plant persistence.

The length of time that a sown perennial grass based pasture is likely to persist is a key determining factor that the farmer must consider when deciding whether or not it is economic to sow a new pasture. The decision will also be influenced by the costs associated with pasture improvement and the extra income that the farmer will likely obtain from the improvement. Decision support tools are increasingly being used to assist in the making of these decisions (e.g. www.evergraze.com.au/tools.htm). However, in any case there will be a minimum amount of time over which the newly sown pasture must persist and produce for the farmer to recoup his investment (break-even period) and this will be influenced by the genetic makeup of the new pasture (i.e. how well it is intrinsically adapted to the environment), and the management that the pasture experiences. Commonly break-even periods of 6-10 years are quoted for pasture resowing although depending upon the rate of return required on investment this may even increase to 20 years (Scott *et al.* 2000). As a consequence persistence is acknowledged as an important attribute that any successful cultivar should possess. Longevity of a perennial cereal crop will too be an important factor in determining its economic viability, though income received from grain yields would likely reduce its required persistence, compared with a perennial forage grass.

When the agronomic practises used for the various types of grasses are considered, the perennial grass crop which is maintained primarily for seed production is the closest analogue we have which mimics a perennial, dual-purpose, forage/grain cereal. The management of any perennial grass will, by necessity be quite different depending upon whether it will be used solely for forage or have a dual purpose as a forage and grain/seed crop. The practise absolutely essential to maximise grain/seed yield is to protect the reproductive tillers from defoliation. This necessitates the removal of grazing animals or the cessation of cutting prior to when reproductive tiller elongation commences. Similarly management practises, e.g. sward renovation, fertilisation, plant protection etc. to maximise the density of fertile reproductive tillers which are initiated will optimise yield potential. In the same way reducing the likelihood of lodging, perhaps by application of straw shortening hormone, during the late reproductive growth stage is increasingly recommended to improve seed yield recovery.

In contrast, for a grass whose primary function is forage production the protection of the reproductive tillers is generally not particularly essential. This is especially so because for most perennial forage grasses recruitment of young plants from seed is not the primary means of sward perenniation but rather the long term survival of adult plants. Perennial grasses grown for forage in Australia are almost always sown with a companion legume the aim being two-fold, to improve sward forage quality and enhance soil nitrogen status through biological N_2 fixation. In contrast, perennial grass seed crops are rarely grown with a companion legume as the seed is usually of high value so that seed producers are able to absorb fertilisation costs. Moreover, the agronomy required for maintaining a mixed grass/legume sward is more complicated than pure grass culture and the favourable returns make additional complexities unnecessary. In contrast, the value of grain produced by a perennial cereal will certainly be much less than seed produced by a perennial forage grass. Consequently the forage produced by the perennial cereal will assume an important part of the overall value of the crop, particularly if as demonstrated in a previous modelling exercise, it is produced, 'out-of-season' in autumn in southern Australia (Bell *et al.* 2008). Whether substantial 'out-of-season' autumn forage production will be achievable from a cool season perennial grass at a time of the year normally quite dry remains to be seen.

MONOCULTURES VERSUS POLYCULTURES

Various authors have suggested that a move toward perennial crops may also represent a move away from the reliance on monocultures (Cox *et al.* 2006; Glover *et al.* 2007; Glover and Renagold, 2010; Glover *et al.* 2012). Recent research in forage species would support the notion that perennial crop-based polycultures could be commercially feasible to the extent that increased species richness on average increases total biomass productivity and weed suppression in perennial herbaceous polycultures (Tracey and Sanderson, 2004; Picasso *et al.* 2008; 2011). However, this is in a pure forage production system – what negative impacts could we anticipate on grain production of perennial cereals grown in a mixed sward?

The fundamental basis for targeting a polyculture system is to enhance resource utilisation through complementarity of companion species (Glover and Renagold, 2010; Picasso *et al.* 2011). The most obvious example of complementarity is the synergy between a N_2-fixing legume providing N to non-legume species growing in the same sward. In designing perennial crop-based polycultures, it would seem the integration of appropriate companion legumes would be an obvious place to start. Nitrogen is a critically important macro-nutrient for forage and grain-crop species alike, and a farming system that reduced or eliminated the need for synthetic nitrogenous fertiliser would quickly achieve many of the fundamental imperatives of a perennial crop, such as reduced nutrient leakage and lower input requirement (Glover *et al.* 2007, 2012; Glover and Renagold, 2010). Yearly nitrogenous fertiliser consumption for annual cereals grown in Australia totals $702x10^6$ kg/ha, the highest use of any agricultural enterprise (Chen *et al.* 2008). A great proportion of the applied nitrogen is lost, with efficiencies of uptake for cereals such as wheat quoted at 41 percent (Chen *et al.* 2008). The loss of nitrogen represents a significant business inefficiency for farmers as well as having negative implications for the environment and human health. Perennial grains grown in polyculture could provide a way of reducing synthetic nitrogenous fertiliser use in cereal grain production systems.

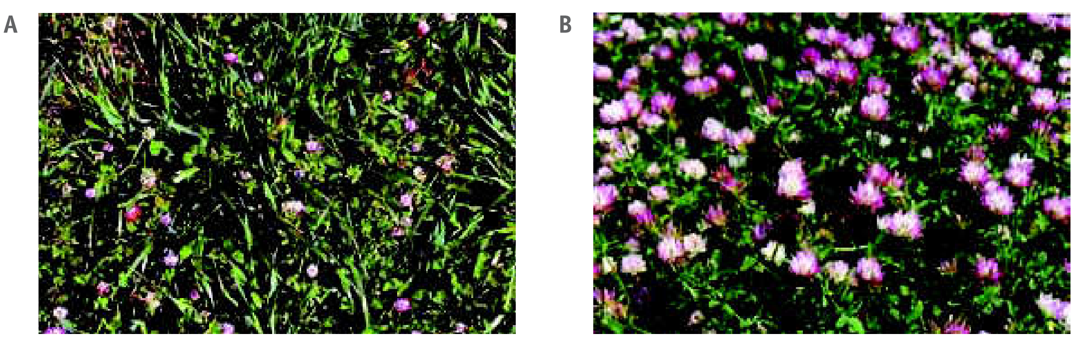
Several surveys conducted across southern Australia (e.g. Fortune *et al.* 1995; Bowman *et al.* 2004; King *et al.* 2006) have commonly found legume composition in commercial mixed pasture swards to be inadequate. The reasons for this are varied but it highlights a practical challenge which is likely to exist if we also expect legumes to coexist with perennial cereal crops. One contributing factor to the Australian experience is the paucity of adapted perennial legume species, particularly in drier cropping-zone environments (Cocks, 2001; Dear *et al.* 2003a; Li *et al.* 2008). Therefore Australian pasture swards are overwhelmingly reliant upon annual legumes such as subterranean clover (*Trifolium subterraneum*) and barrel medic (*Medicago truncatula*). Perennial crops in Australia will also probably be reliant upon annual legume species unless the target environment is the high rainfall permanent pasture zone where white clover (*T. repens*) and Caucasion clover (*T. ambiguum*) are more likely to be adapted (Virgona and Dear, 1996; Lane *et al.* 2000), though seed of the latter species is difficult to obtain at present. Mixtures with alfalfa

(*Medicago sativa*) is a possibility (Boschma *et al.* 2010) in the cropping zone although its supreme capacity to extract soil water in moisture limiting environments (Hayes *et al.* 2010b) is likely to have a negative effect on companion perennial crops similar to its effect on companion annual legumes (Dear and Cocks, 1997) or over-sown cereal cover-crops (Norton and Koetz, 2013).

The nitrogen requirement of perennial cereal crops needs to be determined so that the 'adequate' legume content can be defined. Perennial forage grasses are highly responsive to N fertiliser (e.g. Mills *et al.* 2006) although critical N requirements of common perennial grass forages in Australia are still to be defined. Stork and Jerie (2003) calculated the relative uptake of inorganic N between late autumn and early spring (1 year only) to be 169 kg N ha^{-1} under one year old phalaris. However, Dear *et al.* (1999) demonstrated that a phalaris/subterranean clover mixed sward was only capable of fixing 143-177 kg N ha^{-1} over three years; less than one third the requirement of the perennial grass component, even ignoring the fact that only a proportion of total N fixed in a mixed sward will become available to the grass. Therefore in an Australian system we could expect that perennial grasses grown in mixed commercial swards would typically exist in an almost permanent state of N deficiency. The N-status for perennial cereal crops could be even more constrained due to the elevated N demand for grain production. This needs to be quantified, as does the importance of timing of N supply to a dual purpose cereal crop. The N status of a mixed perennial grass pasture sward in Australia is likely to be better in autumn due to increased mineralisation and reduced N demand over summer, while supply in spring is likely to be much more limiting and it is unclear what implications this would have on grain yield, grain quality and longevity of a perennial cereal crop.

Nitrogen nutrition is more complex than other nutrients because of the strong relationship between plant growth, nitrogen availability and available soil water.

FIGURE 1. PERENNIAL GRASS AND ANNUAL FORAGE LEGUME



A. A mixed forage pasture sward containing a perennial grass (*Phalaris aquatica*) and self-regenerating annual legume species (*Trifolium subterraneum*, *T. michelianum* and *T. glanduliferum*)

B. Gland clover (*T. glanduliferum*); A self-regenerating annual forage legume released commercially in Australia for its superior insect pest resistance

Assumptions can be made to calculate the N requirement of conventional wheat. Following Glendinning (2000); if we assume a grain protein content of 11 percent and a protein conversion factor (PCF) of 1.75[1], the estimated grain nitrogen yield is 11×1.75 = 19.2 kg N/tonne grain. The quantity of soil nitrate required is a function of grain nitrogen yield divided by the N-uptake efficiency (NUE). NUE (efficency with which fertiliser N is converted to grain protein) varies according to the physiological state of the plant, but is estimated to range from 50 percent around sowing down to approximately 15 percent at head emergence (White and Edwards, 2008). Assuming a 50 percent NUE, the estimated quantity of soil nitrate required to produce 1 tonne of grain is 19.2/0.5 = 38.5 kg N/tonne. Therefore an average 3 tonnes/ha wheat crop would require 115.5 kg of nitrate N. However, as the grain protein content increases, the NUE decreases, as the crop has difficulty accessing enough water to use the extra nitrogen required for increased protein (Herridge, 2011). Thus at a grain protein level of 14 percent, NUE falls to 34 percent, requiring 75 kg N to produce a tonne of grain.

Assuming 25 kg of atmospheric N is fixed in annual legume shoots for every tonne of DM of legume shoot biomass produced (Dear *et al.* 1999) and making an allowance for an additional 20 kg fixed N/tonne legume DM associated with or derived from legume roots (Peoples *et al.* 2012), total N fixed biologically is equivalent to 45 kg/tonne of total legume DM. Assuming that 50 percent of the total N fixed becomes available to the crop, a wheat crop yielding 3 tonnes/ha at 11 percent protein would require 5 tonnes/ha of legume biomass to supply nitrogen to the system. A number of limitations are acknowledged with the above calculations:

1. the N requirement to produce 1 tonne of grain from perennial wheat may differ to that estimated for annual wheat due to factors such as a different PCF or different grain protein level
2. the proportion of legume N derived from atmospheric N_2 will vary according to legume species, seasonal conditions and soil factors
3. the actual proportion of legume N available to the companion crop will be dependent upon factors such as grazing strategy, mineralisation rates and transfer mechanisms between crop and legume plants.
4. in a dual purpose crop, an allowance needs to be made for N removed due to grazing

Nevertheless, the above provides a starting point in determining how much N a perennial wheat polyculture might need, and illustrates the high legume content required if biologically fixed N would be the sole source of N. To put these values into context, total pasture herbage production of various perennial-based pasture swards in two representative Australian field environments ranged from 24-31 tonnes/ha over five years (Hayes *et al.* 2010a) or an average of 5-6 tonnes/ha/year. In such an environment where biomass production can be so low, a major question must be whether a perennial crop grown with the robust companion legume component

1 The PCF for other crops is commonly 1.6; the PCF for perennial wheat is unknown and will need to be determined

necessary to supply the crop's full N requirement can be commercially viable? It is possible that a system that uses legumes in addition to strategic applications of N fertiliser be developed to reduce the legume composition necessary to supply adequate N, although Peoples *et al.* (2012) highlight the negative effect N fertiliser can have on biological N_2 fixation.

A polyculture is clearly an advantage relative to a monoculture from the perspective of grazing due to: i) the reduced likelihood of adverse animal health conditions and ii) improved forage quality. Grazing ruminants have evolved to ingest a diverse diet, and significant health disorders can ensue if that diversity is not maintained. In general, the ruminant gut relies on an ecosystem of microorganisms to break down food, and the composition of that ecosystem is dynamic and responsive to a changing feed source (Cottle, 1991). Where an imbalance occurs in the diet, there is risk of an imbalance in the gut which can lead to negative effects on health that are sometimes irreversible. These negative effects can occur even when the diet is of high quality, for example, red gut (Gumbrell, 1997) and bloat (FitzGerald *et al.* 1980) from legume pastures or acidosis and lupinosis from grain diets (Brightling, 1994), highlighting the risks to animal health that high quality but imbalanced diets can present to ruminant livestock. The grass tetany example mentioned earlier relating to grazing annual cereal crops is perhaps more indicative of the type of disorder a monoculture perennial cereal crop may present. Regardless, these disorders can usually be managed if there is a balanced diet highlighting a clear advantage of a dual purpose crop grown in a polyculture as opposed to a monoculture.

In addition, a vibrant legume component can improve forage quality for the grazing livestock. Legumes, such as alfalfa, often have a higher protein content and concentration of minerals in their shoots than grasses (e.g. Hayes *et al.* 2008; Hayes *et al.* 2010a). Thus, their presence in a mixed legume/grass sward presents as a high quality component available to browsing livestock. Moreover, the presence of a legume can significantly enhance the quality of the grass herbage through increased N-supply to the grass. Mills *et al.* (2006) showed that the addition of N increased the crude protein of cocksfoot herbage by up to 4-fold and more than doubled the metabolisable energy, in part a reflection of the doubling of pasture growth rates due to additional N. The ability of legumes to substantially enhance the N supply to companion grasses primarily relies on the pasture sward containing a substantial legume content (Peoples *et al.* 2012) and depends upon the efficiency of transfer of N between the legume and grass components.

In its simplest form, a perennial cereal/forage legume polyculture is only a binary mixture and it is acknowledged that production benefits of mixtures may not be fully realized until three or more complimentary species are included (Tracey and Sanderson, 2004). As described above, nitrogen fixation from a legume component is an obvious and easily defined benefit of a polyculture but there are potentially other benefits. Glover *et al.* (2012) describe the 'push-pull' benefits alternative species may offer in controlling pests, particularly in low input production systems. Very briefly the 'push' refers to species that can repel pests thus pushing them away from the valuable crop plant; the 'pull' referring to plants that can attract pests towards them and away from the crop plant. The effectiveness of a push-pull strategy is likely to be site dependant and will vary according to factors such as the type and severity of the pest incursion and the availability of plants with properties capable of pulling or pushing the pest(s) in question. However, there would appear to be enormous potential for research as the push-pull potential of most species is poorly understood.

There are undoubtedly candidates from Australia's various plant development programmes that may have a use in a push-pull context despite this not being the primary motivation for their development. Gland clover (*T. glanduliferum*) was commercialised by Australian scientists for use as a novel alternative in the pastures of mixed farming systems in medium rainfall environments (Nichols *et al.* 2007), particularly on heavier soils (Dear *et al.* 2003b). It has a unique resistance to various insect pests such as redlegged Earth mite (*Halotydeus destructor*), as well as blue green (*Acyrthosiphon kondoi*) and cowpea (*Aphis craccivora*) aphids and although it has been evaluated in forage mixtures (Dear *et al.* 2002; Hayes *et al.* 2008), its potential as a 'push' species was never specifically tested. Biserrula (*Biserrula pelecinus*) is another novel annual legume species also released by Australian scientists as a viable small-seeded legume for pasture crop rotations, particularly where acid soils constrain production (Nichols *et al.* 2007). Sheep tend to avoid grazing this species at certain periods during the year which has fostered its promotion as part of a non-herbicide weed control strategy. It is possible that this species could be incorporated in a non-herbicide weed control perennial crop based system.

These examples highlight two potential opportunities for future perennial grains research. Firstly, they demonstrate that alternative species already exist in commerce around the globe that may have potential to provide complimentary benefits to perennial crops but are yet to be tested in this context. Secondly, it reminds us that germplasm may have existed in previous plant development programmes with similar potential but which were never commercialised because the target market at the time was not focussed on complimentary benefits to other species (certainly not perennial crops) but instead the potential contribution these species could make to production systems in their own right. In a perennial grains context it will be important to define the essential characteristics required of companion species to guide the selection of companion species with which early generation perennial crops should be tested. Both examples above are legume species capable of high rates of biological N_2 fixation, highlighting the likelihood that companion species in a perennial crop context will be required to perform more than one function.

GERMPLASM AND FARMING SYSTEM CO-DEVELOPMENT

The vision for diverse perennial grain cropping systems to replace monocultures of annual crops has been described by various authors previously (e. g. Glover *et al.* 2007; Cox *et al.* 2010). However, in contrast to Cox *et al.* (2010) who suggested that "before such systems can be deployed and tested, new perennial…crops must be developed through breeding", we contend that the process of crop development and farming system engineering should not be separated.

Moreover, the perennial grain crop will ultimately be more successful in commerce and achieve greater environmental impact if the development of both the crop and the farming system occurs concurrently, and better still, if one informs the other in an iterative, multi-disciplinary process.

The temperate perennial forage grass experience in cropping environments of southern Australia provides a useful example highlighting the importance of co-development of the germplasm and the grazing system. Phalaris – another example of an exotic forage species that was primarily developed in Australia (Oram *et al.* 2009) – and cocksfoot are key temperate perennial grass forages in Australia. However, though they are used widely in higher rainfall, permanent pastures, only a few cultivars of either species exist that are suited to drier cropping environments and seed of these cultivars is incredibly difficult to obtain - Australia is currently experiencing market failure in regard to these cultivars. We contend that a major cause of the current market failure was the failure of the local industry to develop the farming system adequately. There is little doubt that the cultivars, primarily Sirolan phalaris (Oram *et al.* 2009) and Kasbah cocksfoot (Oram, 1990), are agronomically suitable to their target environment (Hackney *et al.* 2006 and unpublished data). However, their addition to the phased farming system of southern Australia brought additional complexity to the management regimes which was never adequately explored by the research community and probably explains much of the reason why farmers felt it easier to leave these species out of their rotations. For example, no selective grass herbicides currently exist which are registered for use to control annual grass weeds in establishing perennial grass-based swards (Dear *et al.* 2006) and no integrated weed management strategy has been developed or tested to provide farmers with workable strategies to control their grass weeds in a perennial-grass based sward. Likewise, no previous research has tackled the nitrogen question in relation to perennial grass swards. Farmers require their pasture phase to leave adequate residual soil N for use by subsequent crops (Angus, 2001). Perennial grasses are known to be highly competitive with annual legumes and therefore suppress nitrogen fixation of the total sward (Dear and Cocks, 1997; Dear *et al.* 1999; Dear *et al.* 2000). But no research has yet answered the question of how perennial grasses can be included into cropping rotations in such a way that maintains adequate levels of biological N_2 fixation. Due to the lingering questions about management issues such as weed control and N supply, Australian farmers in the mixed farming zone have avoided utilising these grass cultivars, which has sent feedback through the seed supply chain over the last two decades rendering these cultivars commercially unviable and culminating in a situation in which even a progressive farmer would find incorporating these species problematic due to the paucity of commercial seed.

An existing research project, EverCrop™ (Llewellyn *et al.* 2013), is currently examining the problems around the inclusion of perennial grasses into cropping systems and is trialling the practice of planting mixed swards in monoculture rows. However, an additional problem facing this project is the negative perceptions that some farmers have of perennial grasses in these systems on account of their previous bad experience with the technology. Because the cultivars were developed in isolation from agronomy management research, they failed to meet the expectations of farmers. On account of prejudices which exist with some farmers in relation to these grasses, it is now much more difficult for researchers to achieve meaningful practice change on farm. It is our contention that perennial wheat developers should heed the lessons of Australia's perennial grass experience; perennial wheat technology is likely to be much more successful if a suitable farming system exists at the time the germplasm first becomes commercially available, and the integration and adoption of the new technology will be easier to achieve if bad commercial experiences are avoided.

REFLECTING UPON INITIAL EVALUATION OF PERENNIAL CEREALS

The initial evaluation of perennial wheat derivatives undertaken in Australia (Hayes *et al.* 2012) established the feasibility of the concept of perennial wheat and helped researchers define a strategy for continued development of the wheat × wheatgrass germplasm (Larkin and Newell, 2014). Despite the constraints of limited seed supply hampering the evaluation, a number of inferences could be drawn from the initial study with regard to the likely farming system required of a perennial wheat crop in Australia. It was established that early-generation perennial wheat derivatives were unlikely to persist unless they were grown in high-rainfall environments. Without the introduction of summer dormancy traits the germplasm is unlikely to be able to persist through the hot and dry summer conditions typical in most conventional Australian cropping environments. This is certainly the experience of temperate perennial forage grasses in Australia (Hackney *et al.* 2006; Hayes *et al.* 2010a) and elsewhere (Malinowski *et al.* 2005; Norton *et al.* 2006a,b). However, as with perennial forage grasses it is acknowledged that zones of adaptation can change with continued plant breeding and development. This insight on zone of adaptation immediately provides direction as to the initial companion species that might be targeted in an Australian context; annual and perennial legume species suited to higher rainfall/permanent pasture regions.

However, the initial evaluation was conducted on monoculture, and in many cases, on single row plantings, neither of which is likely to be relevant to commercial perennial wheat plantings. We acknowledge that there will always be a role for testing germplasm in monocultures and, as with the initial evaluation in Australia, monoculture testing is sometimes unavoidable. But if perennial wheat is ultimately envisaged to be grown in polycultures, we suggest that evaluations of perennial crop technology in polyculture occurs early in the development pathway to ensure that the technology is relevant to the situation for which it is intended and that when a perennial crop technology becomes commercially available, a good body of knowledge already exists as to the appropriate management strategies. Most evaluations of forage species in Australia, both legumes and grasses, assess species and cultivars in monocultures. It is understandable why this occurs in the context of measuring relative performance and eliminating all possible sources of error. However, for species that are never to be used as monocultures commercially, surely it is a failing never to test them in their commercial setting until after release. The case for evaluating perennial grains in polycultures is even stronger than for forage species in Australia because not only does the evaluation process screen germplasm, it also develops and refines management strategies for this novel technology.

One final observation: the initial evaluation of perennial wheat in Australia (Hayes *et al*. 2012) was unexpectedly successful. The project had a relatively small budget, none of the germplasm tested was developed for the Australian environment, and none of the research team had previous experience in growing perennial cereal crops. However, the project was able to establish the biological feasibility of perennial wheat crops in Australian environments and could associate the capacity for PHR with the addition of one extra genome equivalent from the perennial donor, thus paving the way for the development of a breeding strategy for the crop (Larkin and Newell, 2014). The success of the research initiative was in no small way attributable to the collaborative, multi-disciplinary approach the project took. The collaboration first relied upon an institution, the Future Farm Industries Cooperative Research Centre, to invest in genuinely '*blue-sky*' research and on research providers (NSW DPI, CSIRO and Charles Sturt University) to co-invest with infrastructure and the valuable time of their staff. Second, it relied upon generous contributions by partner agencies on the other side of the globe, The Land Institute and Washington State University, to provide free and ready access to their best available germplasm. Third, it relied upon the competency of a research team which collectively possessed a broad range of skills including crop agronomy, pasture agronomy and adaptation, physiology, genetics, molecular biology and cereal chemistry. The Australian team also had an advantage in that they were not constrained to biological methods for conducting experiments. This meant they were free to use herbicides, fungicides and fertilisers as appropriate which no doubt assisted in evaluating the genetic potential of the germplasm. It is likely that future success in the challenging field of perennial grain development will also require a multi-disciplinary, multi-institutional and probably international approach.

SUMMARY AND CONCLUSION

Triticale, the most successful hybrid crop, establishes a precedent by which genetic improvement in perennial wheat might be achieved. Despite its superior adaptation to a range of biotic stresses triticale is underutilised in Australia due to its inferior grain qualities, particularly properties important to commerce viz. baking and malting, rendering its grain less valuable than other cereals such as wheat and barley. This is a reminder that the end use of the product is an important consideration determining the extent to which benefits of the genetic gain achieved in the breeding of this crop are realized in the commercial world. So too, the end use of perennial crops needs to be defined and articulated early in the development process to facilitate maximum impact of the technology.

Existing grazing crops provide confidence that the dual-purpose attributes of a perennial cereal will likely add to the flexibility and resilience of mixed farming enterprises, capitalising on the financial benefits associated with diversified income streams as well as improved adaptation to variable weather patterns. Avoiding animal health risks associated with grazing monocultures, and meeting the elevated N requirement caused by N-removal from grazing livestock will be key challenges to be met in perennial cereal production systems. However, the use of perennial cereals in polycultures with legumes will potentially overcome both these constraints.

The temperate perennial forage grass experience in southern Australia provides both hope and caution for the development of viable perennial cereal production systems based on polycultures. Perennial forage grasses in Australia typically rely almost entirely on biological N_2 fixation from pasture legumes and thereby present as an example of a viable polyculture production system. However, a range of factors such as the paucity of legume species available (particularly perennials), the variability of N_2 fixation in the field and the competition between the grass and legumes growing in the same sward mean that perennial grasses likely exist in an almost permanent state of N-deficiency. Using figures from existing industries, early indications suggest that the N-requirements of perennial cereal crops would be even greater than that for perennial forage grasses due to the need to maximise grain yield and grain quality. The suggestion offered in this paper of 5 tonnes of legume DM required in a polyculture to supply adequate N for 3 tonnes of perennial wheat grain could be proven incorrect in time if our various assumptions are wrong, but it paints an ambitious picture of the potential composition of a perennial wheat/legume polyculture raising questions as to whether a polyculture that supplied 100 percent of the crop's N requirement is commercially feasible. This is a priority area of research in perennial crop development. If a polyculture remains the preferred model for perennial cropping systems, the multiple roles of the companion species need to be defined so that suitable species are identified and tested. This paper highlights the potential of legumes commercialised in Australia to perform multiple functions as companions in perennial cropping systems, but there is a need to screen a wider range of potential species for their suitability.

Many challenges lay ahead on the road to developing a viable perennial crop. Germplasm development itself is not trivial, but the need for novel farming systems adds to the challenge. It is unlikely this challenge will be met by individuals operating in isolation. The *Perennial Wheat Feasibility Study* undertaken in Australia presents as an example of the unexpected success that can be achieved in this challenging field of research particularly where vibrant multi-disciplinary, multi-institutional and global collaboration exists. We contend that future challenges in perennial crop development will be best met by a similar but scaled-up collaborative approach.

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26

BACK TO THE FUTURE! THOUGHTS ON RATOON RICE IN SOUTHEAST AND EAST ASIA

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In China *Oryza sativa* has been grown as an annual for perhaps 10-12 000 generations although ratooning certainly survived until about 3 500 years ago. By contrast, in Southeast Asia, including marginal areas populated mainly by ethnic minority peoples such as India's northeastern territories and parts of Bangladesh, the cultivation of perennial strains extended into the twentieth century. The degree to which this practice survives to the present is not known. Despite being grown as an annual, many strains of rice retain a perennial habit to some degree though yields are commonly very much lower from ratoon crops than from initial plantings. In Japan, a ratoon yield of about 15 percent of the first harvest has been reported. No systematically-gathered data on ratoon-crop yields have been found, though Hill (2010) has drawn together historical accounts of the practice. He reported observing it in Johor, Peninsular Malaysia in the 1960s and in northern Laos in the 2010s.

The need for Asian rice-growers to move from highly labour-intensive methods to less labour-intensive methods arises from a general rise in the cost of labour. In the 1960s the opportunity cost of rice-growing in China and much of Southeast Asia was probably close to zero. In most of the region it is now much above that level, a situation reflected in substantial short-term circular migration by rice-growers and in some cases by production at an economic loss, as was already reported in parts of Peninsular Malaysia in the 1960s.

Because tillage, nursery-preparation and planting, and, especially, transplanting, may require half to two-thirds of labour input per crop, any system of production that can reduce such inputs, without an excessive yield penalty is very desirable for the cost of labour will inevitably continue to rise.

Keywords: ratooning rice, Southeast Asia, East Asia, agricultural development

INTRODUCTION

In Asia rice ratooning has a long history, one which is generally little known among rice scientists or farmers. For Southeast Asia, Hill (2010) has examined that history in some detail, pointing out that much of the documentary record has been misinterpreted by later commentators. This paper extends the analysis to China and Japan though for linguistic reasons this author does not have access to works in Japanese or in Chinese. Drawing on the resources in his on-line bibliography on the history of Southeast Asian agriculture (Hill, 2007), an outline of the historical record for the region is given. This is followed by a consideration of some important areas for the future study of ratooning and assessment of the feasibility of promoting ratooning in the region.

Over the last half century the region has seen a remarkable structural transformation of agriculture in general and rice production in particular. Generally there has been a long-continued process of commercialization of production, though in some areas this has had limited effects, largely because of structural limitations in production, such as very small size of farms and, especially limited alternative activities. Fifty years ago it seems likely that in much of the region, Japan and Southeast Asian plantation areas accepted the opportunity cost of rural farm labour was close to zero. That situation has largely changed with urban employment as a rapidly-emerging economic alternative. This has been and continues to be linked with permanent rural-urban migration but also with widespread temporary circular migration. For example, a study some years ago showed that the population of Bangkok in the dry season was about nine percent higher than in the wet season. This was the result of farmers flocking to the towns for temporary employment, partly in manufacturing but especially in construction, as the Thai case suggests (Hill, 2002).

Urbanization and the overall growth in real incomes together with demographic changes have also had the effect of reducing per person demand for rice, though total demand has continued to rise partly for demographic reasons. This situation is unlikely to last. The population fertility rates of Japan and Thailand, as well of major urban concentrations such as Hong Kong and Singapore, are now well below replacement level which is about 2.2 children per woman of child-bearing age. China's population growth rate is forecast to fall to zero around 2026 and the total population will fall substantially thereafter unless its government abandons its 'one-child' policy and adopts a more pro-natalist stance. Even if it does that there is likely to be a substantial increase in the cost of labour for around two decades until the new generation reaches the labour force.

Globally, the consumption of rice per person has levelled out the late 1980s (Rejesus *et al.* 2012) though demand in Africa continues to rise. Estimates of very large increases in demand are probably not well-founded. Fageria (2007), for example, estimated a requirement of 60 percent more rice by 2025, just over a decade away. The reality is that since the 2007-8 season, global rice stocks have tended to rise, reaching close to an estimated 35 percent of annual global consumption by 2013-14 (FAO Rice Monitor, July 2013). This will give something of a breathing space to develop alternatives to the region's current highly labour-intensive methods.

At the same time, an emerging consideration in the production of rice is urban expansion, in many areas onto prime rice-growing land. Politically, governments continue to be faced with a need to ensure a continued supply of rice to urban markets at reasonable prices. Every government in the region is aware of the need to hold rice prices at a reasonable level for urban workers. Given that farm labour costs are inevitably rising and that labour mobility is increasing, there is a need to control the costs of rice production. One method of doing this is to ratoon, for this approach substantially reduces the labour cost of traditional methods involving nursery preparation and transplanting, probably by around 50 to 60 percent per crop (Flinn and Mercado, 1988). One competing strategy, of course, is to abandon transplanting and to substitute for it broadcast sowing. However, this has the considerable disadvantage that satisfactory weed control in the early stages of growth requires enhanced applications of herbicides, the long-term effects of which are not fully-known. This may emerge as an issue with ratooning as well, especially if a main crop is followed by two ratoons, as seems to have been practice in some areas in the past.

RATOONING - THE HISTORICAL RECORD

Ratooning clearly has a long history. In China, so far considered to be the home of the longest-running sequence of rice cultivation, it seems likely that ratooning was abandoned as a general practice in early historical times, perhaps 3 000 years ago or even more. If this is so, then the practice of growing *Oryza sativa* as an annual may have led to genetic drift away from good yields from ratoons. Certainly, the limited data for ratoon yields from present-day varieties show a wide range. An analysis of such literature as is available to me gives claimed ratoon yields ranging from around 8.7 tonnes/ha (Xu *et al.* 1988; Prashar, 1970) to about 0.3 tonnes/ha or even less. Chauhan *et al.* (1988) give comprehensive data. Parenthetically, it should be noted here that almost without exception writers on the subject of yields fail to give data on the size of the plots employed in making their yield estimates. Many are probably serious over-estimates, seemingly being based upon small-scale trials.

The origins of rice cultivation have been the subject of much debate, some of it perhaps underlain by nationalistic considerations. Oka and Morishima (1997) review several hypothesized routes to the evolution of Oryza *sativa*, pointing out that many common wild rice varieties tend to differentiate into *indica* and *japonica* types. Watanabe (1997) briefly examines the origin and differentiation of cultivated rice in Asia. As a crop, rice may go back 6-8 000 years in China though whether it was fully-domesticated at that time is a matter of some doubt (Sweeney and McCouch, 2007; Liu Zhiyi, 2000). Similar ages have been claimed for India. Rice-growing in Japan dates back to the late Jomon period, around 3 000 BP at the earliest (Matsuo *et al.* 1997). This is somewhat later than the earliest rice in mainland Southeast Asia where the crop dates back four or five millennia, possibly more. Even in equatorial Southeast Asia, the crop may date back as much as six millennia, as recent data from the Niah Cave, Sarawak, suggest (Hunt and Rushworth, 2005). Their finding at this low latitude, just south of four degrees north latitude, may imply an early existence of non-photoperiodic varieties or at least of varieties responsive to very small differences in day-length. What can be asserted with some degree of confidence is that *O. sativa* probably differentiated into two subspecies, the more northerly and temperate *japonica* and the more equatorial *indica*, as a result of at least two independent series of steps leading to domestication (Tao Sang and Song Ge, 2007).

Arguably, many of the early varieties of rice in the region had a significant ability to ratoon though wherever it may have been grown it seems likely that it would not have been grown beyond a second ratoon at the most, for by that stage the competition from weeds would probably have rendered yields so low as to be not worth harvesting. A search of the modern literature failed to find a single case of anything beyond a first ratoon, though as I have argued elsewhere, it seems likely that a second ratoon was probably taken in Indochina and in other parts of Southeast Asia in earlier historical times (Hill, 2010). Documentary and field research has shown that the practice of ratooning survived into modern times in the Malay Peninsula, in Laos, and reportedly, in one-crop areas in Japan (T.S. Stanley, personal communication, 10 Dec. 2007).

Earlier, ratooning seems to have been fairly widespread. While not quite a 'free good', ratoon rice avoids the need to till the soil, to prepare nurseries and to transplant seedlings to the extent that this practice may reduce labour demand by about half. Certainly it may increase the labour demand for weeding but not to a level comparable to the demands of soil preparation, nursery preparation and transplanting. For China, Ho Ping-ti has assembled firm evidence for what was probably perennial cultivation, likely more or less contemporaneous with annual cultivation, dating from the Shang dynasty (*ca* 1 600 BC to *ca* 1 046 BC), though Ho refers to it as a wild rice (Ho, 1957, 1969). Cultivation of some kind, or at least weeding and replanting are probably indicated because weed invasion inevitably overtakes any abandoned rice-field. Fuller, Harvey and Qin (2007) have pointed to the cultivation of what they rather paradoxically refer to as 'wild' rice, as early as the 5 000 BC.

The documentary record for Southeast Asia is rather more extensive though bedevilled by major gaps, for example for Indonesia. Clercq (1871) is just one of a host of papers in Dutch on agricultural practices in colonial times in Indonesia to be silent on the matter of rice ratooning. It is unlikely to have been altogether absent. For Japan the evidence for ratooning at any period linguistically accessible to this author is exiguous. The four-volume compilation by Matsuo and his colleagues seemingly makes no mention of the practice though it is difficult to be certain because that work lacks an index. Papers in that collection make no mention of the practice (Matsuo *et al.* 1997).

The early literature has been beset by problems of interpretation, as Hill, (2010) has noted. In particular, in archaeological contexts, is the formidable difficulty of distinguishing the remains of annually-grown rice varieties from their perennial cousins. What is clear is that much of the work of historians of the region dealing with the documentary evidence has been bedevilled by a lack of knowledge of field practice by present-day cultivators. It is simply beyond belief that the rice-growers of thirteenth-century Cambodia had the means to complete three or four full cropping cycles in a year for even today, two are not common, depending as they do upon an adequate supply of irrigation water. The notion of three 'crops' in a year is also to be found in Chapman's account of Cochin China in the late eighteenth century but again the probability must be that this refers to three harvests rather than to three full crop cycles (see Lamb, 1961). If this account be a little equivocal, that of Father Pierre Poivre for Siam, published in 1770, very likely refers to ratooning though an alternative explanation is that the rice was a shattering variety.

> *'It is astonishing, however, to observe, these lands, frequently neither laboured nor sown for years together, produce extraordinary crops of rice. The grain, reaped negligently, sows of itself, and reproduces [sic.] annually another harvest, by the help of the river Menam....' (Poivre, 1770).*

Another early account is that of Ma Huan for Java in the early fifteenth century. He noted that rice ripened twice in a year and that the kernels were small. The latter observation is probably a clincher for it is now known that the grains of perennial varieties tend to be smaller, on average, than those of more annual varieties. Other examples are quoted by Hill (2012). In seventeenth century Siam, now Thailand, Nicholas Gervaise reported in 1688, 'One sort that grows without anyone sowing it...' Perennial though it must have been, however, it could not have survived colonization by adventitious vegetation but for human intervention. A century or so later the Abbé Raynal spoke of rice that 'bore plentiful crops spontaneously' – surely again a reference to a perennial variety. More equivocal is an account of Assam by Neufville dating from the early nineteenth century. He spoke of the lowlands producing two crops annually, possibly referring to a main crop and a ratoon (Neufville, 1828).

Rather later is a report for the Philippines by Alfred Marche who travelled in that region in 1879 to 1881. Like the others already mentioned, he reported up to three harvests in a year in Laguna Province, with parts of Tarlac and Pampanga, the location of dry-season harvesting described 40 years later by Apostol.

Even more recent are several accounts of a small area in what is now Arunachal Pradesh by the German, later British, ethnographer Christoph von Fürer-Haimendorf (1946, 1955, 1962). He described two types of rice-fields at an elevation of about 1 500 metres – those kept permanently wet and those that allowed to dry out soon after harvest. On the former class of land the soil was not tilled, the rice being perennial though where there were gaps in the plant cover these were made good by the planting of seedlings early in the growing season. Von Fürer-Haimendorf's 1962 paper speaks as if this form of cultivation still existed but whether it still survives and whether there are holdings of the ratooned rice varieties in any repository are not known.

This author has seen ratooning in the field for consumption as food only once. In the early 1960s he visited the Orang Kanaq, a small group of aboriginal people whose ancestors were settled in Johor from the Indonesian province of Riau. They no longer grow the crop (Mahani Musa, 2011). On a much later visit to a rural area east of the northern Lao town of Vientiane some ten years ago, ratooning was again seen but then it was unlikely that the crop was being harvested, for the area was being grazed by cattle, a practice widespread in most of SE Asia before double-cropping became common.

RATOONING – THE PRESENT SITUATION

The modern literature on the ratooning of rice is quite scattered. A good deal relates to India rather than to East and Southeast Asia though much of that is relevant because it deals with general agronomic matters of wide applicability. A useful starting point is the IRRI collection of essays *Rice ratooning* (IRRI, 1988), though the appearance of that monograph, the reportage has increased steadily. Basically, a ratoon crop has the major advantages over a transplanted crop of requiring only about half of the labour input of the main crop and perhaps 60 percent less water (Oad *et al.* 2002; Oad *et al.* 2002). There is, however, a very wide range of genetic potential for ratooning with some cultivars giving very small yields, or none, and others giving yields that are greater than the main-crop yield of the same cultivar. (see, for example, Krishnamurthy, 1988).

Incidentally it may be noted in this context that seasonality may play a part here. Many research reports fail to mention the obvious point that in theory a proper comparison of main-crop (transplanted) and ratoon yields requires that the crops be compared over the same time-period, a condition not readily met given the much shorter growing period of the ratoon. Replication over several seasons may reduce errors of estimation arising from this source.

While there is some lack of knowledge among present-day rice scientists that ratooning has been of some significance in the more-distant past, there is a small body of publications on the subject, mainly by Indian workers, dating from the 1970s. (see *Rice ratooning*, 1988, for examples, especially papers by Krishnamurthy and by Mahadevappa, for overviews). There is a small literature by Chinese workers, mainly in Chinese. For Japan there seems to be very little literature, at least in English or any other western language. Ichii and Kuwada's paper of 1981 and some of their references are exceptions. The major four-volume work edited by Matsuo *et al.* (1997), a translation from Japanese into English, seemingly makes no mention of the practice though it is difficult to be certain for the work is not indexed. The standard international work on the subject, the IRRI *Rice ratooning*, 1985, is now rather dated but brings together a good deal of what rice scientists were investigating at that point.

Although there is a considerable body of modern literature on ratooning, some of its value is reduced by deficiencies in research methodology and reportage. An early paper by Prashar (1970) for example, compared the ratoon and main crop yields of two modern HYV's, IR 5 and IR 8, reporting remarkably high yields ranging from 6 tonnes per hectare to almost nine, with IR 8 outperforming the earlier cultivar. As with many later studies, it may be suspected that the yield data are derived from very small scale cutting trials.

The study by Ichii and Kuwada (1981) gave yields for ratoons harvested at varying intervals with the highest yields at 10 and 20 days after heading but fail to give the areal unit to which they refer. Many papers also fail to give details of the plot size to which their data refer. This is a considerable weakness for it has long been known that reported yields from square-metre scale experiments often far outweigh those from plantings at larger scales. Xu *et al.* (1988) for instance state that their results 'were obtained from small areas' but fail to indicate how small. Their results therefore suffer from the common defect of such studies as giving unrealistically high yields. They give main crop yields ranging from 5.6 to 9.8 tonnes/ha and ratoon yields from 3.1 to 8.7 tonnes/ha, in one case, for IR 24, with a ratoon yield of 8.7 tonnes/ha/day with a main crop of 8.4 tonnes/ha.

More comprehensive data, covering 124 experimental plantings, many in India, are those of Chauhan *et al.* (1988). Outstanding were ratoon performances by the variety Intan, reported from Karnataka, India, at 2.3 to 7.7 tonnes/ha, the variety Milbuen 5 from the Philippines, at 5.6 tonnes/ha, and IR 8 at 8.2 and 8.7 tonnes/ha, all above the main crop yields. By contrast, moderate ratoon yields were reportedly obtained from IR 42 and IR 97523-71-3-2, ranging from 33 to 49 percent of the main crop yields with ten cultivars giving a ratoon yield of less than 10 percent of the main crop yields. One early comparison of IR 5 and IR 8 is that of Prashar (1970) for Ethiopia. He claimed that IR 8 outyielded IR 5 for both the main and ratoon crops though his yield data, ranging from 6.3 to 8.7 tonnes/ha, like many others, may be suspect.

Another relevant paper is that of Chauhan *et al.* (1988). These workers screened 24 modern genotypes and found that of the 24 examined, only ten showed any regeneration at all, with RP 1664-4461 showing a very modest ratoon yield of 1.7 tonnes/ha and IET 7613 a yield of only 0.8 tonnes/ha. This result raises the suspicion that ratooning ability may have been bred out of some of the modern cultivars. If this notion is sustained, important considerations are raised as a strategy for future research is developed. Of particular concern is the fact that IRRI has screened for their ratooning ability only a tiny proportion of its vast holdings of cultivars.

On the other hand, work in Karnataka, India, with six modern cultivars, including IR 28, showed excellent yields from both the main crop and the ratoon (Krishnamurthy, 1988). Main crop yields reportedly ranged between 8.7 and 11.8 tonnes/ha for the main crop. In percentage terms the ratoon yield ranged between 67 and 90 percent of the main-crop outturn where the main crop had been direct-seeded, compared with a range of ratoon yields between 59 and 78 percent of main crop yields where the main crop had been transplanted. A later study of lowland genotypes, by Santos *et al.* (2003), involved five early maturing modern varieties and four medium-term types. For the former the average ratoon yield was 59 percent of the main crop outturn but for the latter types the average was a disappointing 39 percent.

Flinn and Mercado (1988) have a most useful overview of the economic aspects of ratooning, concluding that the technique offers major advantages by reducing both labour and water requirements by about half compared with the main transplanted crop. Another advantage is the reduced length of the crop year, opening the possibility of a further crop, other than rice in the same crop year, and the freeing up of labour and other resources for alternative uses. This is a particular advantage where temporary circular migration and the earnings from urban employment have become important. But these authors also point to economic disadvantages. Included are uneven maturing of the ratoon crop, uneven grain quality and generally low and uncertain yields, matters of no great concern where production is for subsistence perhaps, but important where the crop is marketed.

The question of whether or not technical innovations are gender-neutral is one of considerable importance. It is widely-known in Peninsular Malaysia and Indonesia, for example, that beginning in the 1960s, the harvesting of rice panicle by panicle over the course of several weeks by women using the traditional small harvesting knife was replaced by men wielding sickles. Given that in the major rice-growing states of northern Peninsular Malaysia and in nearby Peninsular Thailand, gangs of women were employed as harvesters, this was a severe loss of income in some villages of that region. One further consequence was that quality immediately fell as immature panicles were cut together with the mature ones. In turn that necessitated much closer attention to field levels since uneven ripening in part reflected variations in soil moisture across the fields (Baker, 1940; Colani, 1940; Fukuda, 1986). In the Minangkabau areas of Peninsular Malaysia, where little rice-growing still survives, the introduction of machine tillage in the 1960s had a reverse effect. There tillage by women, who mostly owned the land, was gradually replaced by men driving hand tractors.

A further clear advantage of ratooning may be added. For regions frequently vulnerable to damage from tropical cyclones, notably the Philippines north of Mindanao, the southern provinces of China within about 100 km of the sea, and the central and northern provinces of Viet Nam, ratooning potentially reduces the length of the growing season compared to double-cropping thus avoiding the effects of late-season cyclones. In this context it is worth noting that studies of climate change are forecasting an increase in the number and intensity of tropical cyclones, probably also to be accompanied by more, and more intense rain.

Since 1988, understanding of some of the 'mechanics' of ratooning has increased. For example, a Texas study by Turner and Jund (1993) showed that good levels of total non-structural carbohydrate (TNC) in the main crop were essential to satisfactory yield from the ratoon. They also suggest that cultivars may differ widely in their ability to accumulate TNC prior to heading. Both findings have been confirmed for an Asian context by Cheng and Li (1994) who also noted that only one of the five *indica* hybrids they examined showed good ratooning ability.

One area of research that has attracted some attention is that of the optimal height for cutting the culms of the main crop to ensure a good yield from the ratoon. This is because the ratoon yield depends upon the total carbohydrate content in the stem base (Oad *et al.* 2002a,b). A Texas study by Jones (1993) suggested that ratoon yields for the two American varieties used, 'Lebonnet' and 'Lemont', could be optimized by lowering the cutting height of the main crop to 20 - 30 cm. Other authors, with South American or Asian experience, suggest that the optimal level may be somewhat lower at 10 - 20 cm (see Santos *et al.* 2003, and for example, Bahar and De Datta, 1977; Calendacion *et al.* 1992). Ahmed and Das's work (1988) rather contradicts that finding for they noted that ratoon yields remained about the same for heights from 15 - 45 cm but declined drastically below the lower level. An earlier study, by Prashar (1970), showed quite a contrary pattern. He found that the ratoon yield was significantly higher where the main crop was cut at ground level rather than at four, eight and 12 cm, though the maturity period was shorter with higher cutting. Clearly, as with many other characteristics, there is considerable variability but it seems likely that cutting the main crop stems at a low level, can, other things being equal, be compensated by a delay in harvesting. That, of course, raises issues of reliable water supply and in climatically marginal areas, sufficient warmth to continue growth.

One issue that has received rather limited consideration is that of the quality of the ratoon crop, not a major consideration where the crop is for self-consumption by the cultivator and his family but an important issue for the commercial and semi-commercial producer because lower quality means lower income. No reportage on the physiology of ratooning that may lead to uneven ripening has been found.

Part of the problem is asynchronous ripening of the ratoon (Calendacion *et al.* 1992). This is certainly so where, as is general in commercial production, harvesting is done in a few hours rather than over weeks. That was once general practice in many parts of insular Southeast Asia. At lower latitudes in Southeast Asia, panicle-by-panicle harvesting using a small knife was general until the 1960s though it has now been largely replaced by the sickle and a single harvest. Practised only in single-crop areas, that method meant that harvesting could be spread over as much as two months so that variable ripeness was much less an issue. Presumably, were that method to be applied to the ratoon crop, the problem of uneven ripening might be mitigated, but only at the cost of a considerable increase of labour input, one so large as to make that approach unattractive to commercial producers.

CONCLUSION

Just how widespread ratooning may currently be is difficult to establish. For the Philippines, for example, it has been claimed that more and more farmers gain extra income from ratooning, especially in Bulacan and Nueva Ecija provinces (Lacanlale, 2004). One newspaper report indicates that in Leyte 5 000 ha of potential ratoon-crop land has been identified (*Sun Star* 17 July 2013). But for most of the region, good data are lacking. In Malaysia, for example, where rice-growing is heavily subsidized by government, the problem of the rising cost of agricultural labour has been met from two sources. One is the growing practice of broadcast sowing, requiring the enhanced application of selective herbicides, and the other is by the importation of low-paid field labour from outside the country. In this context, a study of the costs and benefits of this approach compared with ratooning is desirable. This might include consideration of the social costs of such migrant labour.

For farmers a key question is whether to ratoon or not. On this issue the size of the main-crop harvest is not a good indicator, for the key question is the level of TNC – total non-structural carbohydrates – in the stems of the main crop. A high level means that, other things being equal, it is safe to proceed with ratooning (Boyd, 2000). This test offers reinforcement to the rather subjective method of observing the speed at which stubble was regrowing after the main-crop harvest. By lowering the main-crop cutting height to about 20 cm d with the usual 45 cm, it has been found that the ratoon yield is enhanced quite substantially, to the extent of 1.1 to 3.3 tonnes/ha as reported by Boyd for Texas. So far as is known, no such test is available in Asia.

One novel approach is that of Calendacion (1992) and his colleagues. They deliberately flattened the standing straw after the main crop harvest thereby locking it prone upon the soil surface, an action they term 'lock-lodging'. This was done manually. At a mean of about 1.5 tonnes/ha, yields from plots thus treated were significantly higher than from conventional ratooning at about 1.1 tonnes/ha, though otherwise the treatments were the same. This procedure requires more labour than conventional ratooning. Perhaps a similar effect might be achieved by the application of a heavy roller, perhaps a toothed type, to improve aeration on heavy clay soils especially.

Clearly, one thing that must be avoided at all costs is the kind of rice development debacle represented by attempt to develop a million hectares of rice land from forest in Kalimantan

(Boehm and Siegert, 2001; Rieley, 2001). This project, launched in 1995, aimed at the development of what is mainly peat land, from the outset, a very problematic undertaking. It ultimately directly affected some 1.5 million hectares, while burning in 1997 is estimated to have covered 15 million km^2 in smoke for a period of several weeks and to have added 0.5 parts per million CO_2 to the global atmosphere (Rieley, 2001).

Ratooning must be a viable alternative to that approach. The Philippines government is promoting it as a means of attaining national self-sufficiency in rice (*Sun Star* newspaper, 17 July 2013), though to this observer, the estimate of only 45 days to obtain a ratoon crop seems highly optimistic. The approach is also being promoted in Pakistan (Hafeez ur Rehman *et al.* 2013).

But beyond ratooning is the development of truly perennial systems of cropping similar to that described for the Apa Tani by von Fürer-Haimendorf long ago. In this endeavour Sacks and his colleagues have been active (Sacks *et al.* 2003a,b) though warning that it is likely to take five to ten years to breed suitable perennial rice varieties for upland areas. Perhaps there are high-production ratooning varieties currently hidden among the very extensive holdings at the IRRI, for that institution has never made a systematic search for them. Given the very large holdings of materials at IRRI that is a significant challenge. A simple start would be to find out if the perennial rice among the Apa Tani still survives and whether there are other communities that use similar cultivars.

In the Association of Southeast Asian Nations (ASEAN) region, which accounts for 22 percent of global consumption, the consumption of rice is driven largely by population growth (Wailes and Chavez, 2012). That has fallen sharply and is now only around 1.1 percent annually. This can probably be met from improved yields, particularly as consumption per person declines, though only slowly at present (Zhang 2007; Wailes and Chavez, 2012). Japan has long seen falling demand for rice though its home production has been artificially sustained by large subsidies. China's demand is also likely to fall. Globally, rice stocks are steadily rising and actual prices show a slight downwards trend, in real terms perhaps more than slight, given rates of inflation in the region. Throughout the region the cheaper grades of rice are already being used as animal feed or in the production of beer. But whatever scientists may think and do, the reality is that the region's increasingly urban people will continue to demand cheap rice, even as the per person consumption falls, possibly at an accelerating rate in future. Ratooning offers a potential to obtain increased production at relatively low cost. That is a bargain to be promoted, but on firm scientific bases.

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PRESENT SITUATION CONCERNING THE INTRODUCTION OF PERENNIAL HABIT INTO MOST IMPORTANT ANNUAL CROPS

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There are two main options available for developing perennial crops. The first is through the introduction of perennial traits from wild species into related domesticated crops by crossing or by transferring pertinent genes. The second is through the domestication of wild perennial species using a selection of available biodiversity or through the introduction of domestication characteristics from related domestic species. The first method seems to be the most rapid, while the second could be more difficult and time consuming.

PERENNIAL RICE

Perennial rice is currently the most advanced of the perennial cereal species, as some cultivated rice strains are already able (in humid tropical areas) to have regrowth after crop harvesting. In fact, humid tropical areas could be the first areas to adopt new perennial rice types. In temperate areas the most important limitations for perennial rice may be drought, cold resistance and longevity.

PERENNIAL WHEAT

A high number of progenies derived from crosses of hexaploid and tetraploid (*T. carthlicum*) wheats with several *Thinopyrum* species are available because of crosses made from transferring disease resistance into wheat species. At least a dozen selected perennial wheat lines (out of more than 250 crosses) have now been tested and analysed in international trials. In this material, the main characters to be improved are: shorter straw, earlier ripening, shorter spikes, larger grains, resistance to cold, higher production per hectare, potentiall a smaller number of chromosomes (now most lines are octoploid 2n=56) and chromosome number stability. In the future, some lines could be adopted, especially in polycultures and marginal areas and because of consistent production and cost savings. Some lines could also be useful for dual-purpose grain and forage production.

PERENNIAL RYE

Several selections derived from crosses with the perennial *Secale montanum* are available and adapted to acidic soils and mountain areas, where some rains last the entire year. Further selections should be developed, especially for improved bread making.

PERENNIAL SORGHUM

Several selections of perennial sorghum are now available which are derived from crosses of *S. halepense* (4x) with *S. propinquum* (2x). Some lines of *S. bicolor* are also examples in which regrowth is present. The breeding is looking for both 2n and 4n types. The main limitations are now: small seeds, cold resistance, and shorter straw. The realization of perennial sweet (sucrose) sorghums should also be a priority in order to have the production of seeds, sugar and of straw to be used for animal feed, production of methane or cellulose transformation into sugars. The resilience to drought is an important characteristic of perennial sorghum and its adoption in farming systems affected by climatic events should be further promoted.

PERENNIAL MAIZE

Given the increase in maize seed production obtained in the last 50-60 years, the realization of perennial maize types showing a decent production seems to require several more decades of research, in part because of the very large differences in morpho-physiological characteristics of the perennial related species.

PERENNIAL MILLET

At least two perennial species related to *Pennisetum* are available to transfer perenniality into pearl millet. At the moment there is very little information on breeding for perennial types. Further research and development is essential as perennial millet, sorghum and other drought tolerant crops are key for the food security and livelihood of millions of people in dryland agricultural systems.

PERENNIAL BARLEY

The utilization of *Hordeum bulbosum* for transferring the perennial habit into barley seems difficult because of *bulbosum* chromosome eliminations in F1 crosses. The utilization of other perennial *Hordeum* species should be further explored, especially in lines adapted to marginal areas (e.g. northern, cold climates), requiring short growing cycles.

PERENNIAL OATS

The most likely perennial species present in the *Avena* genus that could be used is the 4n *Avena macrostachya*, found in Algerian mountains and is well suited for areas that require short growubg cycles with limited water. At the moment no information is available concerning this objective.

OTHER SPECIES

Perennial species are also present in *Milium, Panicum, Echinocloa* etc. and related to cultivated ones, which could be used for the introduction of perenniality. Increased policy and research attention should be placed on the wide range of poorly explored and domesticated cereals in order to have the genetic base which allows for a shift towards more sustainable and flexible agricultural systems, enabling farmers to expand their farming options.

GRAIN LEGUMES

At the moment only *Cajanus cajan* is normally used as a perennial grain crop in India and Africa. However, related perennial species are present in *Cicer* (chickpea), *Glycine* (soybean), *Lathyrus, Lupinus, Vigna* etc. which could possibly be used. Grain legumes increase nitrogen availability in soil and are important sources of protein.

SUNFLOWER

There are several perennial *Helianthus* wild species in North America. The introduction of bulbs into *H. annuus* (sunflower) from *H. Maximiliani* (2x) and from *H. tuberosus* (4x) are ongoing, particularly in the United States, with interesting results.

OTHER OIL CROPS

In several annual oil producing species, such as *Carthamus tinctorius*, *Linum usitatissimum* (flax), *Sesamum indicum* (sesame), *Gossypium* (cotton) wild perennial species are present: *Carthamus lanatus, Linum perenne, Sesamum calycinum, Gossypium arboreum* (2x) or *G. barbadense* (4x) etc. that could be used for perenniality transfer.

FORAGE LEGUMES AND GRASSES

Several cultivated forage legume genera (e.g. *Lotus, Coronilla, Onobrychis, Vicia*) perennial related species which could be used to further develop perenniality.

CONCLUSIONS

The objective of introducing perennial traits into many domesticated crop species could interest many breeders working with the most useful species for the improvement of their performance and for saving production costs and labour. Permanent forage species are fundamentally important for improved crop-livestock systems. A wider adoption of diverse perennial forages needs to be further explored by researchers and supported by policy instruments to meet the increasing demand for livestock products and environmental sustainability.

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RECOMMENDATIONS
PERENNIAL AGRICULTURE AND LANDSCAPES OF THE FUTURE

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INTRODUCTION

Agriculture has always integrated perennial plants (fruits and forages) and annual crops in different farming systems to enhance diversity and productivity of landscapes while enabling functional ecosystem services and processes to build long-term resilience. But only in the past thirty years have the potential benefits of perennial grain-based cropping systems been recognized as contributing to preventing soil erosion and soil biodiversity degradation, as well as holding the potential to contribute to carbon sequestration. Perennial crops also require reduced amounts of energy, and capture nutrients and water more efficiently relative to their annual counterparts.

As feeding nine billion people in 2050 with increasingly scarce and degraded natural resources is the main challenge faced by humankind, reinvigorating agriculture in a sustainable and productive way on a large scale will take nothing short of a significant shift in agriculture as we know it. With this in mind, there have been a handful of progressive scientists, pioneering practitioners and investors that have been working for over several decades to advance the development of perennial versions of staple crops to be integrated into agricultural systems as a means for operationalizing a true sustainable intensification and the makings of perennial agriculture.

WHAT IS THE CURRENT CONTEXT REGARDING MAJOR STAPLE CROPS?

Globally, there are over 100 million hectares of maize, 240 million hectares of wheat and 158 million hectares of rice. The yields per hectare of these main staples vary widely depending on the presence of abiotic and biotic stresses, inputs and management practices (irrigation, nutrients, pest management, technical support, etc.). And, even though yields have doubled to quadrupled over the past 40 years, these yields have stabilized in the last decade and are further under scrutiny for the concomitant trade-offs in environmental health. It is currently estimated that demands for these products are going to increase dramatically over the coming decades (a doubling in demand for maize is expected by 2050 and a 22 percent increase in demand for rice by 2020) accompanied by increases in demand for inputs (energy, water, fertilizers) if production, consumption and losses systems are not transformed. At the same time, climate change is going to negatively affect yields and reduce the areas conducive to growth. (For example, it is anticipated that maize yields will drop by 10 percent in sub-Saharan Africa and 17 percent in South Asia; wheat yields by 20-25 percent in South Asia; rice will also suffer from yield reductions due to expected water shortages, floods and other extreme weather patterns (Global Futures, 2013). Agricultural systems need to be transformed to be able to address the demand, environmental degradation and issues associated with the impacts of climate change. Perennialized agriculture is an avenue that offers great promise to address some of these issues.

How to get perennial crops?

While historical efforts saw limits in technologies, plant breeding of grains, oilseeds and legumes has undergone a number of advances that promise to make the development of perennial grain crops possible in the next 10 to 20 years. These advances take advantage of traditional breeding techniques such as domestication and wide hybridization to hybridize annuals with perennial relatives in combination with new technologies such as marker assisted selection, genomic in situ hybridization, transgenic technologies and embryo rescue (Glover and Reganold, 2010). Traditional and new technologies are being applied to a host of species including wheat, rice, maize, sorghum, secale, flax, oats, lepidium, camelina, pigeon pea, adlai grass, field pennycress, intermediate wheatgrass and sunflowers - as well as underutilized fruit trees and forages – to serve in new farming systems as perennial food, feed, fibre and fuel crops for the future. In the breeding process, characteristics from wild relatives can be drawn upon to make crops more nutritious, more resistant to pests and with greater adaptive capacity to the impacts of climate change, all of which can increase the capacity of agriculture to address food demands and security.

Progress on all perennial crop species needs to continue, however there are a few systems for which expectations in both the timeline and potential contribution tend to place at priority, including perennial rice systems, dual purpose wheat for grain production and grazing, intercropping perennial legumes and cereals, and boosting of existing perennial systems such as agroforestry and grasslands.

HOW TO FAST TRACK EFFORTS TO TRANSFORM TO A MORE PERENNIAL AGRICULTURE?

The domains that need the greatest attention in the short and long term fall in the categories of research, communications and mainstreaming, enabling policies and public and private investments. While integration among these is needed, the immediate actions needed are articulated by category.

Research

1. **A new generation of breeders and breeding programmes.** Within the context of research, there are a number of tools and assets, include germplasm collections, genomic resources, evolutionary information, cytogenetics and breeding capacity. But above all there is an urgent need for more breeders and breeding of perennial crops, grains and legumes to date, to be adapted to developing country contexts and to investigate new cropping system options. Historically, research in this domain has been more or less supply driven, predominately coupling scientists' interests in a particular crop and the agro-ecosystem of choice. Thus, participatory approaches that fully engage farmers' priorities in diverse contexts must be integrated into the breeding programmes. This can be done through building constituencies and capacities among researchers from Africa, Asia, North America and Europe of relevant disciplines in National Agricultural Research Institutions and programmes and the CGIAR. Simultaneously, farmer-based platforms for assessing, monitoring and promoting practices

can be put in place. Possibly a Centre for Perennial Grain Research could be established allowing for a global collaboration for integration and application of perennials to diverse farming systems and landscapes.

2. **Get the evidence into circulation.** The onus is on the scientific community to provide hard evidence to clearly demonstrate the contribution of perennials to agriculture in order to generate further research investments and farmers communities engagement. There is clearly a need to implement a systematic analysis to screen the highest potential crops, farming systems, and regions and socio-economic contexts in order to achieve short-term goals and early successes for maximum return on investment early on. Field trials and modelling can assist in this prioritization. There is also a need to incorporate robust economic studies to better quantify the overall value of the contribution of perennials.

3. **Breed for innovative farming systems.** There is a need to recognize the short-comings of monocropped farming and embrace efforts to integrate perennials into complex systems including intercropping, rotational cropping, and multi-story cropping systems and integrated crop-livestock-tree systems. Increasing grain production is important, but the added value may be greatest in terms of dual-purpose crops and the co-benefits of perennials for ecosystem services. A coordinated action by the public and private sector, policies, market, and farmers with an integrated effort to assure food security, environmental maintenance and economic returns is fundamental if we have to continue producing food for future generations.

Communications and mainstreaming

1. **Framing the concept.** Language matters in all fields and caution must be taken not to pit annuals against perennials. It is better to frame perennialization as an innovative, complementary and parallel breeding and management effort. That said, it is imperative that perenniality is integrated into mainstream agro-ecological farming and sustainable intensification concepts, and sustainable agriculture and landscape approaches in temperate, humid and dry tropic environments. In this regard, the concepts and benefits of perennial landscapes and perennial agriculture need to be brought more strongly into the conversation as a means to contend with climate change, enhance biological diversity and get back on track to attain safe space in terms of food and environmental security.

2. **Naming new crops.** Some breeders have chosen to provide new names to perennialized annuals as they can be considered new crops. This may be a valuable dimension for markets as well as for increasing the uptake by farmers. Examples include Kernza (perennial wheat) and Montina and Timtana (gluten free Indian rice grass and timothy grass used as grains, respectively).

3. **Actively participating in fora and media.** Each breeding programme needs to emphasize communication and coordination with the global community, taking learning beyond the specific crop dialogues for greater overall learning and benefit. There is a public good on offer that needs to be demonstrated. From the scientific community, communications will be bolstered through key meetings of professional societies (e.g. AAAS, Tri-Societies), dedicated journal issues (e.g. Field Crops Research, Crop Science), and collaborative scientific meetings, particularly held in regions such as Africa and Asia. The Perennial Grain Blog at Michigan State University is a valuable way to share insights among the perennial grain community. (See pwheat.anr.msu.edu/index.php/about/).

Enabling policies

The adoption of perennial crops, agroforestry, and mixed crop/livestock systems to sustain production, food security and rural livelihood, contribute to moving farming systems towards providing multiple economic, environmental and social performance.

Policies promoting this shift of agricultural systems at farm, territory and food chain levels require great commitment and vision coupled with a concrete approach to fit the many local situations. Direct public support (regional and national policies, programmes, subventions, tax, credits) and indirect public support (research, education, development) have contributed in the last sixty years to increase total agricultural production and food chains, but this increase has been obtained with increased energy consumption, Green House Gas emissions, loss of biodiversity, and soils and water degradation.

Renewed policies and programmes need therefore to be developed to reverse this negative trend and also assign a value to public goods such as the maintenance of biodiversity (above and below ground), or the generation of other ecosystem services which are essential to sustain the agriculture of the future.

Some countries have already moved along this direction and developed research programmes adopting a cohesive vision and engaging multiple stakeholders (farmers and their associations, agricultural industry and consumers), schemes to reward production of ecosystem services, land rehabilitation programmes, measures to reduce water and air pollution. Many different labelling schemes have been developed (e.g. organic agriculture, integrated pest management), national programmes to support family farmers, use and maintenance of minor crops, adoption of green technologies and biofertilizers and bio pesticides. Recently some countries have also adopted agroecology laws and are committed to enhance the full potential and diversity of agriculture by combining its economic and social potential while maintaining natural resources.

Hopefully all these programmes and policies will play a catalytic role to promote the shift of agriculture towards securing the food, profitability and ecosystem services that societies want.

Public and private investments

1. **Invest for the long-term outcome**. To develop and scale up the use of perennial grains, oilseeds and legumes take years. Historically, those progressive breeders who undertake these challenges have to do so on the periphery of their other work. Donors need to be willing to invest for the long term with the knowledge that it will be cheaper in many respects than continued short term investments. The recent USAID investment in grain sorghum for sub-Saharan Africa is an excellent example. Farmers and supply-chain companies will need to be sustained in their willingness to engage in testing and adopting innovative farming practices including agroforestry and some of the perennial crops which are in advanced stages for adoption.
2. **Imbed perenniality into programmes and projects**. Both scientists, practitioners, donors, NGOs and other investors have an opportunity to ensure that perenniality gets placed in different programmes and projects that are being designed to enhance progress toward sustainable development goals.

WHAT ARE THE NEXT STEPS FOR FAST-TRACKING PERENNIAL CROPS?

In summary, the integration of perennial species into farming systems, whether crops, forages, or trees can contribute to achieving multiple functions including increased food security and nutrition, climate change resilience and mitigation, increasing energy efficiency and production, and enhancing ecosystems services such as biological diversity, water, nutrients, and land health. In addition, perennial systems can reduce input and labour costs, but many relevant aspects require additional research and extended field tests. Breeding and testing of new management practices will need to provide responses beyond increasing annual yields including evaluation of resistance to cold, dry, humid weather conditions, new pest and weed cycles, soil feedback, and water uptake.

Among the next steps that would be most valuable for enhancing the integration of perennials of all kinds into agriculture, and for fast-tracking the development of perennial grains, oilseeds and legumes forward would include key investments in:

- Ramping up research to advance promising perennialized species, ensuring a global network that is addressing demand and co-research and learning with farmers' platforms in the context of developed, emerging and developing country contexts;
- Ensuring cross learning and collaboration among scientists globally working on various species and hosting workshops and conferences in key regions and countries (e.g. East, West and Southern Africa, China, Brazil);
- Enhancing communications of the evidence of perennialized species' contributions to addressing local and global development challenges;

- Mainstreaming the concept of perennial agriculture into research, practice and national, regional and global policy and investment fora as well as through a variety of communications and social media;
- Identifying a small team to articulate the specific architecture and costs of a virtual and ultimately bricks and mortar Centre for Perennial Grains Research or Centre for Perennial Agriculture;
- Articulating and developing an impact pathway for achieving a global target of hectares of annual-based agriculture transitioned to perennial agriculture in a diverse set of countries.

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