Viable options for enhancing agricultural food production in sub-Saharan Africa

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ABSTRACT

Intensification of agricultural food production is of paramount importance as a means of increasing food security in sub-Saharan Africa. However, achieving this aim faces several challenges including the ongoing climate change, extreme environmental degradation, land tenure and management practices and national population growth. Above all, an emerging predicament is that non-native plant species tend to display greater adaptation capacity to environmental stress than the native species that have historically been used, thus, suggesting a need to choose new crop combinations that better achieve sustainability of crop production. Based on their high reproductive output and benefits, we propose that the consumptive use of non-native plant species and/or the genetic modification (that is, using transgenic and classical breeding techniques) of native species might be viable options for addressing escalating food demand in this region. Consumptive use of non-native plant species in food production could reduce their invasiveness capacity and this should be accompanied by low cost conservation agricultural practices that may promote the gradual recovery of natural capital and ecosystem services. This multidimensional and integrated approach to agricultural food production is not well-developed in sub-Saharan countries, but may be required to achieve a food-secure future under climate change.

Keywords: Crop yield, non-native plants, conservation agriculture, biodiversity, climate change.
global land mass. Of this, 12% is used for producing harvested crops, 27% for pasture land and 32% for forestry (Food and Agricultural Organization, 2013; Pimentel et al., 2009). However, there is spatial variability in the contribution of the agricultural primary sector in food security and human well-being. About 70 to 80% of the population in sub-Saharan Africa depends on agriculture for their livelihood (Food and Agricultural Organisation, 2013; Niang et al., 2014; Shackleton et al., 2008).

In addition, about 70% of employment which indirectly allows people to secure food in sub-Saharan Africa is provided by the agricultural sector (New Partnership for Africa’s Development, 2003). Studies identified several major factors that account for the current food insecurity in sub-Saharan Africa, including climate change which is likely to be aggravated by high population growth and poverty (Pretty et al., 2011; Food and Agricultural Organization, 2013; Niang et al., 2014).

Previous assessments (Niang et al., 2014; Burke et al., 2009; IPCC, 2007) have also shown that agricultural food production in sub-Saharan Africa is highly vulnerable to direct changes in climate seasonality, mainly of crop microclimates and precipitation. In fact, there is high confidence for risk of food insecurity and the breakdown of food systems that are linked to climate warming, drought, flooding and precipitation variability and extremes, particularly for poorer populations in both urban and rural settings (Niang et al., 2014; Porter et al., 2014).

In Figure 1, the countries shown in dark brown are predicted to be at high risk of food security in terms of agricultural productivity and their relative ability to cope with physical impacts of climate change, while lighter colours progressively show moderate to low risk. Indeed, some countries may be at high risk due to climate change and this problem might be compounded by several factors including political instabilities and land availability (Niang et al., 2014).

Various studies indicated that the yield of several important staple food crops including maize, millet and sorghum may be negatively affected by climate change in
sub-Saharan Africa (Lobell et al., 2008; Schlenker and Lobell, 2010; IPCC, 2007; Misra, 2014). Many crop yields have shown large sensitivity to extreme daytime temperatures of around 30°C throughout the growing season (Niang et al., 2014) and direct impacts may be declining yields under persistently high temperatures. According to the Intergovernmental Panel on Climate Change (IPCC), an increase of 5 to 8% of arid and semi-arid land in Africa is projected under a range of climate scenarios by 2080 (IPCC, 2007). There is high confidence that other downstream aspects of food security are also affected by climate change including food access and its utilization (Porter et al., 2014). Furthermore, evidence suggests that substantial fluctuations in crop yields following climate extremes in key producing regions can result in volatility in food prices (Porter et al., 2014; Mueller et al., 2011).

Changes in precipitation may influence the availability of water for irrigation (Niang et al., 2014; Misra, 2014). Water is an essential resource in agricultural food production (Food and Agricultural Organization, 2013; Pimentel et al., 2009; Strzepek and Boehlert, 2010) which is however at high risk due to climate change (Niang et al., 2014). It was predicted that climate change might lead to 18% reduction in the availability of worldwide water for agriculture by 2050 and this is likely to be exacerbated by increasing water demand estimated to be > 200% due to population increases alone (Strzepek and Boehlert, 2010).

Indeed, Global Climate Models (GCMs) project significant changes to averaged regional and global precipitation and these changes are expected to impact groundwater recharge and thus the maintenance of all ecosystems, including agriculture (Misra, 2014; Kurylyk and MacQuarrie, 2013). In many parts of Africa, it is likely that the net effect of warmer climates in combination with changes in precipitation will be a reduction in agricultural productivity and yield (Niang et al., 2014) and these changes have potential to undermine the production systems that provide food security, irrespective of any associated changes in political and socio-economic systems (Strzepek and Boehlert, 2010; Thornton et al., 2011). These climate changes will impact on regions that are already experiencing agricultural productivity risks (Figure 1). By 2020, yields from rain-fed agriculture could be reduced by about 50% in some sub-Saharan Africa regions (IPCC, 2007). Seasonal and event-scale rainfall volatility can also be a major factor of food insecurity through crop failure, flooding and soil erosion loss (Niang et al., 2014; Misra, 2014). These impacts, therefore, require effective adjustments throughout the food production and supply chain, not just addressing food production yield but also with the flexibility to manage future uncertainties.

Indirect impacts of climate change on agricultural food production in sub-Saharan Africa include increased the vulnerability of farming land to invasion by non-native plant species (Niang et al., 2014; Burke et al., 2009; Millennium Ecosystem Assessment, 2005). Changes in temperature and precipitation regimes may also extend the distribution and increase the competitiveness of invasive non-native species (Niang et al., 2014). For instance, Walther et al. (2009) reported that non-native woody plants (especially non-native C₄ plant species) (Chuine et al., 2012) are likely to thrive under warmer temperatures and increased atmospheric CO₂.

Environmental colonization by non-native species tends to capitalize on ecosystem disturbances resulting from extreme climatic events and poor agricultural land use practices (Sakai et al., 2001; Hierro et al., 2006). However, there is evidence that some agricultural food crops are responding positively to climate change. For instance, C₃ and C₄ crop species such as sunflower (Helianthus annuus L.) and maize (Zea mays L.) respectively, are expected to show a positive response to elevated CO₂, increased productivity and variably high water use efficiency (Chuine et al., 2012; Vanaja et al., 2011). Consequently, this suggests that certain non-native plant species might provide an important ecosystem goods and services and thus shift human preference and usage away from native species that have permanently provided important food resource base.

In this review, we explore potential solutions to mitigation of food insecurity in sub-Saharan Africa focusing in particular on a consumptive use of non-native plant species, genetically modified native food crops and better agricultural practices that may mitigate against environmental degradation. Compared to native crops, the higher reproductive capacity, faster growth rates and higher resilience to climate change-induced stresses offered by some non-native species (Rejmánek et al., 2005; Richardson and Pyšek, 2012; Walther et al., 2009; Richardson and Blanchard, 2011) suggest their exploitation could be a viable option to increase agricultural food production in sub-Saharan Africa. Furthermore, their requirement for minimal labour and capacity to perform well in degraded landscapes (Achten et al., 2010; Blanchard et al., 2011) could also be helpful in areas where poverty is a major factor limiting agricultural food production. The aforementioned crop attributes were also recommended in several studies assessing the requirements for successful intensification of agricultural food production under climate change (Pretty et al., 2011; Ziska et al., 2012; Burke et al., 2009; Foran et al., 2014; Hawkesford et al., 2013; Walker et al., 2010). Improving the yield of food crops with non-native species’ genomes and more widespread consumptive use of existing non-native species might help in containment and control of the negative impacts of invasive species on existing ecosystems.

Recently, several studies innovated risk analysis methods in order to better understand how and in what contexts
potentially invasive species can provide net benefits with minimal loss (Richardson and Blanchard, 2011; Pheloung et al., 1999; Wilson et al., 2013; Lalla, 2014; Department of Environmental Affairs, 2014). Finally, we suggest that low-cost ecosystem-based farming practices (that is, conservation agriculture and agrobiodiversity) can be adopted and can contribute to the gradual recovery of lost natural capital and ecosystem services.

Evidence from different studies across sub-Saharan Africa to support the need to consider the use of non-native plant species for intensification of agricultural food production was explored. We looked into different ways of how the reproductive attributes of non-native species can give advantages to desired crop varieties; the direct and indirect uses of non-native species in food security and the potential use of non-native plant species’ genetic materials to improve the yield attributes of native species (GM crops). It was also proposed that sustainable agricultural food production practices (that is, ecosystem-based) should be pertinent to minimize environmental degradation.

**MATERIALS AND METHODS**

A literature review process was contacted using the five-step systematic searching of the information. To capture as many relevant citations as possible, a wide range of environmental and scientific databases (for example, linked to google search engine) were searched to identify the primary studies. The following key words and themes were typed to guide the search: “climate change and agriculture”, “agricultural food production”, “agroecology” and “biodiversity conservation”. We prioritized documents (Stromberg and Gasparatos, 2012) including peer-reviewed articles, book chapters and reports that explored a relationship between agricultural food production/security and climate change, impacts of climate change, adaptation attempts to environmental changes by farmers as well as the best-practice approaches. Other set of materials included in the review provided the conceptual understanding of the explored scientific concepts. The role of natural resources in agricultural landscapes in order to highlight how the ecosystem goods and services can support food security in different ways was also reported.

The review was motivated by a need to understand how smallholder farmers and rural communities respond to the challenges associated with climate change in agricultural food production. Trends suggest that the dramatic environmental variability associated with the ongoing climate change is partly a major factor accounting for poor agricultural food productivity in the past (Shackleton et al., 2004; Franzel et al., 2014). Unpredictable seasonality changes force the farmers to find alternative solutions of the better-adapting crops (for example, high drought resilient varieties) and this has consequently led to the adoption of the exotic crops and genetically modified crops to improve productivity and crop resilience to climatic changes in Limpopo (Capricorn Municipality) and KwaZulu Natal (uMshwathi Municipality) Provinces (Unpublished data). At least 60 smallholder farms were visited in respective provinces (that is, 35 and 25) and the crop species, sources and reason for choice of each were documented. The sought attributes of crops to be resilient to climate change were compared with those alien and invasive plant species.

**Alternative strategies for enhancing agricultural food production**

There are several strategies that can be used to increase agricultural food production in sub-Saharan Africa. These include the use of higher-yielding non-native species, further adoption of GM food crops and adjustment of agricultural food production strategies to low-input conservation agricultural practices which are relevant to subsistence farmers. Nevertheless, invasive non-native species created negative impacts on native biodiversity in Africa (Boy and Witt, 2013), yet, biodiversity provides an important food resource base for humans (Millennium Ecosystem Assessment, 2005). However, studies in South Africa have shown that negative impacts of these species on natural resources (for example, water) tend to be much greater where they grow in high densities and over large areas (Holmes and Marais, 2000; Le Maitre et al., 2000; Meijninger and Jarmain, 2014)). This suggests that the ecological balance of these species with respect to native species and ecosystems is also important. In spite of their negative environmental impacts, invasive non-native plant species may help achieve crop yields that sufficiently reduce levels of malnutrition in sub-Saharan Africa if they are used with careful planning and firm control measures (for example, by including biological control (Richardson and Blanchard, 2011). Indeed, biological control is deemed the best strategy for managing biological invasions and has yielded tangible benefits in South Africa (Moran et al., 2013). Emerging bioeconomy industries (for example, aquaculture, floriculture, forestry and bio-energy) that rely on potentially invasive non-native species require a complex and multi-layered understanding of climate, soils and geology; biogeochemistry; species’ biology and ecosystem interactions; socio-economic drivers of sustainability; bioethics and security; and local community cultural systems and structures (Knight, 2015). These are significant challenges that cannot be achieved using a single ecosystem management approach.
the use of the sustainable ecosystem-based farming techniques as a way of mitigating food insecurity in sub-Saharan Africa were considered.

### Direct use of non-native plants in agricultural food production

Historically, there has been widespread (both informal and formal) use of non-native plants in sub-Saharan Africa, both directly for food production and indirectly for income generation (Richardson, 1998; Le Maitre et al., 2011; Van Wilgen et al., 2011). For example, about 92,000 non-native plant species were introduced into various ecosystems globally (Pimentel et al., 2001) with Africa’s highest concentration being in southern Africa where 9000 species have been introduced, including 750 trees and shrub species (Le Maitre et al., 2011; Richardson and Blanchard, 2011). Reasons for the introduction of these species in different areas range from accidental incidents to the deliberate importation of species, for example, as horticultural candidates and for landscaping (Richardson, 1998). In the absence of their natural enemies (Colautti et al., 2004) and their ability to evolve increased competitiveness in a new environment (Blossey and Notzold, 1995), non-native species tend to grow faster, compete better and show greater reproductive output than native species (Table 1).

Long-term trends suggest that few species become invasive and impart damage of natural environment (Richardson et al., 2011). In spite of many introductions of non-native plant species for commercial purposes (Richardson, 1998), invasive non-native species are considered the second major threat after climate change to native biodiversity and low-intensity agricultural systems in Africa and beyond (Niang et al., 2014; Millennium Ecosystem Assessment, 2005; Boy and Witt, 2013).

However, non-invasive non-native species can have an explicit role in both elements, through being deliberately adopted as crops or introduced into the wider ecological system through other means (Figure 2). Most of the previous systematic introductions of non-native plant species still remain beneficial and thus in a broad classification, they are either deliberately part of the ecosystem or become escapees to the neighbourhood habitats where they are integrated into the natural biodiversity because of the ecosystem services they provide (Figure 2). This classification is based on observed patterns and current developments on handling controversies associated with the use of non-native plant species.

Having realized that some species can become invasive, different biosafety screening protocols were put in place to alleviate the potential of exacerbating invasion threats in South Africa as both an example and the bearer of the largest number of non-native plant species in Africa (Department of Environmental Affairs, 2014). Indeed, not all non-native species, however, have invasive properties (Simberloff, 2013), whereas other species may take a longer time (for example, 50 years for naturalization) to display any invasive properties (Richardson and Pyšek, 2012). This suggests that other extrinsic factors such as climate and land use change may be responsible for driving species invasion, rather than its alien status alone (Richardson and Pyšek, 2012; Davis et al., 2011). Therefore,

<table>
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<tr>
<th>Terminology</th>
<th>Definition</th>
<th>Potential to improve yield</th>
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<tr>
<td>Native staple crops</td>
<td>“A staple food is one that is eaten regularly and in such quantities as to constitute the dominant part of the diet and supply a major proportion of energy and nutrient needs.” The species may dominantly include native species (Food and Agricultural Organisation, 2007).</td>
<td>They were domesticated indigenous species used for food production in traditional farming (Sorrells et al., 2004; Kumar et al., 2005; Masters and Norgrove, 2010; Tayeng et al., 2012; Pratap and Kumar, 2014).</td>
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<td>Non-native staple crops</td>
<td>These will comprise of introduced species that are used as key food crops (e.g. maize in sub-Saharan Africa) (Karibu, 1993).</td>
<td>They were introduced in 1496 with purpose of improving food production (Karibu, 1993).</td>
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<td>Non-native plant species</td>
<td>“Those whose presence in a region is attributable to human actions that enabled them to overcome fundamental biogeographical barriers (i.e. human-mediated extra-range dispersal).” (Richardson et al., 2011). Non-native species may also include staple crops.</td>
<td>A subset of these species is capable of reproducing prolifically in areas of introduction when they are free from their natural enemies or competitors. They have been predicted to perform well under higher temperature and high concentration Carbon dioxide associated climate change (Richardson et al., 2011).</td>
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<td>Invasive non-native species</td>
<td>&quot;Non-native species that sustain self-replacing populations over several life cycles, produce reproductive offspring, often in very large numbers at considerable distances from the parent and/or site of introduction, and have the potential to spread over long distances&quot; (Richardson et al., 2011).</td>
<td>High reproductive outputs are recommended for increasing food production but need to be stringently managed to prevent the reported negative impacts on the natural resources.</td>
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<td>Exotic species</td>
<td>Synonym of non-native (Richardson et al., 2011).</td>
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Table 1: Definitions of terminology used in the review and description of how each type of plants can improve agricultural crop yield.
current problems associated with biological invasions may arise simply due to poor management of introduced commercial species (Richardson, 1998) and should not negate many of the positive contributions that such non-native species offer (Davis et al., 2011).

Despite the reported negative environmental effects (Pimentel et al., 2001; McDonald and Richardson, 1986; Van Wilgen et al., 2008), the benefits of non-native plant species are significant especially for the majority of African rural communities that have a high vulnerability to the effects of climate change on existing agricultural systems (Shackleton et al., 2004; Franzel et al., 2014). Currently, 80% of the world’s plant-derived dietary material is supplied by only 12 crop species (Gonzalez, 2010). Among them, three crop species, namely wheat (Triticum spp), potato (Solanum spp) and maize (Z. mays) contribute approximately 60% of food energy and proteins (Gonzalez, 2010; Pimentel et al., 2001).

Carr (2001) argued that rapid adoption of high-yielding non-native food crops brought profound food production improvements to many African smallholder farmers. For instance, the arrival of the Portuguese in 1496 was associated with the introduction of many food crops including maize, sweet potatoes, bananas (Musa spp), pineapple (Ananas comosus) and cassava (Manihot esculenta) which became local staples in East Africa and other parts of the continent (Karibu, 1993). Maize is still the most important staple crop in many sub-Saharan Africa countries, although local production is insufficient to meet the demand (Food and Agricultural Organization, 2013). About 28% of maize consumed in Africa is imported from other regions such as the USA (Food and Agricultural Organization, 2013, 2007) and Africa consumes 30% (sub-Saharan Africa 21%) of the 116 million tonnes of global production of maize.

**Indirect benefits of non-native plant species**

Indirect use of non-native plant species for food production includes generation of income by selling harvested products or by employment on plantations/farms. For example, plantations of black wattle (Acacia mearnsii) owned by roughly 2,700 growers can employ up to 30,000 people in eastern South Africa, where rural poverty is dominant (Van Wilgen et al., 2011). In addition, the presence of invasive non-native species in South Africa has also provided jobs for unskilled rural communities in invasive species control and management projects (Van Wilgen et al., 2011; Wilson et al., 2013). Additionally, FAO estimated that the non-native Eucalyptus plantation forestry industry employs at least 300,000 rural people in Mozambique, making it the largest employer in the country (Food and Agricultural Organization, 1999). Also, an
aggressive invader Cinnamon (*Cinnamomum verum*) was propagated in plantations in Seychelles since 1772 and the industry manufacturing products (for example, distilled oil and spices) provide employment for 33% of the working population (Kueffer and Vos, 2004). Other indirect benefits of non-native *Acacia* species in South Africa, for example, include household firewood (Van Wilgen et al., 2011; Shackleton et al., 2004) which supplements 90% of the fuelwood consumption of native species by rural communities at a global scale (Parikka, 2004; Arnold and Jongma, 2007). Indeed, 70% of rural communities in sub-Saharan Africa need wood fuel for domestic energy (Matsika et al., 2013) and alien plantations might provide an alternative energy resource in this regard.

Furthermore, non-native crops could be an effective solution for declining food production in some areas since non-native horticultural trees such as mangoes (*Magnifera* spp.), *Citrus* species, avocado (*Persea* spp.) and banana (*Musa* spp.) are preferential fruits for human consumption in countries such as Malawi and Zimbabwe (Franzel et al., 2014; Ramadhan, 2002; Akinnifesi et al., 2008). Such supplementary resources to the highly degraded natural capital in sub-Saharan Africa may play a vital role in food security. In addition, other indirect uses of non-native plant species facilitate the acquisition of food through selling non-native species’ products to generate income (Shackleton et al., 2007). This includes timber and biofuel production which also provides jobs for a large majority of unskilled rural communities. The income generated helps to indirectly improve food access for rural communities; 65 to 80% of incomes in sub-Saharan Africa are spent on food (Boy and Witt, 2013).

Non-native species can also be categorized based on their functions in the local natural environment and their associated key socio-economic functions (Henderson, 2001; Department of Environmental Affairs, 2014). For instance, the importation of non-native species (for example, Barbados nut *Jatropha curcas* from Mexico) is also being considered for expediting socio-economic development through expansion of the biofuel industry (Richardson and Blanchard, 2011; Blanchard et al., 2011; Pradhan and Mbohwa, 2014). As discussed by Shackleton et al. (2004) this might indirectly reduce poverty and thus food insecurity. Blanchard et al. (2011) reported that biofuel production in South Africa relies on feedstock from non-native and invasive plant species including Wild cane (*Arundo donax*), Chinese silver grass (*Miscanthus* spp.) and Johnson grass (*Sorghum halepense*) and trees (for example, Indian beech *Millettia pinnata* and species of *Acacia, Eucalyptus* and *Populus*).

At the micro scale, use of native and non-native tree species for firewood in the rural areas where smallholder farmers are dominantly located may be another form of biofuel utility of trees. With regard to large-scale production in Africa, FAO (Gepts, 2002; Food and Agricultural Organization, 2009) suggests that small-scale farmers should be included in the biofuel production, following guidelines for alleviating conflicts given the reported successes in Uganda and Mozambique (Stromberg and Gasparatos, 2012).

Since different studies have shown potential for conflict between biofuel production and food production where cereal grains are used as a feedstock (Pimentel et al., 2009; Blanchard et al., 2011; Pradhan and Mbohwa, 2014; Chakauya et al., 2009), the currently invasive non-native species could be screened for a potential to be used as feedstock and development of new products. Such use could help in the control and containment of species invasion capacity and must be coupled with rigorous risk control mechanisms. Indeed, Blanchard et al. (2011) emphasized that success of biofuel production using non-native species would rely on proactive means of minimising the negative impacts on biodiversity which can be addressed by the development of policy, programmes and guidelines that address the conservation of biodiversity in managed and unmanaged areas. Included may also be adequate guidelines and incentives to promote sustainable agriculture. Typically, the risk control and management of invasive non-native plants have been effectively achieved by biological control agents (Richardson and Blanchard, 2011; Pradhan and Mbohwa, 2014; Moran et al., 2013).

Despite the envisaged benefits of biofuels in socio-economic development, a range of conflicts exists in the use of land, water, energy and other environmental resources for food and biofuel production (Pimentel et al., 2009; Richardson and Blanchard, 2011; Pradhan and Mbohwa, 2014). The dependence of food and biofuels on the same ecological, soil and climatic resources means that competing issues of food security, economic security and development are hard to reconcile (Food and Agricultural Organization, 2013). There is also the likelihood of this problem worsening with increasing population stress and climate change, putting pressure on all environmental resources. If non-native plant species become invasive, they may threaten water resources (Le Maitre et al., 2000), but this effect can be controlled and managed in different ways such as reducing density (Gooden et al., 2009) and avoiding excessive irrigation. This all point to a need to manage water resources against the competing agricultural food production and biofuel requirements. Although it is not clear how the use of energy and water can be made more efficient in the production of biofuels, Richardson and Blanchard (2011) suggested that degraded land areas could be targeted to avoid use of arable land and that non-food feedstock species might reduce competing demands of maize and sunflower (Pradhan and Mbohwa, 2014). Strategic foresight planning could be important in using non-native species for human benefit, especially in bio-
economic projects such as food production because most of the plant species used may have potential to become invasive due to mass propagation to maximize yields (Food and Agricultural Organisation, 2013; Pimentel et al., 2009; Shackleton et al., 2008; Richardson and Blanchard, 2011). South Africa developed a national level early detection and rapid response unit whose primary function is to apply screening principles for risk analysis and biosafety when dealing with non-native species (Richardson and Blanchard, 2011; Wilson et al., 2013).

Benefits of genetically modified species and alien gene transfer

Studies addressing the need for future higher crop yield suggested that the further adoption of genetically modified (GM) crops might be a viable future management option (Pretty et al., 2011; Food and Agricultural Organization, 2013; Burke et al., 2009; Reynolds et al., 2010; Hawkesford et al., 2013). Domestication of wild plants through selection and classical plant breeding has been well documented as a technique for enhancing agricultural food production in different parts of the world, including Africa (Sorrells et al., 2004; Kumar et al., 2006; Masters and Norgrove, 2010; Tayeng et al., 2012; Pratap and Kumar, 2014; Gepts, 2002). Genetic modification of crops in agriculture entails insertion of the desired individual genes from one organism into another to enhance either existing characteristics or to suppress undesirable ones (Hawkesford et al., 2013). These crop traits include high germination rates, reduced/toxocity and plant defence mechanisms, changes in biomass allocation to fruits, stem or root and phenological changes, usually shortening the time to fruiting (Hawkesford et al., 2013). Anderson and Jackson (2004) distinguished two reasons for adoption of GM food crops, namely an increase in agricultural yields, and/or increased nutritional quality through biofortification as described by Herren (2013). Despite that increased CO₂ concentration might reduce nutritional quality (Schoof, 2011) genetically modified food crops may be an important strategy to provide food for an expanding and undernourished population in sub-Saharan Africa. Consequently, genetic modification may provide an alternative solution to classical breeding techniques that has yielded good results in improving the performance of agricultural crops in Africa (Masters and Norgrove, 2010; Gepts, 2002).

Current trends in adoption of GM crops indicate that smallholder farmers in developing countries may substantially rely on GM crops with greater possibilities for further expansion in the near future as a response to increased variability of rainfall events and/or decreased availability of river and groundwater for irrigation. The same trend also holds for large-scale commercial farming. For example, South Africa as a leading adopter of GM crops in Africa had about 2.3 million hectares of genetically modified maize, soya bean and cotton in 2011 (James, 2011). The reported global value of the GM seed market alone was US$13.2 billion in 2011 with maize and soybean constituting the major GM commercial grains (James, 2011).

Despite the benefits, concerns on the environmental impacts (that is, about similar impacts to those of the invasive non-native species for example, genetic pollution through hybridizing with indigenous species) of GM organisms were raised (United Nations Environment Programme, 2011; Jeschke et al., 2013). For example, seventeen plant species were threatened by outbreeding depression associated with hybridization with a more abundant non-native invader in Germany (Bleeker et al., 2007). Consistent with this, the United Nations Food and Agriculture Organization (FAO) reported that during the twentieth century 75% of the world’s native food crop diversity was replaced by non-native species and GM crops (Gonzalez, 2010; Food and Agricultural Organization, 2012).

There are specific benefits associated with the use of genetically modified crops in this region. Studies have shown that genetic material from non-native plants can be widely used to enhance yield attributes for important wheat (T. turgidum and T. aestivum) and maize varieties as well as, adaptability to changing environmental conditions (Sorrells et al., 2004; Kumar et al., 2006; Tayeng et al., 2012; Pratap and Kumar, 2014). Moreover, the hybridization of maize traits in wheat production, including drought-tolerance, has been widely reported and is currently a preferred method for producing high yielding wheat (Tayeng et al., 2012; Tadesse et al., 2012).

In comparison to conventional plant breeding methods that take many years to obtain desired traits, the application of biotechnology in plant breeding may allow achievement of results in relatively shorter times and generate genetic diversity that can be incorporated in crops (Food and Agricultural Organisation, 2004; Herren, 2013; Gepts, 2002). Integration of GM crops to wider agricultural ecosystems and communities may also increase agricultural productivity and thus reduce human pressure on consumable biodiversity (Wesseler et al., 2011).

Consequently, agricultural food production policy should encourage molecular innovations in the use of non-native species’ genomes to improve the resilience of native crops in agricultural food production (Masters and Norgrove, 2010; Lin, 2011). Studies have shown that the benefits of genetic modification of crops are likely to be substantial, especially in sub-Saharan Africa where food demand has increased due to population (Anderson and Jackson, 2004; Gepts, 2002). Plant species’ genomes with high resilience to
climate change are urgently required for sub-Saharan Africa where research (Food and Agricultural Organization, 2013; Niang et al, 2014; Lobell et al, 2008; Burke et al., 2009; Burke and Lobell, 2010) has shown that major staple cereal crops are highly vulnerable to future changes in temperature and precipitation regimes. Whereas the use of non-native plant species and the GM crops might be a promising solution for increasing agricultural food production, African soils have seen substantial degradation (A Montpellier Panel Report, 2014) thereby making environmental rehabilitation an obligation for farming to remain sustainable. Thus, we proposed that conservation agriculture practices should be widely adopted to increase chances of sustainability in sub-Saharan agricultural food production.

### Sustainable agricultural food production practices in sub-Saharan Africa

The need for intensification of agricultural food production in sub-Saharan Africa has been emphasised in several recent reports (Pretty et al., 2011; Food and Agricultural Organization, 2013). However, there are several challenges to achieving this through conventional agricultural methods. For instance, conventional agricultural activity accounts for 20% of global CO₂ and NO₃ emissions and these make agriculture a significant driver of climate change (Rodriguez et al., 2004). It is estimated that N₂O emissions from agricultural activity account for 42% of total emissions from Africa or roughly 6% of global anthropogenic N₂O emissions (Hickman et al., 2011) and this is likely to increase in the future through the use of fertilizers. Another challenge is the high level of poverty and insufficient education in sub-Saharan Africa (Pretty et al., 2011; Shackleton et al., 2008, 2004) which might restrict the adoption of highly mechanized and learning-intensive food production methods (Niang et al., 2014; Giller et al., 2009; Friedrich et al., 2012). Other difficulties are expected to result from attempts to intensify conventional food production whilst also trying to minimize negative environmental impacts. Previous strategies using deep ploughing and intensive application of chemical fertilizers are not compatible with sustainable agriculture.

### Adoption of conservation agriculture

Development of sustainable agricultural practices and maintenance of existing ecosystems for future agricultural food production and ecosystem goods and services are important goals for sub-Saharan Africa (Food and Agricultural Organization, 2013; Niang et al, 2014; IPCC, 2007; Björklund et al., 2012; Rey et al., 2015). Therefore, an integration of nature conservation or ecological conservation principles into agricultural food production systems may promote conservation of natural resources (Björklund et al., 2012; Dalgaard et al, 2003; Altieri et al., 2012).

Conservation agriculture is defined by the FAO (Food and Agricultural Organization, 2013) as a concept for resource-saving agricultural crop production that strives to achieve acceptable profits, together with high and sustained production levels, whilst concurrently conserving the environment (Giller et al., 2009; Friedrich et al., 2012; Gowing and Palmer, 2008; Hobbs et al, 2008). Conservation agriculture can include the use of one or several of three different cropping practices to improve crop yields. These are (Pretty et al., 2011) minimum or no-tillage to reduce soil disturbance, (Food and Agricultural Organisation, 2013) permanent soil cover, using crop residues as mulch and (Niang et al, 2014) crop rotations or intercropping, especially with nitrogen-fixing legumes (Food and Agricultural Organisation, 2013, Giller et al., 2009; Friedrich et al., 2012; Corbeels et al., 2014b).

The ‘no-til’ practice can buffer the soil’s organic content for a longer period whilst also maintaining soil productivity and moisture (Food and Agricultural Organization, 2013). Since conventional agriculture has detrimental effects on biodiversity, conservation agriculture offers an attractive alternative to the goal of achieving food security without compromising environmental integrity (Food and Agricultural Organization, 2013) and has been suggested as the best cropping practice for mitigating and adapting to climate change in sub-Saharan Africa (Niang et al, 2014; Friedrich et al., 2012; Kassam et al, 2009).

In this context, widespread adoption of conservation agriculture in Africa (Giller et al., 2009; Friedrich et al., 2012) is facilitated by the fact that advanced machinery is not required. The area under conservation agriculture in sub-Saharan Africa is now nearly one million hectare and already involves more than 400, 000 smallholder farmers (Friedrich et al., 2012). However, for successful adoption management practices must fit local biophysical conditions (Rusinamhodzi et al, 2011; Buffet, 2012; Rey et al, 2015).

Conservation agriculture may be a good production strategy for smallholder farmers already experiencing the impact of climate change in sub-Saharan Africa (Mbowa et al., 2014; Björklund et al., 2012; Kahane et al., 2013) as it also provides for use of supplementary nature-based goods and services important for socio-economic development in African rural communities (Food and Agricultural Organization, 2013; Niang et al, 2014; Shackleton et al., 2008; Millennium Ecosystem Assessment (MEA), 2005; Björklund et al., 2012; Simberloff, 2013; Rey et al., 2015). Conservation agriculture can also help reconcile agricultural food production, nature conservation and
environmental management. The successful smallholder farmers using these strategies may upscale their production and commercialize products for the market (Gowing and Palmer, 2008; Hobbs et al., 2008), thereby strengthening food supply for local communities (Björklund et al., 2012; Kahane et al., 2013).

Despite the benefits of conservation agriculture, several challenges have been raised. For example, conservation agriculture has been criticized for being labour-intensive when weed control, for example, relies on manual labour (Giller et al., 2009; Friedrich et al., 2012; Corbeels et al., 2014a; Buffet, 2012). It also requires substantial adjustments from conventional agriculture and the potential benefits are likely to be household specific (Erenstein and Farooq, 2009). For example, conservation agriculture alters the normal flow and use of farm resources such as the retention of crop residues as soil mulch rather than being used as animal fodder (Corbeels et al., 2014a, b). The returns of such adjustments are seen only through long-term engagement (Rusinamhodzi et al., 2011) while smallholder farmers consider the visible and immediate benefits when considering adoption of conservation agriculture practices (Giller et al., 2009; Friedrich et al., 2012; Corbeels et al., 2014a). In many cases, the recommended crop rotation systems in conservation agriculture are not used by many smallholder farmers, despite the benefits (Corbeels et al., 2014b) because farmers prefer crops that yield more annual profits. For example, farmers tend to maximize their production in cereal crops grown in monoculture systems, rather than the recommended legumes due to the market demand for cereals which acts as a disincentive for change (Ehui and Pender, 2005).

In view of the previously outlined principles of conservation agriculture and its affordability (Corbeels et al., 2014b; Buffet, 2012), conservation agriculture can help tackle the reported negative impacts of high poverty, malnutrition, growing population, and climate change on food crop yield in sub-Saharan Africa. Other environmentally friendly alternative means of supplementing agricultural food production in sub-Saharan Africa are further discussed. Whereas conservation agriculture focused on minimizing environmental degradation during the agricultural food production process (Giller et al., 2009; Friedrich et al., 2012; Corbeels et al., 2014a), agrobiodiversity considers the biodiversity benefits existing within the farming systems as supplementary resources (Simberloff, 2013).

**Supplementary natural capital - agrobiodiversity**

In the context of this review, agrobiodiversity is defined as the variety of wild animals, plants and micro-organisms that are used directly or indirectly for food and agriculture or in association with agricultural systems, including crops, livestock, forestry and fisheries (Food and Agricultural Organization, 1999; Kahane et al., 2013). Altieri and Rogé (2010) distinguished two interacting components of biodiversity that have implications for sustainable agriculture: agricultural systems, as the planned biodiversity comprising the farmed organisms; and the associated biodiversity forming part of the larger ecological system beyond the influence of the farmer (Simberloff, 2013).

Agrobiodiversity comprises the diversity of genetic resources that are harvestable for food, fodder, fibre, medicinal and non-harvested species that support primary productivity in agroecosystems (Millennium Ecosystem Assessment, 2005; Food and Agricultural Organization, 1999; Kahane et al., 2013; Thrupp, 1998; Rey et al., 2015). For example, insects and birds provide important ecosystem services such as pollination and seed dispersal (Millennium Ecosystem Assessment, 2005; Whelan et al., 2008). Wild animals also provide some 30% of human requirements for food and agriculture and 12% of the world’s population live almost entirely on products from ruminants (Food and Agricultural Organization, 1999). Studies suggest that diverse indigenous food crops can provide sustainable complementary resources to the declining production of the few staple cereal crops grown in sub-Saharan Africa (Mbow et al., 2014; Kahane et al., 2013; Keatinge et al., 2011). Many smallholder farmers make extensive and informal use of the ecosystems and biodiversity in the surroundings of their farms (Kahane et al., 2013) and to a certain extent depend on the provisioning, regulating, supporting and cultural ecosystem services that are offered by this biodiversity (Food and Agricultural Organization, 2013; Millennium Ecosystem Assessment, 2005).

Diversification of the diet by using indigenous wild flora and fauna was recommended as an effective means of addressing nutrient deficiency (Kahane et al., 2013). Moreover, African rural populations depend on many wild medicinal plants for as much as 80% of their primary healthcare needs (Boy and Witt, 2013). Since agrobiodiversity is practised in cognisance of ecological conservation principles, over-exploitation of ecological resources is generally considered to be minimal in theory.

Recent research focusing on increasing sustainability of food security in African rural communities by smallholder farmers identified agroforestry as a viable production option (Mbow et al., 2014; Kalaba et al., 2010). Agroforestry entails agricultural land use management where trees or shrubs are grown around or among crops and this strategy involved the use of native tree species in African semi-natural rural landscapes (Mbow et al., 2014). However, fodder trees including many non-native species were also
considered for agroforestry based on their low requirements of labour, capital and land (Rejmánek et al., 2005; Franzel et al., 2014). Agroforestry can boost agrobiodiversity by creating diverse natural habitats attractive to wildlife (Kalaba et al., 2010; Dawson et al., 2014). Non-native trees which commonly show higher ecological performance than native species can also substantially boost biomass production which makes them attractive for biofuels and charcoal/wood (Food and Agricultural Organization, 2013; Dawson et al., 2014; Lamb et al., 2005; Vilà et al., 2011).

There is evidence that commercial forestry plantation comprising non-native species can be manipulated to elicit successful restoration of degraded landscapes and ecosystem goods and services (Dawson et al., 2014; Vilà et al., 2011; Lamb, 1998).

Recently, agroforestry, as a form of mixed farming systems was successfully used to support livestock production in east Africa (Cecchi et al., 2010). This is confirmed by the use of non-native fodder trees by more than 200,000 smallholder dairy farmers along field boundaries where they do not compete with other crops and can help reduce soil erosion (Franzel et al., 2014; Dawson et al., 2014; Rey et al., 2015). In addition, the Kyoto Protocol’s Clean Development Mechanism recognizes that non-native tree plantations can provide important large-scale carbon sinks which can potentially offset CO₂ emissions (Mbow et al., 2014; De Wit and Stankiewicz, 2006; Smith and Mbow, 2014). The high biomass produced by non-native tree species can be important in alleviating poverty in poor rural communities who depend on tree products for sale or consumption (Shackleton et al., 2008; Shackleton et al., 2004; Vilà et al., 2011). Villa et al. (2011) reported that non-native species can enhance habitat primary productivity and several important ecosystems processes thereby elucidating that non-native agroforestry species should have minimal impacts on existing natural resource systems if they are effectively managed (Achten et al., 2010).

**DISCUSSION**

Intensification of agricultural food production in sub-Saharan Africa is of paramount importance as a means of increasing the food security of communities that are already experiencing a range of environmental and socio-economic stresses (Pretty et al., 2011; Foran et al., 2014). Declining agricultural food production in some areas and under some circumstances is partly attributed to the effects of climate change in combination with a range of internal and external political and socio-economic factors that can also reduce adaptive capacity (Pretty et al., 2011; Niang et al., 2014; Burke and Lobell, 2010).

Subsequently, several studies dealt with specific potential solutions to food security. For example, biotechnology and crop-climate suitability modelling studies have emphasized a need for improved environmental tolerance of crop species and improved reproductive attributes of crops using genome manipulation (Hawkesford et al., 2013; James, 2011; Food and Agricultural Organization, 2004; Burke and Lobell, 2010). Such solutions, however, may not be individually suitable to the socio-economic and cultural situations of smallholder farmers in sub-Saharan Africa and may be incompatible with the principles of sustainable agriculture. Therefore, we propose a combination of context-based (that is, suited to local environmental settings) management strategies which emphasize strategic foresight planning (that is, including methods to minimize potential negative impacts) in the use of non-native plant species as viable option, given their adaptive ability to environmental stress induced by climate change as opposed to native species. In addition, we explore possibilities for further adoption of GM crops.

The genetic modification of crops may be reinforced by the use of existing highly resilient alien genomes (for example, for drought resistance, fast-growth and high reproductive output, etc) to improve reproductive attributes of native crops and consideration for adopting conservation agriculture practices to mitigate environmental degradation associated with agricultural food production.

**Strategic foresight and planned management**

Strategic foresight planning and better use therefore facilitates the better management of already introduced non-native species which might help in their containment and pest control and any possible negative impacts on native species, ecosystems and biodiversity and soil fertility and hydrology. It is widely acknowledged that management and control strategies become difficult where non-native plant species provide keystone services (for example, horticulture and timber production) for the local communities (Richardson, 1998; Van Wilgen et al., 2011; Boy and Witt, 2013; Moran et al., 2013; De Wit and Stankiewicz, 2006).

However, based on a review of the historical benefits of non-native plant species in food production in sub-Saharan Africa, the use of existing stocks of non-native species and/or the genetic modification (that is, using transgenic and classical breeding techniques) of native species might be viable options for future agricultural sustainability in this region. Planned exploitation of non-native species for poverty alleviation in sub-Saharan Africa was previously highlighted by Shackleton et al. (2008) and non-native species are still widely used in Africa to enhance production.
by smallholder farmers. Non-native plant species tend to display much better adaptation to environmental stress induced by climate change and have higher reproductive ability than many native species, which therefore give them their invasive qualities (Porter et al., 2014; Rejmánek et al., 2005; Daehler, 2003). In agricultural food production, they require less labour and grow faster (Rejmánek et al., 2005; Richardson, 1998; Shackleton et al., 2004). Managing non-native tree stocks as forestry plantations or biofuels requires consideration of their benefits versus the need for agricultural food production (Pimentel et al., 2009).

Recent studies that have explored beneficial uses (for example, socio-economic developments and biodiversity conservation) of non-native species that have potential to harm the environment (Moran et al., 2013; De Wit and Stankiewicz, 2006; Mokotjomela et al., 2009; Mokotjomela et al., 2013; Rogers and Chown, 2014) suggest the integration of management and control strategies to minimize risk. Nevertheless, different regions of sub-Saharan Africa might require context-specific risk management plans, dictated by the particular mix of species and socio-economic/environmental conditions.

Food production strategies: Genetically modified crops versus conservation agriculture

Biotechnology and genetic modification of native crop species by non-native species can be used to improve the yields and climatic resilience of native crops (Schoof, 2011; Herren, 2013). Several countries in sub-Saharan Africa are adopting GM crops (James, 2011), which may be able to help address regional food security and nourishment (food crop quality). GM crops was approved for commercial release in Burkina Faso, Egypt and South Africa, while contained and confined testing of them was performed in Kenya, Nigeria, Uganda and several other countries (Falck-Zepeda et al., 2013). The relationship between GM crops and low-cost conservation agriculture as well as, agrobiodiversity is complex, but these are not mutually-exclusive solutions and can be used in combination.

The use of non-invasive, non-native plant species in food production may promote recovery of natural capital, ecosystem services and environmental conservation. Conservation farming practices are an excellent way of minimizing environmental degradation whilst sustaining agricultural food production in sub-Saharan Africa (Niang et al., 2014; Mbow et al., 2014; Björklund et al., 2012; Simberloff, 2013). Agrobiodiversity can increase the wealth of natural capital (for example, through the exploitation of wild vegetables, bush meat, medicinal plants and honey bees etc) in both on- and off-farm situations (Simberloff, 2013). Both conservation agriculture and agrobiodiversity can maximize benefits from natural capital that is crucial for building resilience to impending climate change impacts (Mbow et al., 2014; Millennium Ecosystem Assessment, 2005; Shackleton et al., 2008). Adoption of conservation agriculture principles can reduce the ongoing tension between the impact of conventional agriculture on biodiversity loss versus climate change control and its mitigation to achieve climate-smart agriculture.

Conclusions

Whilst ensuring that food security remains a priority for sub-Saharan Africa where more than half the arable land is degraded (A Montpellier Panel Report, 2014), there are several socio-economic, environmental and climate change challenges that must be addressed. It is apparent that there are limitations to the application of single approaches as earlier reviewed to increase agricultural food production despite the significant contribution of these approaches in specific environmental settings such as conservation agriculture in areas that are vulnerable to environmental degradation. Any agricultural strategy on the ground is dependent, however, on first identifying and then applying best-practices to different agricultural systems and crops in different physical settings, climatic regimes and soil types and also considering the different needs and capabilities of commercial versus subsistence farmers (Knight, 2015). Any coherent agricultural strategy can only be enacted through political will and linked to parallel strategies in rural economic and social development, education, health care, transport and marketing (Knight, 2015; Rey et al., 2015). This means that enhancing food security by increasing food production is only one element of a wider development agenda required to adapt to predicted climate change impacts. Moreover, agricultural food production is just one stage of the food supply chain and therefore, its sustainability may also be achieved by increasing the adaptability of crops and stabilising production of relatively higher yields.

Low-technology and long-term strategies discussed in this study such as conservation agriculture have a relatively low risk but by themselves are unlikely to meet future food demand due to the complexity of global change (Knight, 2015). Increased and more innovative use of non-native plants may be a better strategy to increase food yields over shorter time scales especially in areas where poverty is a major obstacle to achieving adequate food production through agriculture.

However, a proposed option may require greater economic investment, monitoring and management, including ensuring biosecurity and no negative impacts on native ecosystems (United Nations Environment Programme, 2011; Department of Environmental Affairs, 2014; Rey et al., 2015). Yet, this multidimensional and
integrated approach to agricultural food production is not well-developed in many sub-Saharan countries but is required to achieve a food-secure future under climate change.

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