Supporting human nutrition in Africa through the integration of new and orphan crops into food systems

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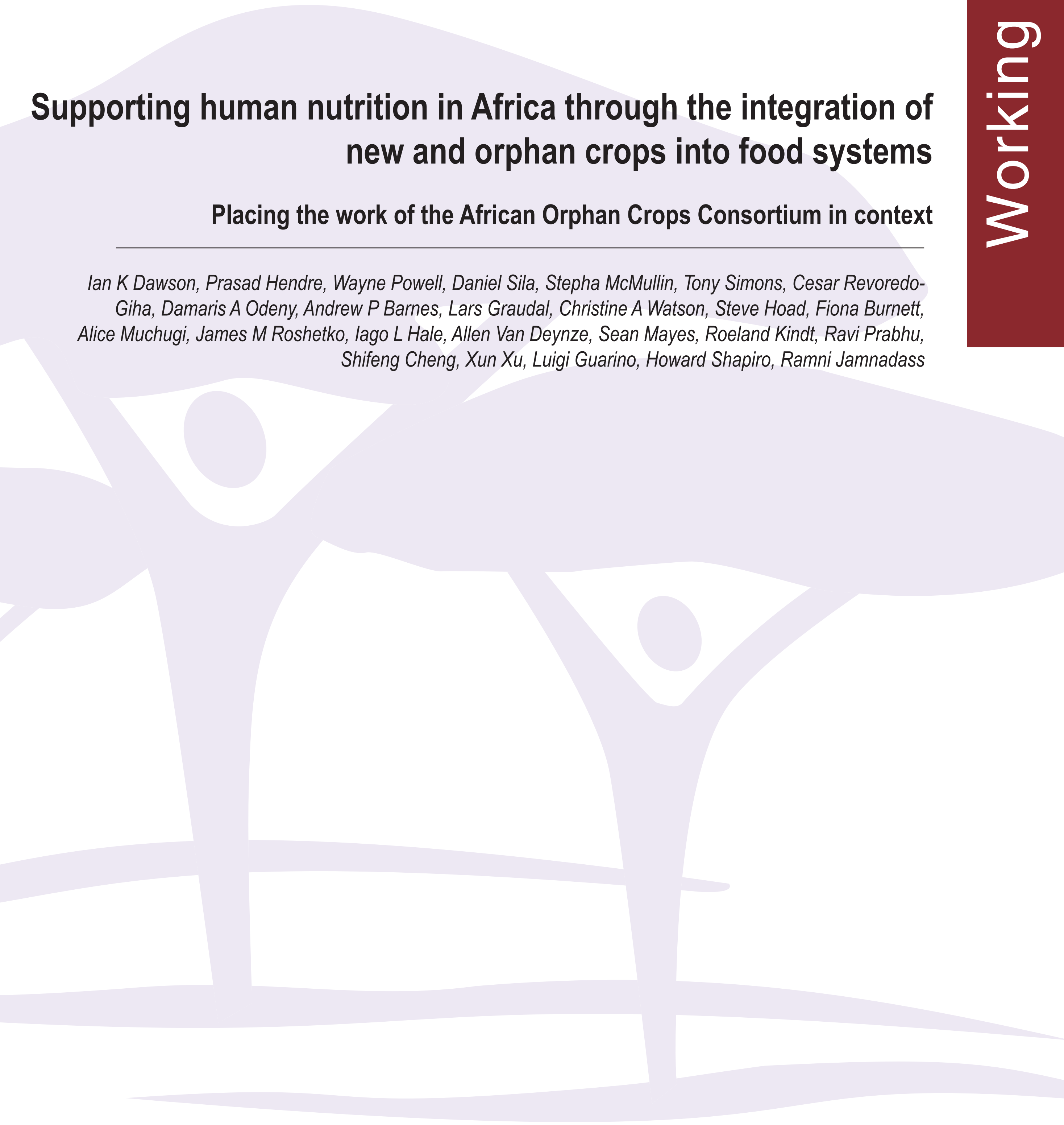

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INTERNATIONAL CROPS RESEARCH
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JOMO KENYATTA UNIVERSITY OF AGRICULTURE AND TECHNOLOGY
TECHNOLOGY FOR DEVELOPMENT

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List of abbreviations & acronyms

AfPBA	African Plant Breeding Academy
AOCC	African Orphan Crops Consortium
ASTI	Agricultural Science and Technology Indicators
CCAFS	CGIAR Research Program on Climate Change, Agriculture and Food Security
CFF	Crops for the Future
DFS	Diversity of Food Supply
DNA	Deoxyribonucleic acid
ENM	Ecological Niche Modelling
ESA	Eastern and Southern Africa
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
GBIF	Global Biodiversity Information Facility
ICRAF	World Agroforestry Centre
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
IFAD	International Fund for Agricultural Development
IFPRI	International Food Policy Research Institute
ISPC	Independent Science and Partnership Council
JKUAT	Jomo Kenyatta University of Agriculture and Technology
LSMS-ISA	Living Standards Measurement Study-Integrated Surveys on Agriculture
NCBI	National Center for Biotechnology Information
NEPAD	New Partnership for Africa's Development
NOC	New and Orphan Crops
NRC	National Research Council
RNA	Ribonucleic Acid
SDG	Sustainable Development Goal
SNP	Single Nucleotide Polymorphism
SPIA	Standing Panel on Impact Assessment
SRA	Sequence Read Archive
SRUC	Scotland’s Rural College
SSA	Sub-Saharan Africa
UK	United Kingdom
UN	United Nations
UNICEF	United Nations Children’s Fund
US	United States of America
USDA	United States Department of Agriculture
USD	United States Dollar
WACCI	West Africa Centre for Crop Improvement
WFP	World Food Programme
WHO	World Health Organization

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Abstract

Better integrating currently under-researched nutrient-rich new and orphan crops (NOC) into food systems could play an important role in addressing poor human diets. Understanding the multiple interventions required to support effective integration is, however, not straightforward. Current research to support this objective has generally been inadequate, in large part because insufficient attention has been given to draw together the multiple disciplines needed to explore and reach solutions. A broad interdisciplinary research programme is needed to provide answers to the following questions: how do dietary diversity and crop diversity interrelate at national and local food system levels? What drives crop integration or exclusion in food systems over time? How can new technologies be embraced in combination with best existing practices to genetically improve, better manage and more effectively process crops? And what are the best approaches to bring about behavioural change among farmers, food processors, consumers and other stakeholders to introduce new practices and foods?

These questions are of particular pertinence in sub-Saharan Africa (SSA) where the problem of ‘hidden hunger’ is especially significant. Specific initiatives such as the African Orphan Crops Consortium (AOCC), which seeks to apply new technologies to genetically improve 101 nutritionally-important annual and perennial NOC in the region to help address hidden hunger, have to be viewed within a food system context if they are to be effective. Here, we explore food system issues affecting the SSA region, consider the specific crops and interventions of the AOCC initiative, and draw out six possible ‘quick win’ knowledge-generating activities that, if undertaken, will support AOCC objectives and NOC integration. Through setting out research needs, our intention is to promote the creation of broad interdisciplinary teams to carry out systems-oriented work on NOC. We also hope to encourage other stakeholders, including funding agencies, to support this important research, in SSA and elsewhere.

1. Introduction

1.1. Background on food systems, nutrition, and new and orphan crops in Africa

Global food systems that focus on an ever narrower range of calorie-rich but nutritionally-limited crops (Khoury et al., 2014) endanger human health. Improving food nutritional quality through measures such as diversification and biofortification (Box 1) is therefore a key challenge (Frison et al., 2011; von Grebmer et al., 2014; SDG, 2017). The integration into food systems of nutrient-rich new or orphan crops (NOC) is recognised to have an important role (Gruber, 2017; Mabhaudhi et al., 2017; Tadele, 2017). These are crops that, though locally or regionally valued by consumers and farmers, have received relatively little attention by researchers, such that their potential for dietary improvement by contributing important minerals, vitamins, anti-oxidants and other micro- and macro-nutrients has not been fully explored. In the face of climate-related shocks and other global challenges that negatively affect food security, however, diversification with NOC provides opportunities to increase the resilience as well as the nutritional value of food systems (Altieri et al., 2015).

Sub-Saharan Africa (SSA) has some of the areas of highest ‘hidden hunger’ and nutritional insecurity in the world, with acute deficiencies exacerbated by climate change (von Grebmer et al., 2014). These deficiencies lead to serious developmental underachievement and disease. Girls do not achieve proper growth and become unhealthy mothers whose ability to breastfeed their children is compromised by continued inadequate diet, leading to underweight babies; older children do not achieve their full potential cognitive ability; working age men and women are unable to work due to sickness; and the elderly find it difficult to remain active (FAO et al., 2017). Improving nutrition in SSA is therefore a priority for national governments, who have highlighted the important role of diversification of food production (Covic and Hendriks, 2016). At least in theory, therefore, supportive national frameworks exist for NOC integration in the SSA region, aligning closely with UN Sustainable Development Goals (SDGs) including SDG1 (reducing poverty through creating value chains), SDG2 (promoting the accessibility and use of nutritious foods, promoting sustainable agriculture), SDG11 (contributing to the food security of growing cities) and SDG13 (providing resilience to climate change) (UN, 2017).

One measure taken in the last few years to help address nutritional deficiencies in SSA through NOC promotion has been the establishment of the African Orphan Crops Consortium (AOCC). This initiative supports the mainstreaming of 101 annual and perennial NOC of nutritional importance to African consumers into SSA food systems through the application of new genomic methods to enhance crop improvement (AOCC, 2017). The Consortium, which at its inception was promoted by Mars Inc., NEPAD and ICRAF, involves a wide array of research-oriented and development-focused institutions, many of which are represented in the authorship of this Working Paper. The partnership includes institutions from both public and private sectors, which work on major and less-used crops, and that are based in high-, middle- and low-income nations, to promote knowledge and technology transfer. The Consortium also links with initiatives such as the CGIAR Genebank (CGIAR, 2017a) and Excellence in Breeding (CGIAR, 2017b) platforms, the Crops for the Future (CFF, 2017) programme, DivSeek (2017; which promotes genomic-level characterisation of the genetic diversity of crop gene pools) and specific NOC initiatives such as BamNetwork (2017;

network for Bambara groundnut research). The work of the Consortium has received significant international media attention recently because of its potential and novelty (Guardian, 2016; Economist, 2017).

Box 1. Strategies to improve diets: diversification and biofortification

Diversification: this strategy for improving diets is based on widening the range of food produced by farmers and available to consumers, under the assumption that such widening can positively influence nutrition. It has both a qualitative component – for example, the number of crops grown and consumed in a particular location – and a quantitative one – for example, the balance of consumption across crops, with reference to total dietary intake and the nutritional compositions of foods. The approach is considered to have strong advantages in the context of climate-change-related food system challenges; for example, production diversity can contribute to food system resilience by risk spreading and through positive stabilising interactions (Altieri et al., 2015). However, as is explored later in this Working Paper (see section 2.1.1), just because farmers produce a more diverse range of crops it does not necessarily mean that local consumers have a more diverse or more nutritious diet – relationships between production and diets can be complex.

Biofortification: this strategy for improving diets involves breeding crops to be more nutritious. It is generally applied to globally or regionally important staples that are consumed in large quantities (Birol et al., 2016). The approach has the advantage that it is based on crops that farmers already plant and consumers recognise, which means that there is a ready pathway to the adoption of improved varieties and products. However, the approach does not benefit from the extra resilience that the diversification strategy can provide.

Do NOC improve diets through diversification or biofortification? New and orphan crops with their often excellent existing nutritional profiles provide a wide range of more nutritious food options for consumers and therefore have an obvious role in a food-system-diversification approach to improve diets. Some orphan crops are also often already regionally – or locally – important staples, so further enhancing their nutritional quality in such cases represents a biofortification approach to improving diets. The mechanisms by which NOC support nutritional improvements can involve combinations of diversification and biofortification, as any change to an individual crop will influence the balance of incentives for production and consumption of other crops compared to that crop. Understanding how the consumption and production of one crop influences the consumption and production of other crops is therefore an important research question in food systems.

1.2. Objective of this Working Paper: placing AOCC in the context of African food systems

It has always been evident to AOCC partners that the specific work of the Consortium in supporting crop production, while essential, is only part of what is needed to mainstream NOC into African food systems. Almost a decade ago, Dawson et al. (2009) took an evidence-based approach to review the existing and potential utility of biotechnology-based approaches for promoting the use of NOC and the factors that limit impact. Genuine progress requires that the many interconnecting factors that determine the diets of African communities – including culture, economics, infrastructure, government policies, farming environments and living conditions – are better understood, so that suitable interventions to address current barriers to integration can be put in place along the entire ‘food-production-to-use’ chain (Covic and Hendriks, 2016).

Past research on NOC in Africa and elsewhere, however, has generally focused on single aspects of this chain, giving limited consideration to food systems in their entirety. This fragmented approach to research has resulted in a lack of understanding of the key drivers involved in the integration – or, conversely, that determine the exclusion – of NOC in diets, and many questionable assumptions about the value of particular consumption-based or production-oriented interventions for positively influencing human health. Not surprisingly, this has resulted in 'solutions' for NOC integration that when implemented have failed to have the desired effect. A similar lack of joined-up-thinking has been evident in the development of agricultural nutritional interventions more generally, but – possibly because of limited consistent investment in their promotion – the situation appears to have been worse for NOC (Ruel and Alderman, 2013).

This Working Paper aims to provide appropriate context on food systems research so that the crucial work of the AOCC initiative is properly integrated into this context and thus enhanced in its effectiveness. The required content of a food systems research programme is outlined in section 2. This content has been developed and structured by wide discussion of research needs among many different stakeholders, inside the Consortium and more widely, and by a review of the relevant literature. The two institutions central to this 'needs assessment' have been ICRAF and SRUC. Section 2 describes the types of questions that need to be addressed to overcome existing barriers to ensure the integration of NOC into African food systems. Through this presentation of needs, a shared perspective among scientists of different backgrounds can be developed, allowing the creation of the broad interdisciplinary teams needed to undertake the required research. Through the presented analysis, the intention is to encourage funding agencies, governments, food processors and other stakeholders in both public and private sectors to support the required work.

In section 3 of this Working Paper the work of AOCC is described in some detail, including the crops and approaches that the initiative covers. Based on preceding sections, section 4 discusses several useful 'quick win' knowledge-generating activities that should be undertaken in the near future to support the AOCC initiative.

2. A research programme for integrating new and orphan crops into African food systems

To identify important research needs to support NOC integration into food systems, a wide range of stakeholders were consulted, including scientists within our own and partner institutions, as well as many other public and commercial food system specialists[1]. Those consulted comprised agronomists, agricultural and social economists, behavioural change scientists, crop conservationists, crop breeders, food technologists, food processers, nutritionists, geographic information system specialists, and production and consumption system modellers. The results from this consultation have been supported by a survey of the global literature on the sustainable intensification of agricultural production systems (with particular emphasis on references to cropping systems) and on the processes involved in food supply and crop domestication (including the limited references available on NOC). Much of this literature has been reviewed in other publications led by various authors of the current study (see especially Jamnadass et al., 2015; Prabhu et al., 2015; Dawson et al., 2018). Key texts are indicated again in this Working Paper, but for a wider understanding of these topics the above reviews should be consulted. Based on consultations and the literature review, four research areas that are crucial for supporting NOC integration into food systems were identified, as outlined below. A more detailed exploration of needs in each of these research area remains ongoing through further stakeholder and expert consultations.

2.1. Understanding food consumption patterns and value chains

2.1.1. Exploring relationships between consumption diversity and production diversity

Crucial for understanding how NOC can beneficially alter consumers' diets is an exploration of the sometimes complex relationships between what foods are produced and what foods are eaten at local and national levels. Proper examination involves exploring the various contexts of consumption, including rural, peri-urban and urban settings, as well as the age, gender, education, cultural background and income of consumers. With this knowledge, opportunities for influencing human diets through targeted diversification with NOC foods, and the possible trade-offs that may need to be negotiated in devising more nutrient-rich consumption systems, can start to be developed.

Research on this topic can utilise existing sub-national food consumption panel data sets available for some countries (Hassen et al., 2017). These can be compared with food composition databases to draw nutritional implications (INFOODS, 2017). There are, however, major gaps in existing sub-national food consumption surveys for African nations, which mean that *de novo* data collection is essential. Such surveys need to characterise the seasonal availability of foods as part of the collection of socio-ecological location-specific food production and consumption information, to devise 'crop portfolios' that support nutrient provision year-round, including during traditional hunger periods (McMullin et al., 2017). Ideally, the collection of such production and consumption data should be repeated every few years to help assess trends (for a few fortunate African countries, there has already been regular location-specific sampling of household consumption data; e.g., four rounds of

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[1] Many of those consulted are listed in the Acknowledgements section of this Working Paper.

sampling in Ethiopia between 1995 and 2011; Hassen et al., 2017). In the absence of resources to undertake repeat sampling, however, long-term recall data collected on a single occasion may be useful in providing insights into previous years' and decades' food systems (Shibairo et al., 2016). The importance of analysing changes in food systems over time is explored further in section 2.2 of this Working Paper.

Existing research illustrates major factors related to food consumption patterns. Based on a simple diversity of food supply (DFS) indicator – the share of calories supplied by non-staple foods – Choudhury and Headey (2016) indicated that increased age, increased income and a move from rural to urban living are all important for predicting increased DFS in a range of countries sampled globally. They also found that time-invariant geographical and infrastructural factors are significantly associated with DFS, corresponding with some countries having lower or higher DFS than expected compared to their level of economic development. Choudhury and Headey's analysis suggests that specific measures to drive dietary diversification could be targeted to particular portions of countries' demographic compositions – to young and old people, to rich and poor, and to urban and rural populations. It also suggests particular opportunities for NOC integration into food systems where economies are most improving and there are the greatest shifts to urban living.

Further research has sought to explore relationships between local crop diversity and individual and household dietary diversity measures. In a review of such work, Powell et al. (2015) found a positive association between crop diversity and dietary diversity in six of the eight available studies that reported a relationship, supporting the utility of a nutritional improvement strategy based on crop diversification (assuming that dietary diversity and dietary nutritional quality are related; Lachat et al., 2018). The issue is complex, however, as illustrated by Sibhatu et al. (2015), who found that when on-farm production diversity is already high, the association with dietary diversity can turn negative, likely because of foregone income benefits based on production specialisation that could have been used to purchase food. The same authors established positive relationships between both off farm incomes and market access – expressed in terms of lower geographic distance from farm households to the closest food markets – and dietary diversity.

It is evident therefore that there are many issues beyond crop production diversity that determine nearby consumers' diets. Research priorities for future studies of the influence of agricultural biodiversity on local nutritional outcomes include extending beyond measures of dietary diversity to nutritional quality, at species and crop variety (sub-species) levels, and considering scale effects (Jones, 2017).

2.1.2. Examining food value chain structures

Essential for determining how market-based interventions can best be targeted to where and how food is purchased and produced is an understanding of how food value chains currently function and interact for rural, peri-urban and urban African populations (Revoredo-Giha and Renwick, 2016). The expansion of international markets for healthy foods may take on increasing importance as SSA countries' economies transform, but focus on local markets is likely to be crucial when the emphasis is on domestic nutrition (Blare and Donovan, 2018). Where local, national and international markets are all in operation, these need to be properly coordinated so that any potential conflicts are minimised, such as vibrant export markets pricing out access to food for domestic populations (Bellemare et al., 2016).

Existing value chains, including their market infrastructure, socio-cultural and gender-specific dynamics, and finances, need to be properly characterised to determine which value chains work well – and which do not – for consumers and producers (Nang'ole et al., 2011). An important issue is understanding structural barriers to the equitable participation of women, who may be more involved than men in the initial production, processing and trade of NOC foods than they are for 'major' crop foods, but who may be excluded by further commercialisation (Shackleton et al., 2011).

Any impacts on NOC commodities of supply chain concentration around a few major crops also need to be assessed. Research should also include *ex ante* mathematical modelling of the factors – such as improved crop varieties, technical training, market intelligence, financial services, infrastructure and value addition – that may lead to the upgrading of chains.

2.1.3. Defining transformation options for new and orphan crop ingredients

It is essential to identify opportunities for healthier NOC ingredients to substitute for staple crop ingredients in processed food production. Understanding the properties of NOC ingredients is therefore crucial. This is especially important for peri-urban and urban populations whose diets are increasingly based on processed foods. Research involves exploring the processing and nutritional properties of NOC ingredients, and then trialling possible innovations for their integration with commercial food processors. For example, the rheological properties of NOC flours mixed with wheat flour can be investigated with bakers to determine the potential value of NOC flours in the production of bread whose dough retains its functional properties but is of higher nutritional quality (Bakare et al., 2016).

An interesting example recently has been the exploration of the integration of edible seed oil from the African allanblackia or vegetable tallow tree, a new domesticate on the AOCC list (see section 3), into margarine production in Europe by Unilever and others (Allanblackia Partnership, 2017). In this case, the interest is in the ideal melting properties of the oil, which make it suitable for creating spreads with lower levels of saturated fats than current products, while retaining the structure and texture that consumers expect. The food industry is particularly interested in identifying novel functional ingredients for processed food production. New and orphan crops, with their interesting but under-researched properties, may present particular opportunities in this regard, when they are more fully understood.

An important avenue of research is to understand the successful features of existing ingredient substitution initiatives. The ICRISAT-led Smart Food programme (ICRISAT, 2017) is an example that can be learnt from. This works to create a demand pull for less-utilised crops grown in Africa and Asia by developing and promoting new food products such as gluten-free pancake mixes, breakfast cereals, porridge flours for babies, and composite flours for cakes and confectionaries. This work has been accompanied by media popularisation programmes (e.g., Smart Food Reality Show, 2017).

2.2. Understanding food consumption and production trends

2.2.1. Exploring the determining features of winner and loser crops in food systems

Crucial for indicating where and how to better integrate NOC into future food systems is a longitudinal analysis of what has driven the inclusion or exclusion of crop plants in food systems over time. Understanding what has made some crops global 'winners' – with a relative increase in importance – and other crops 'losers' – with a relative decline in importance – in food systems over the last decades and longer is, however, not straightforward. Nevertheless, there are opportunities for researching this issue that are presented by existing global- and country-level time series data sets on crop production and value, and on food balances (e.g., Lywood et al., 2009; Khoury et al., 2014; Beal et al., 2017).

In their analysis of FAOSTAT food balance data from the last half century, for example, Khoury et al. (2014) indicated that global food systems have homogenised. They suggested this may be due to a range of factors, including: greater international trade in crops; the increased reach of multi-national food companies; the wider adoption of more western diets; government subsidy patterns that relatively support major crop consumption and production over NOC; a focus on a narrow range of crop options in education; farm mechanisation; the consolidation of plant breeding companies; and limited investments in NOC breeding.

The value of longitudinal analysis of FAOSTAT data sets for designing NOC-based food system interventions is illustrated in Box 2. A major limitation of FAOSTAT data sets, however, is that the maximum detail extends only to the country level, while changing patterns in consumption and production are often sub-nationally specific (Ray et al., 2012; Choudhury and Headey, 2016; Roser and Ritchie, 2017). Another constraint is that the FAOSTAT food balance measure is only a proxy for actual food consumption. A further limitation is that FAOSTAT data sets only contain limited information on specific NOC. This further confirms the importance of *de novo* collection of sub-national data sets on actual food consumption that include NOC; if long-term recall data are collected in such surveys, or if surveys are repeated over time, they will allow for trend analysis (see section 2.1.1).

Box 2. The value of longitudinal analysis of global FAOSTAT production data for new and orphan crop promotion

For an initial assessment of the utility of FAOSTAT data sets for understanding how to promote NOC, we selected a wide ranging panel of 35 annual and perennial crops or crop groups and extracted global level production information for the last half century from the online FAOSTAT portal (FAOSTAT, 2016; details of data extraction and analysis are given in Appendix 1). Most of the 35 chosen crops are 'major' ones that have been the focus of data collection, but some are orphans. For the production of each crop, we derived an index to explore the changes in the relative contributions of 'yield' and 'area' (area harvested) to annual global output over the last half century, and plotted the results in Figure 1.

Although the analysis revealed that not all crops have demonstrated a linear relationship in how yield and area have supported changes in global output over the time series (apples and cloves being obvious exceptions), in most cases a linear regression of values of the chosen index against year appeared to provide a reasonable fit for crop profiles. This indicated that combining data across all 35 crops based on the gradients of linear regressions of individual crop profiles and the magnitudes of total output changes over the last half century could provide interesting insights into production trends, as is demonstrated by the plot shown in Figure 2.

Figure 1. (On next page.) *Trends in the relative contributions of yield and area to total output over a half century time series for 35 individual crops. Profiles are based on FAOSTAT (2016) production data. Calculation of the index on the y axis is described in Appendix 1. A value > 1 indicates a greater relative contribution from yield and < 1 a greater relative contribution from area, compared to a mean 1961-1965 baseline. The x axis represents an annual time series 1961 to 2013, where 1961 = 0. Linear regression lines and regression equations are shown. Crops are ordered from top left to bottom right by the total change in output over the time series, starting with the greatest increase in output at top left (only two crops, oats and rye, at bottom right, have seen an absolute decrease in output). For each crop, the value given in parentheses indicates the total change in output (e.g., the value of 17.81 for oil palm [fruit] indicates that global reported output was 17.81 times greater in 2013 than in 1961).*

Box 2 (continued) (See previous page for figure legend)

Box 2 (continued)

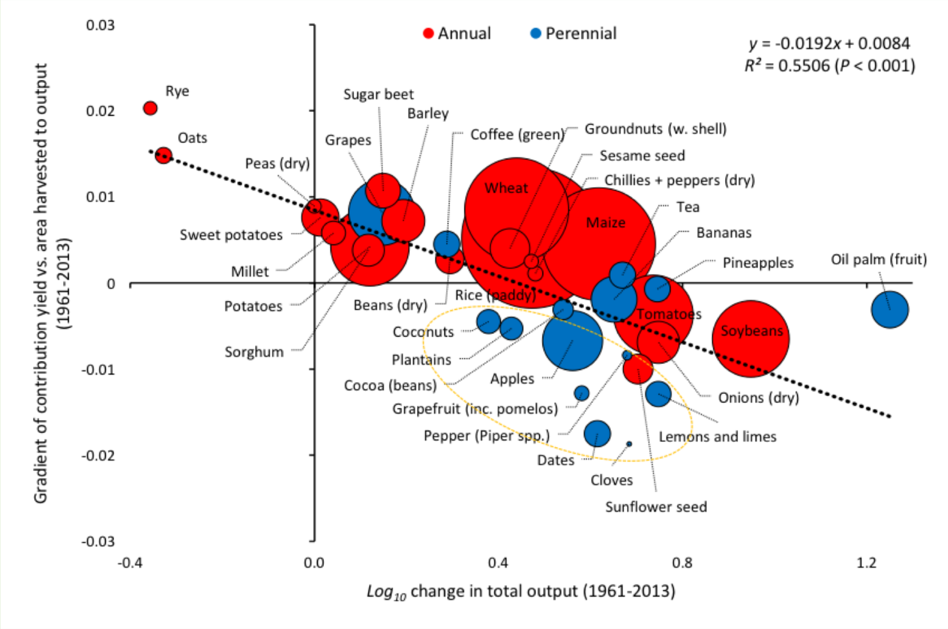

Figure 2. *Combined analysis of the relative contributions of yield and area harvested to the change in total output over a half century time period for 35 crops. The analysis shown is based on FAOSTAT (2016) production data. The graph shows values for the gradient of a linear regression of an index of the relative contributions of yield and area in supporting crop output over a half century annual time series (values from Figure 1) plotted against log10 values of the total change in output over the period, as described in Appendix 1. A linear regression indicates that the relationship between the two variables is negative and highly statistically significant. A group of nine crops where yield contributions to changes in output appear markedly lower than the trend line are encircled. Point size is relative mean current gross production value.*

Following expectations, a linear regression of the points in the profile of Figure 2 demonstrated a strong negative gradient, and was highly statistically significant, indicating that yield increases have not been able to ‘keep up’ with required output when increases in output have been very high over the time period (i.e., total output has relied more on area expansion in such cases). Of interest, however, is the position of a group of nine crops (encircled) that have clearly performed badly compared to the complete crop panel in terms of the relative contributions of yield to output changes over time.

Eight of the encircled crops – apple being the exception – have only a relatively low annual global gross production value (less than USD 10 billion, with the mean for the 35 crops being USD 25 billion). Lower gross production value could be a proxy for more limited investments in breeding and in the development and adoption of more optimal agronomic practices for crops. This could explain the difference between banana, which is slightly above the trend line in Figure 2, and plantain, which is well below it, as banana has a significantly higher production value, while the two crops otherwise have rather similar biologies and are both vegetatively propagated, and could therefore be expected to face similar breeding challenges. Investment level, reflected in production values, may then have been an important factor in determining the relative performance of these two crops; in future, however, the advent of new cheaper advanced breeding methods may reduce investment barriers for NOC which could then result in significant production gains.

Of the nine ‘underperforming’ crops highlighted in Figure 2, eight are also perennial – with sunflower being the annual crop exception, while six – cloves, coconut and sunflower being the exceptions – are generally vegetatively propagated as grown by farmers. Whether either of these features is a determining factor in relatively poor year-on-year yield performances is interesting to consider, as it could determine in the case of NOC which crops and which promotion activities to target resources to. Perennial crops can also be markedly above the trend line (cf. oil palm), indicating that they are not necessarily trapped in weak productivity gains. Crucial, then, is to understand where new breeding methods could overcome potential inherent biological constraints in improvement and lead to transformational opportunities.

Box 2 (continued)

Finally, because FAOSTAT production data sets contain information on gross production value, indirect longitudinal analysis of consumer accessibility and farmer profitability is possible. We therefore explored this option for analysis with our 35-crop panel. In the case of consumer accessibility, we generated a proxy from FAOSTAT data by calculating crop farm gate value per unit output. In the case of farmer profitability, we generated a proxy from FAOSTAT data by calculating crop farm gate value per hectare. For each crop, the change in both of these measures over the last half century was then plotted against the change in total output (Figure 3; again, see Appendix 1 for details of analysis).

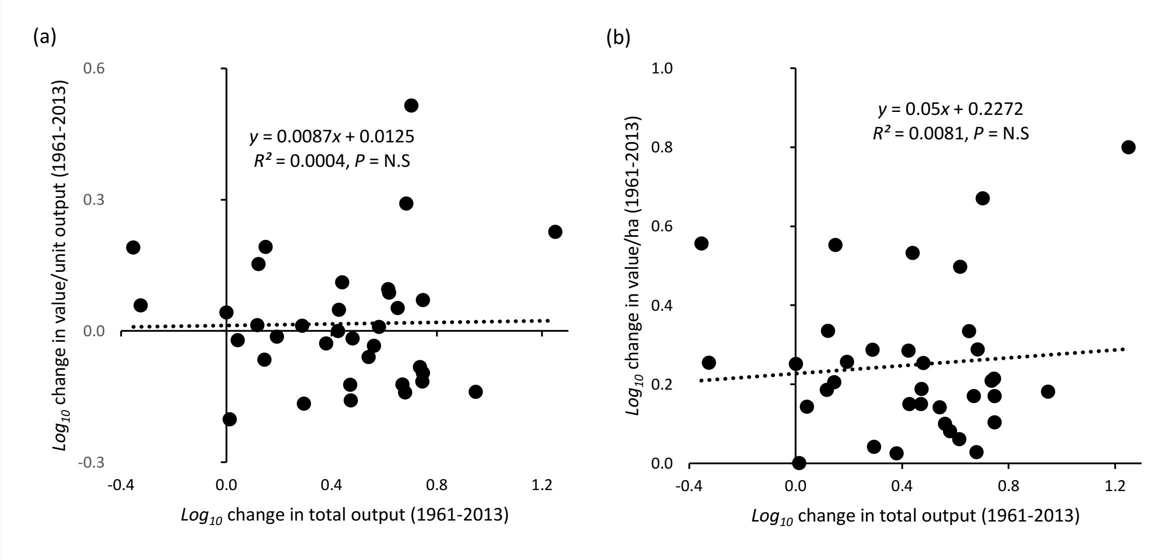

Figure 3. *Comparisons of crop farm gate value per unit output and per hectare with changes in total output over a half century time period for 35 crops. The profiles shown are based on FAOSTAT (2016) data. Profile a) is value per unit output and profile b) value per hectare. Graphs show* log_{10} *changes in values comparing the start and end of the time period, as described in Appendix 1. Linear regression lines and equations are shown, indicating no significant correlations between variables.*

Theoretically, it would be possible for scenarios in which both consumers' access and farmers' profitability have both increased over the time period and have been a factor in driving output expansion, but there was no evidence of this from linear regressions of the variables in Figure 3. In fact, and perhaps contrary to expectations, the analysis provided no indication that the proxies for accessibility and profitability are important in driving output expansion over time.

It is proposed that the lesson for NOC promotion of this analysis of accessibility and profitability proxies for crops is that market development interventions that stimulate demand are likely to be crucial elements of a strategy. The current analysis expressed in Figure 3 is however preliminary and should be treated with caution, because of the use of simple but likely limited proxy measures. The trajectories for market integration of NOC may also be rather different to those followed by the major crops that make up most of the crop panel. More detailed analysis is therefore required.

For the future, country-level analyses of FAOSTAT data are necessary, comparing with other reported country-level metrics such as agricultural research investments (ASTI, 2017). At the country level, crops demonstrating non-linear contributions from changes in yield and area to output over time (based on assessing equivalent longitudinal profiles to those shown in Figure 1, but for individual crop-country combinations) may be informative in guiding novel and transformative strategies for NOC integration. Our early analysis (not shown) indicates that country-level non-linear profiles may reflect redirections in national policy toward or away from particular agricultural production sectors and/or the opening up of once state-based production economies to private enterprise (e.g., a large jump in coffee production in Vietnam from the 1980s, which corresponds with a large relative increase in the contribution from area expansion rather than yield in supporting output, may reflect the relaxation of collectivisation and the rise of private enterprise at that time).

2.2.2. Examining the impacts of changing food consumption patterns on farming systems

There is a trend to reduced heterogeneity in farming systems (Clay, 2004). In the face of this, it is important to understand where diversification with NOC is likely to be possible and most useful. This understanding can be supported by a longitudinal analysis of the impacts of changing food consumption patterns on configurations of crop production across farm to country scales. Building on the analysis of Khoury et al. (2014), we explore this issue through our own assessment of production systems that is provided in Box 3.

Recent efforts to support consumption-based interpretations of crop configurations have been made by overlaying nutritional contributions of specific crops on production maps (e.g., Beal et al., 2017; Herrero et al., 2017). Herrero et al. (2017), for example, indicated that smaller farms with greater crop diversity tend to produce a wider range of nutrients. Analysis is, however, limited by the absence of real consumption data at the sub-national level, again reinforcing the importance of such data collection (see section 2.1.1), and by the absence of data on farming system changes along the important time axis.

To some extent, undertaking farm inventories along transects through agro-ecologically transitioning landscapes, at points more and less advanced in the transition process, is a possible approach for understanding the time dimension. Farmer-based recall surveys of changes in crop production over time may also provide useful inputs into an analysis. Diverse farming systems also provide important environmental services (Cardinale et al., 2012). These services should also therefore be taken into account when considering how farming systems change, especially how NOC could restore lost services such as nutrient cycling, pollination and pest control (Dawson et al., 2018).

Box 3. The diversity of winner and loser crop production systems and new and orphan crop promotion

Khoury et al.'s (2014) food system analysis indicated varying food usage trends for specific crops over the last half century, with some crops winners in the global food system and others losers (see also section 2.2.1). Extracted from their analysis, a panel of 20 crops was selected. These crops ranged from those with large increases to large decreases in relative importance as human foods for any of the specific dietary components of energy, protein and fat. The diversity of the typical production systems of which each of these crops is part was then estimated by extracting information from Clay's (2004) review of world agricultural impacts on the environment. This diversity was expressed in terms of the level of intercropping and/or retained natural biodiversity generally found within production systems (Figure 4; but not accounting for crop rotations).

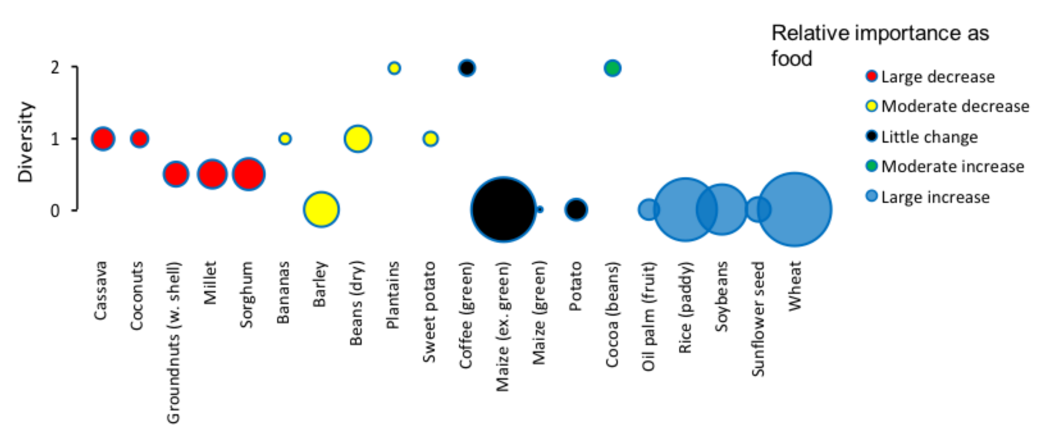

Figure 4. *The diversity of production systems for each of 20 crops, ranging from strong winners to outright losers in the global food system, over a half century time period. Strong winners are those crops with large increases in importance over the time period, while outright losers are those with large decreases in importance. Crops are a subset of those analysed by Khoury et al. (2014). Data on production system diversity are expressed as the level of intercropping and/or retained natural biodiversity in systems. Point size represents mean current production area for the crop (mean 2009-2013; for reference purposes, the actual mean value for wheat for 2009-2013 = 220 million ha and for bananas = 5 million ha). Dawson et al. (2018) provide further information on crop categorization.*

The analysis revealed interesting features. Crops with the greatest increases in relative importance in global food consumption systems over the last half century are generally produced in farming systems of low diversity, illustrating the importance of – and challenges involved in – production system diversification in a direction that is counter to current production trends.

Of the five crops in the chosen panel of 20 that had the largest increases in relative importance in global consumption over the last half century, three (rice, wheat and soybean) are currently planted on at least 100 million ha annually, meaning that the production environments of these crops should be particular targets for diversification to support the sustainability and resilience of food systems.

2.2.3. Describing cross-sectoral relationships in food systems

Important for defining more optimal routes for fulfilling human nutritional requirements in the coming decades is an understanding of the relationships between the crop production sector and other food production sectors such as livestock and aquaculture, and how these change over time. For example, the production and per capita consumption of meat, milk and eggs from livestock has increased hugely compared to crop foods in several locations globally over the last half century (FAO, 2009a). Rapid growth in aquaculture (FAO 2009b) has also occurred in some locations in recent decades. The growth in these two sectors has resulted in increased competition for land and/or water that can be used either to raise crops for human food or for feedstuffs, grazing, etc. (Cassidy et al., 2013).

Cross-sectoral longitudinal analysis, combined with understanding relationships between the diversity of foods that are consumed and those that are produced in and across specific locations (see section 2.1.1), is required to inform the nutritional profiles of the crops that will need to be incorporated into diversified cross-sectoral food systems to maximise human nutrition in the future. In theory, this will indicate particular opportunities for NOC with their varied across- and within-species nutritional compositions; these opportunities need to be grasped through effective targeting.

As well as comparing existing longitudinal sectoral data sets including those of FAOSTAT on crops, livestock and aquaculture/fisheries, information on food-feed competition and trade-offs is needed. The value of collecting *de novo* sub-national consumption data sets, including information on past diets, was highlighted in previous sections; to enhance their utility, these surveys should collect information across food sectors.

2.3. Understanding the value of new crop production approaches

2.3.1. Modelling new and orphan crop integration into farming systems

To determine opportunities for NOC integration into particular production settings, an understanding of how crop combinations and other production components such as livestock interact within farming systems is required. From a purely production perspective, interactions can range from strongly positive to strongly negative (Yu et al., 2015). A knowledge of the extent of interactions and their sign within specific contexts therefore helps inform, for example, whether intercrops or crop rotations involving NOC are most appropriate for supporting diversification, and the particular crops that should be involved. This understanding is especially important when the objective is to diversify staple crop production systems that occupy large land areas (see section 2.2.2).

Understanding how components interact is important at the genetic level as well as at the species level (Hersch-Green et al., 2011), as an understanding at the genetic level can guide the specific traits targeted in crop improvement programmes (section 2.3.2). ‘Interaction traits’ are likely to include plant architecture and associations with nitrogen-fixing bacteria, as well as the timings of growth, flowering and production (Litrico and Violle, 2015).

The starting point for modelling NOC integration is an understanding of existing production systems and the interactions they contain, to evaluate how these may be complemented or damaged by the introduction or reintroduction of NOC. In recent years, a wide range of medium- to high-resolution production system maps have become available that can support such analyses (e.g., Herrero et al., 2013; Fritz et al., 2015; Barona et al., 2016). Other information on crop combinations in farming systems is provided by Living Standards Measurement Study-Integrated Surveys on Agriculture (LSMS-ISA; Christiansen, 2017) and CGIAR Climate Change, Agriculture and Food Security (CCAFS) benchmark surveys (Laderach et al., 2014), among other surveys (see e.g. references to production in section 2.1.1). Global data sets on crop harvesting dates, which are important for understanding temporal synching in production systems, are also available (e.g., Sacks et al., 2010; USDA, 2018). Natural vegetation maps also provide useful information on the context of natural vegetation assemblages interacting with crop production (e.g., vegetationmap4africa, 2017).

Combining this information with data on NOC distribution ranges and knowledge on trends in production system configurations (section 2.2.2), cropping system framework modelling (which also considers the economics, e.g., labour costs, and social aspects of production) can be used to explore specific options for NOC integration into farming systems (Reckling et al., 2016). These options can then be investigated for their potential to address known location-specific nutritional deficiencies, and their viability can be trialled with farmers. A degree of future proofing can be incorporated in trials by considering how climate change will influence the interactions between NOC and other crops, with different crops responding differently to altering conditions, and adjusting trialled combinations accordingly.

2.3.2. Defining traits for improvement for new and orphan crops

Crucial for defining NOC genetic improvement strategies is an understanding of the product needs of consumers, food processors and retailers, and the crop production constraints of farmers. At the level of the consumer, the prioritisation of traits for improvement should take into account the different perceptions and needs of women, men and children. Gender-differentiated traits may relate to nutrition, acceptability and palatability (for the consumer), as well as the labour requirements of production, harvesting and processing (more widely along the supply chain). The determination of important traits for improvement also needs to consider trend-based analysis of winner and loser crops in food systems (as described in section 2.2.1), since this provides a perspective on where improvements may drive food system integration, and where they may not make much difference.

Although the results of trait prioritisation will be crop- and context-specific, some generalisations are possible. For many NOC there is a need to focus on addressing low yields, propagation constraints, extensive juvenile phases, pest and disease pressures, high labour costs, and harvest and storage difficulties (Tadele and Assefa, 2012). Anti-nutritional compounds that require extensive and energy-intensive processing and/or long cooking times are also of concern for several species. While addressing these issues, it is clearly important to retain (and in some cases enhance) the nutritional value of the crops (see Box 1), minimising any negative correlations between traits such as yield and nutrient concentration (Murphy et al., 2008).

Prioritising traits that reduce labour costs may be of particular importance. This is because labour intensiveness is likely to be an important factor driving ‘loser’ crops out of African food systems, as rural labour supplies decline with urbanisation and as farmers consider mechanisation. Here, genetic improvement could better target NOC production to periods of the year when major crops do not require large labour inputs (e.g., avoiding their planting and harvesting times). In addition, the breeding out of anti-nutritional compounds that mean foods currently require long cooking times to remove them could greatly reduce the labour expended by rural women in food preparation. This is because collecting woodfuel for cooking purposes is a time-consuming activity that would require less effort if less fuel were needed due to reduced cooking requirements (Iiyama et al., 2014; any reduction in woodfuel use would also protect the environment).

On the other hand, increases in labour availability in and around cities occurs in tandem with urbanisation. This extra labour could be used for processing NOC foods in urban and peri-urban locations. This could mean paying greater attention to the genetic improvement of traits that influence the processability of NOC. In addition, genetic improvements in storability (as well as the development of more appropriate storage methods) could revolutionise fresh product access to urban markets where market infrastructure is currently poor.

Importantly, the prospects for the genetic improvement of NOC are often excellent. This is because many NOC are only semi-domesticates or – in the case of new crops – are essentially wild. They therefore often have extant semi-wild and wild populations that provide large gene pools of useful genetic variation (Jamnadass et al., 2011). These gene pools include variation in features that support interactions with other species in complex production systems that advanced cultivars of high input monoculture crops have lost (Palmgren et al., 2015). Exploiting these gene pools by assembling germplasm and using new crop improvement approaches, as described in section 2.3.3, has the potential therefore to transform production. When particular NOC are currently grown both in Africa and elsewhere, the introduction of new varieties developed outside the African continent into Africa could also be transformative for the continent's production. A process of adaption to the continent's particular conditions may however also be required (see section 3.1.1).

Interesting insights into traits of possible importance for genetic improvement in new and rapidly-evolving crops come from considering past crop domestication processes. So-called 'domestication syndromes' are revealed by comparing current-day crops with their cultivated and wild progenitors. For annual crops, the domestication syndrome is defined by a reduced ability to disperse seed, reduced seed dormancy, increased seed size, reduced physical and chemical defences, and alterations in reproductive shoot architecture (Larson et al., 2014). The domestication syndrome is not as well defined for perennial crops (Miller and Gross, 2011), but for fruit trees there has been a shift from seed- to vegetative-propagation and an increase in the regularity of fruit bearing (Goldschmidt, 2013). In a review of 203 food crops, Meyer et al. (2012) indicated that most have altered in several traits during domestication, with the domestication syndrome consisting of a mean of 2.8 traits. In several crops, the genes behind domesticated traits have been sequenced and further studied (Meyer and Purugganan, 2013). Common changes observed in these genes were the presence of loss-of-function alleles and alleles varying in cis-regulatory elements altering expression.

Of course, production improvements come not only from selection and breeding, but from the adoption of better agronomy. Along with crop variety development, analysing where new farm management practices could improve production is therefore an important activity. If possible, understanding the relative roles of genetics and agronomy in improving production of exemplar crops will be useful for informing how to find the balance in interventions for NOC (Mackay et al., 2011). (E.g., when is it better to focus on genetic improvement and when on agronomic improvement, and how do these two improvement approaches interact?)

2.3.3. Exploring new and orphan crop improvement methods

To apply the most appropriate crop improvement methods to NOC requires an understanding of the value and limitations of different approaches or combinations of approaches – such as genomic selection (Hickey et al., 2017) and participatory domestication (Tchoundjeu et al., 2006) – in context-specific and primarily low-input production systems. Working out the appropriate approaches for improvement considers the genetic architecture – the number of underlying genes and their interactions – of the desired traits for improvement. Where negative interactions are observed with conventional breeding approaches, it may be possible to break unfavourable linkages with advanced breeding methods. Mathematical simulation and field validation work are needed to compare the efficacy of different breeding models for realising particular levels of genetic gain for unit cost (de los Campos et al., 2013).

Another essential issue to consider is how farmers will actually obtain planting material of improved NOC varieties, since different breeding approaches support different delivery strategies (Walker et al., 2014). An important issue is the lack of formal annual (McGuire and Sperling, 2016) and perennial (Lillesø et al., 2011, 2017) crop planting material delivery systems in the SSA region. The lack of these systems is one reason why some scientists have chosen to focus on decentralised participatory domestication approaches that can reach end users without well-developed formal delivery systems, but which instead make use of local networks (Tchoundjeu et al., 2006).

Current gaps in germplasm delivery systems require new public-private partnerships to develop approaches that can reach farmers; such developments have been the subject of recent annual crop work in SSA, with the emphasis placed on entrepreneurial seed companies being actively supported by (rather than being in competition with) public parastatal institutions (Lillesø et al., 2011).

The biology of NOC and their relatedness to other crops are also important features determining appropriate genetic improvement approaches; we explore these issues later in this Working Paper for the specific crops on the AOCC list (section 3.1.4).

2.4. Understanding food consumption and production system adoption

2.4.1. Exploring the implementation of behavioural change toward new and orphan crop options

Essential for driving NOC adoption in food systems is an understanding of how to support decision-making towards overcoming existing barriers to their integration. Identifying key barriers to current uptake – whether these are structural, institutional, informational (including misinformational), legal, cultural, agronomic, economic, market or otherwise – requires detailed analysis and extensive consultation with stakeholders, followed by the co-determination of solutions to overcome constraints. Important information on barriers can come from consumption and production surveys where consumers and farmers are asked why they do/do not use and grow particular crops (section 2.1.1). Important information can also come from consulting plant breeders, food processors, retailers and others.

The absence of knowledge on how to use and produce NOC may be a particular barrier to their wider integration into food systems (Jackson et al., 2012). Available knowledge among consumers and producers is unevenly shared, depending on geographic location, the origin of the community (if indigenous or immigrant), age and gender (Thomas, 2008; Kuhnlein et al., 2009; Faye et al., 2011). Lack of knowledge extends to government advisory services, development agencies and food processors, with the lack of knowledge of the last group being a particular concern for reaching increasing urban populations with healthier foods.

Absence of knowledge among policy makers may result in perverse policies that inadvertently favour more uniform and less healthy diets (Covic and Hendriks, 2016).

Evaluation of motivations behind consumers', food processors' and producers' choices will frame the nature and positioning of interventions to encourage the use and supply of NOC products. Testing the utility of possible interventions is required to reveal those with the most significant effects in supporting consumption and production, in rural, peri-urban and urban spaces. Making conclusions can however be complex. For example, carefully teasing out of sequence between farming families' nutritional security and farmers' adoption of innovative production practices, such as growing new crops, is required; this is because farming families' food security may be a prerequisite for, rather than a result of, farmers' innovation (Kristjanson et al., 2012). For farmers to innovate in planting crops that are new to them, a proper explanation of risks and benefits is required, including not only for incomes but of the health benefits possible through home consumption. Advanced methods exist for risk-return modelling of decision-making processes, and these should be applied (Shepherd et al., 2015).

3. The African Orphan Crops Consortium

The primary purpose of AOCC is to support the integration of NOC into food systems in SSA based on the development and application of genomic methods for crop improvement (AOCC, 2017). Recent cost reductions and quality improvements in these methods, supported by new statistical approaches to handle large data sets more efficiently, mean a lower investment threshold; genomic methods have thus become relevant to a wider range of crops than a decade ago, extending possibilities for analysis from major to regionally and locally important species (Pingali, 2012; Varshney et al., 2012; Østerberg et al., 2017).

In section 3 of this Working Paper, we first outline the NOC considered by the AOCC initiative and provide some contextual information on them, including on: genomic research to date; their geographic distributions in Africa and the availability of germplasm for genetic research; and their taxonomies and biologies. We then describe the work undertaken on these NOC by the Consortium.

Biotechnology terms used in this section of the Working Paper are given in Box 4.

Box 4. Glossary of biotechnology terms

Database curation: the activities related to the organisation, publication and presentation of genomic data, to make it available in a usable form now and into the future.

Genome sequence: an organism's complete sequence of DNA, including all of its genes.

Genomics: the branch of biology concerned with the structure, function, evolution and mapping of genomes.

Marker-assisted selection: selection for phenotype based on DNA-based markers associated with the trait in question. Traditionally, a relationship between marker and trait will have been established by comparison of DNA marker profiles with field trial or other evaluation data.

Platform assembly: the development of a set of resources – for example, a set of useful SNPs (see section 3.2) for important genes brought together onto a 'SNP chip' – that can be used to explore informative polymorphisms among individuals.

Resequencing: the sequencing of an individual's genome (or part of genome) in order to detect sequence differences between a particular individual (chromosome) and the reference genome sequence of the species.

Sequence annotation: the process of identifying the chromosomal locations of genes and an exploration of their likely functions, based on searches for similar sequences and contexts in existing databases.

Single nucleotide polymorphism (SNP): a variant among chromosomes at a single position in a DNA sequence (variation between bases A, C, G and T).

Transcriptome sequence: the sequence of all DNA transcripts, mostly messenger RNAs, in a cell or tissue. Transcribed sequences can vary based on tissue, age, stress and other factors. Transcript sequences provide information on gene function and cellular and organismal processes.

3.1. The new and orphan crops of the African Orphan Crops Consortium

3.1.1. Introduction to the Consortium's new and orphan crops

The AOCC initiative considers the 101 NOC listed in Table 1 (see also Appendix 2); background on a subset of these species is given in Box 5 (such information for all of the 101 NOC is available at AOCC, 2017). The species on the AOCC list were identified as priorities for inclusion in the initiative by scientists and development practitioners. This was based on the current or potential role of species for supporting human nutrition in SSA, as well as prospects for improving farmers' livelihoods. In addition, all species on the AOCC list are considered to be in some way neglected in Africa (e.g., in terms of adaptation of crops to African farming conditions), although some entries have received more attention globally.

The origin of species was not a determining factor for inclusion on the AOCC list. Although many of the entries are indigenous to Africa and some of these species are currently essentially wild (i.e., they are being develop into new crops), other species originated outside Africa. In these cases, the dates of first introduction to the continent, when known, vary from centuries ago to only decades. Many of these crops were subject to some level of domestication prior to their arrival in Africa; since introduction their 'domestication trajectories' on the continent and elsewhere have often deviated. This is as crops have become adapted to specific local environmental conditions, production practices and users' preferences, and as target traits for breeding (e.g., to respond to geographically-specific disease pressures) and methods of crop improvement have diverged.

As is evident below (section 3.1.4), the biological characteristics and taxonomies of the 101 NOC chosen by AOCC are broad, although with common elements across crops. Overall, the list contains an approximately equal number of annuals and perennial species, reflecting wide interest in perennial as well as annual crop domestication in the SSA region (Tchoundjeu et al., 2006). (The large number of perennials on the list explain the particular interest of the World Agroforestry Centre in the AOCC initiative.) The 101 chosen NOC are also very broad in the types of food they produce, including edible bulbs, seeds (grain and oil), fruits, roots, tubers and leafy vegetables.

Table 1. Latin binomials and common names of the 101 AOCC crops

Latin binomial	Common name	Latin binomial	Common name
Abelmoschus caillei	Okra	*Icacina oliviformis*	False yam
Adansonia digitata	Baobab	*Ipomoea batatas*	Sweet potato (leaves)
Adansonia kilima	Baobab	*Irvingia gabonensis*	Sweet bush mango
Allanblackia floribunda	Vegetable tallow tree	*Lablab purpureus*	Lablab bean
Allium cepa	Onion	*Landolphia* spp.	Gum vines
Amaranthus blitum	Amaranth	*Lannea microcarpa*	Tree grape
Amaranthus cruentus	Grain amaranth	*Lens culinaris*	Lentil
Amaranthus tricolor	Vegetable amaranth	*Macadamia ternifolia*	Macadamia
Anacardium occidentale	Cashew	*Macrotyloma geocarpum*	Geocarpa groundnut
Annona reticulata	Custard apple	*Mangifera indica*	Mango
Annona senegalensis	Wild custard apple	*Momordica charantia*	Bitter gourd
Artocarpus altilis	Breadfruit	*Moringa oleifera*	Drumstick tree
Artocarpus heterophyllus	Jack tree	*Morus alba*	Mulberry
Balanites aegyptiaca	Balanites	*Musa acuminata* AAA Group	Banana
Basella alba	Vine spinach	*Musa balbisiana*	Banana
Boscia senegalensis	Aizen, nabedega	*Musa x paradisiaca* AAB Group	Plantain
Brassica carinata	Ethiopian mustard	*Opuntia monacantha*	Prickly pear
Canarium madagascariense	Canarium nut	*Parinari curatellifolia*	Mobola plum
Carica papaya	Papaya	*Parkia biglobosa*	African locust bean
Carissa spinarum	Carissa	*Passiflora edulis*	Passion fruit
Casimiroa edulis	White sapote	*Persea americana*	Avocado
Cassia obtusifolia	Sickle senna	*Phaseolus lunatus*	Lima bean
Celosia argentea	Celosia	*Phaseolus vulgaris*	Green bean
Chrysophyllum cainito	Star apple	*Plectranthus esculentus*	African potato
Citrullus lanatus	Watermelon	*Plectranthus rotundifolius*	African potato
Cleome gynandra	Spider plant	*Psidium guajava*	Guava
Cocos nucifera	Coconut	*Ricinodendron heudelotii*	Groundnut tree
Colocasia esculenta	Taro	*Saba comorensis*	Rubber vine
Corchorus olitorius	Jute mallow	*Sclerocarya birrea*	Marula
Crassocephalum rubens	Yoruban bologi	*Solanum aethiopicum*	African eggplant
Crotalaria juncea	Sunn hemp	*Solanum scabrum*	African nightshade
Crotalaria ochroleuca	Rattlebox	*Sphenostylis stenocarpa*	Yam bean
Cucumis metuliferus	Horned melon	*Strychnos spinosa*	African orange
Cucurbita maxima	Pumpkin	*Syzygium guineense*	Water berry
Cyphomandra betacea	Cape tomato	*Talinum fruticosum*	Ceylon spinach
Dacryodes edulis	African plum	*Tamarindus indica*	Tamarind
Detarium senegalense	Sweet detar	*Telfairia occidentalis*	Fluted gourd
Digitaria exilis	Fonio	*Tylosema esculentum*	Marama bean
Dioscorea alata	Yam	*Uapaca kirkiana*	Wild loquat
Dioscorea dumetorum	Bitter yam	*Vangueria infausta*	African medlar
Dioscorea rotundata	Yam	*Vangueria madagascariensis*	African medlar
Diospyros mespiliformis	African persimmon	*Vicia faba*	Faba bean
Dovyalis caffra	Kei apple	*Vigna radiata*	Mung bean
Elaeis guineensis	Oil palm	*Vigna subterranea*	Bambara groundnut
Eleusine coracana	Finger millet	*Vitellaria paradoxa*	Shea
Ensete ventricosum	Enset	*Vitex doniana*	Chocolate berry
Faidherbia albida	Acacia (apple-ring)	*Xanthosoma sagittifolium*	Elephant ear
Garcinia livingstonei	African mangosteen	*Xanthosoma* spp.	Cocoyam, Arrowroot
Garcinia mangostana	Mangosteen	*Ximenia caffra*	Sour plum
Gnetum africanum	African gnetum	*Ziziphus* spp.	Jujube
Hibiscus sabdariffa	Roselle		

See AOCC (2017) for information on each crop

Box 5. Background on a range of AOCC-prioritised new and orphan crops

African plum (*Dacryodes edulis*) is a medium-sized evergreen tree native to the humid tropical zone of Central and West Africa. It has been cultivated by farmers in southern Nigeria and Cameroon for many years, and is considered semi-domesticated in some areas, based on planters' selective seed sampling. Widely sold in local markets, the highly nutritious fruit have an oily texture similar to avocado and are eaten boiled or roasted. The fruit pulp is rich in vitamins and amino acids.

Bambara groundnut (*Vigna subterranea*) is an annual crop native to West Africa. It produces seed (nuts) in pods underground that are high in protein and are the third most important grain legume in semi-arid Africa. The nuts can be cooked and eaten whole or are dried and ground into a flour that is used in porridge, dumplings, cakes and biscuits.

Baobabs (*Adansonia digitata* and *A. kilima*) are trees with large swollen trunks. Native to arid and semi-arid savannahs in SSA, they are very long-lived, with extant specimens up to 2,000 years old. The edible powdery pulp found in the fruit is very rich in vitamin C and vitamin B_2 and is used to make a refreshing drink. Young leaves are also rich in vitamin C and those of *A. digitata* are in high demand in West Africa as a soup vegetable. The global market for baobab continues to grow since the formal clearance of fruit pulp by EU and US markets as a novel food product.

Finger millet *(Eleusine coracana* ssp. *coracana*), an annual cereal widely grown in the arid areas of Africa and Asia, is native to East Africa. It is rich in micronutrients and contains high levels of the essential amino acids methionine, leucine, tryptophan and phenylalanine. The crop has good malting characteristics and the grain has high storage quality as a result of its polyphenol content. Finger millet accounts for around 10% of the 38 to 50 million hectares sown to all types of millet globally; in East Africa it covers ~ 50% of the millet area. Finger millet flour is boiled in water to produce porridge, often in combination with maize, cassava or sorghum flours. Mixed finger millet and wheat flour can be used to produce chapatis and bread.

Grain amaranth (*Amaranthus cruentus*) is an annual (pseudo-)cereal domesticated in Central America as long as 6,000 years ago that was probably introduced to Africa during the colonial period. The leaves are used widely as a green vegetable in East and West Africa. It also yields a nutritious grain whose flour can be incorporated into other foods. In arid regions, the leaves are dried and the leaf powder used in sauces during the dry season. Leaves are high in protein, with high lysine content.

Groundnut tree (*Ricinodendron heudelotii*), native to the forests of Central and West Africa, is a fast-growing perennial reaching 50 m in height. A spicy sauce made from the kernels is widely used in stews, and the high oil content of the seeds makes them suitable for use in soap production. In Cameroon, it is used in traditional medicine to treat constipation, dysentery, eye infections and female sterility, and is an antidote to poison.

Marula (*Sclerocarya birrea*) is a long-lived tree with an extensive natural distribution across dryland savannah habitats in SSA. The fruit pulp of *S. birrea* subsp. *caffra*, a subspecies widely distributed in southern Africa, is used to produce jam, juice, beer and, in South Africa, the internationally available liqueur Amarula Cream. The oily kernels are consumed raw, roasted and in sauces. Archaeological evidence indicates human harvesting of fruit extending back 10,000 years.

Spider plant (*Cleome gynandra*), an annual species native to Africa that has become widespread in the tropics and sub-tropics, produces leaves, shoots and flowers that are used as a green vegetable in stews, especially in southern Africa. The leaves are high in a number of vitamins and minerals and have anti-inflammatory properties.

3.1.2. Genomic research to date on the Consortium's new and orphan crops

Understanding the current level of genomic research on the 101 NOC of the AOCC initiative is required to properly target activities and ensure synergy. We therefore collected National Center for Biotechnology Information (NCBI) citations for each of the 101 species (NCBI, 2016; Appendix 2). The number of citations varied enormously between species. For example, high-throughput DNA and RNA sequence read archive (SRA) citations varied from zero (for several species) to 596 (for green bean; mean across NOC = 27 SRA citations). Even for the most cited of the AOCC species, however, the level of genomic work indicated by NCBI citations was low compared to major crops such as maize and rice (with > 7,000 and 45,000 SRA citations, respectively).

Web of Science (2017) citations, using both the Latin binomial (genus and species name) for each NOC and 'genom*' as topic search terms, also provided an indication of the level of current genomic work on AOCC species (Appendix 2). Similar to NCBI citations, these indicated high variation across the 101 species, with no citations for several NOC to 891 for green bean (mean across NOC = 28 citations). Again, similar to NCBI citations, Web of Science Citations were modest for AOCC species compared to major crops such as maize and rice (with > 2,500 and > 4,900 citations, respectively).

Both of the above methods support the importance of genomic research on NOC based on a lack of current genomic resources. Both methods are, however, limited in exploring specific African needs, as neither discriminated the location of the plant material evaluated in the work. This is an important issue especially for those of the 101 NOC that are exotic to Africa, since work on these species targeted to other regions of the world may be of only limited relevance to the particular requirements of African countries.

3.1.3. African distributions of the Consortium's new and orphan crops and the availability of germplasm for research

Understanding the geographic distributions of the 101 AOCC species in Africa is important for knowing which species to focus on in specific locations, how to model integration into geo-referenced production systems, what the effects of climate change on where crops can be cultivated are likely to be, and how to stratify sampling in genetic evaluations and any future germplasm collections. We therefore collected Global Biodiversity Information Facility (GBIF) and Genesys citations for each of the 101 species (GBIF, 2016; Genesys, 2016; see Appendix 2, which also explains the data compilation approach). The Global Biodiversity Information Facility is an open access database that contains point location observation data among other biodiversity data, while Genesys is a genebank portal that lists collection sites for conserved germplasm.

Both GBIF and Genesys indicated high variation in the number of African geo-referenced citations for AOCC species. For GBIF, citations varied from zero for several species to 1,075 for carissa (mean across NOC = 147), while the values for Genesys varied from zero for several NOC to 2,307 for green bean (means across NOC = 87). Closer observation that took into account outliers in both data sets indicated that AOCC species are much better represented in GBIF than in Genesys. This is an important observation because it suggests that, for many NOC, genebank representation of African material is poor. This possibly reflects limited collection initiatives as well as the difficulty of storing germplasm in genebanks for AOCC species that have non-orthodox seed.

To support the resequencing work of AOCC (see section 3.2) and to develop field trials for many AOCC species, *de novo* African collections of germplasm are therefore likely to be required. Such collections are underway in some locations: for example, the perennial recalcitrant-seeded species on the AOCC list are being integrated into ICRAF's live genebank and trial programme. Unfortunately, although the costs of genomic methods have plummeted in recent years, germplasm collection and field trial costs have not. In recent decades it has also become more difficult to exchange germplasm and other genetic material (e.g., leaf samples from which DNA can be extracted) across countries for non-commercial research purposes, increasing transaction costs (Koskela et al., 2014). This limit on research has been an unintended consequence of the adoption of access and benefit sharing arrangements designed for the important purpose of protecting communities' and countries' rights to genetic resources (van Zonneveld et al., 2018).

Combined GBIF and Genesys data indicated high AOCC species richness in eastern, West/Central and southern Africa (Figure 5), suggesting that good opportunities for NOC cross the SSA region. Combined citations from these two databases also indicated that for almost two-thirds (66) of the AOCC species there are at least 30 geo-referenced sample points within Africa. If these are unique citations (i.e., if multiple citations do not map to the same location), they may represent a sufficient number of reference points for ecological niche modelling (ENM) of the distributions of these species under current and future climates (van Proosdij et al., 2016).

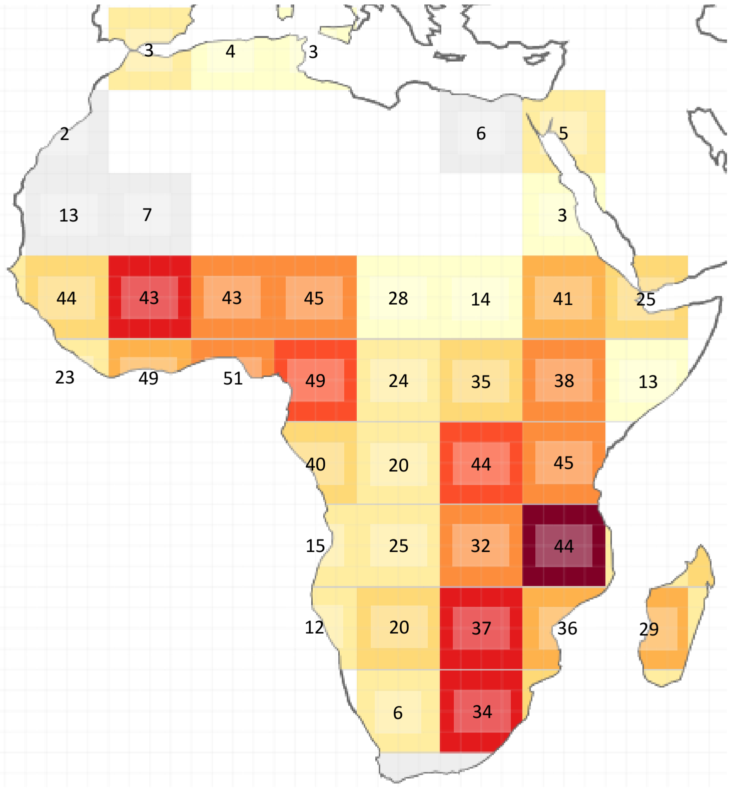

Figure 5. *Mainland African and Madagascan distributions of locations for AOCC species. Distributions are given on a 4o grid for the 67 AOCC species with at least 30 point locations based on GBIF (2016) and Genesys (2016) data, with the addition of one extra species to the original 66 (see text) based on other sources of point location information. Grid cell shading indicates the total number of observations across species for that cell (grey = very low, through yellow = low, to purple = high; blank = < 20 observations). The number centred on each grid cell is the total number of AOCC species for that cell. Values for grid cells were calculated with the Infomap Bioregions software (Edler et al., 2017). Future analysis should undertake rarefaction of species number by observation sample size, to standardise comparisons across grid cells. Non-standardised values, however, already indicate that multiple AOCC species are distributed widely across SSA, with hotspots in eastern, West/Central and southern Africa.*

3.1.4. Taxonomies and biologies of the Consortium's new and orphan crops

Knowledge on taxonomy is important for understanding domestication approaches for AOCC species. The more closely related two species are, the more likely it is that the same genes, gene arrangements and gene pathways control particular traits. Thus, if an under-researched crop is highly related to a better-researched species, the more likely it is that knowledge developed for improvement of the latter can be applied to improve the former. Similarly, if two under-researched species are genetically highly similar, then the same domestication approach with the exploration of the same gene sets may be undertaken in parallel.

On the other hand, as the genetic distance increases between any two considered species, the more likely it is that convergent rather than parallel evolution underlies a similar change in phenotype across them (Larson et al., 2014). The point at which such a divergence in mechanism occurs is an important high-level research question (Meyer and Purugganan, 2013) that a collection of NOC provides the opportunity to explore. Just because similar phenotypes across crops have been reached through convergent evolution in past domestications, however, this does not preclude the adoption of parallel approaches for domesticating new crops, using advanced breeding methods such as genome editing to target cross-species-identified candidate genes (Østerberg et al., 2017).

To explore taxonomic relatedness between AOCC species, an online flora search was carried out for the botanical family of each species, based on its Latin binomial. This indicated that the 101 species belonged to 47 families, with Fabaceae being the most represented family with 17 crops; on average, each AOCC species had four additional botanical family members among the AOCC entries (see Appendix 2, which also explains the data compilation approach). Only eight AOCC species had no other additional entries from the AOCC list in the same botanical family or related family members within the relevant plant order.

We then checked Meyer and Purugganan's (2013) selection of 353 'domesticated' crops to assess how many of these were from common botanical families to AOCC species. The AOCC list and Meyer and Purugganan's list had 57 crops in common, with AOCC species having on average an additional 9.5 botanical family members. Only 12 AOCC species did not have additional family members in Meyer and Purugganan's list. Considering our total comparison, only four AOCC species (African gnetum, balanites, false yam and sour plum) had neither additional botanical family/order members in the AOCC list nor additional members according to Meyer and Purugganan's list.

Based on the above analysis, it is evident that for most AOCC species there are taxonomically-related internal or external (to the AOCC initiative) species comparisons available for exploring parallel processes in crop domestication. Important 'major' crop references for families represented by at least five members in the AOCC list include cacao (Malvaceae) and soybean (Fabaceae).

Similar production biologies as well as genetic relatedness determine the cross-transferability of particular genetic improvement approaches. This is illustrated through an initial comparison of the biologies of a subset of AOCC species with other more extensively researched crops that is described in Box 6. Future work should extend this analysis to more species to widen application and consider a greater range of biological features to improve resolution (using information on biology recorded, e.g., by Free, 1993; Klein et al., 2007; NRC, 1996, 2006, 2008).

Box 6. An initial comparison of the biological features of AOCC species and better-researched crops

Devising efficient approaches for NOC domestication considers the methods used for better-researched crops with similar production biologies. To explore this issue, biological information was extracted for 38 of the AOCC species from the data provided by Meyer et al. (2012) to support their global analysis of domestication processes for major and minor food crops. From the same data set, information on 34 of the 35 crops that were used in the earlier longitudinal analysis of FAOSTAT data described in Box 2 was also extracted. Since these two sets of crops had six entries in common, the final extracted data set was for 66 crops.

The biological data extracted from Meyer et al. (2012) covered the following features: breeding system (if self-fertilising and/or outcrossing, two categories in total); propagation method under cultivation (if vegetatively propagated or not, single category); life history (annual, perennial and/or biennial, three categories in total); and plant part used for food (leaf, seed and/or fruit, etc., six categories in total). We took the 0/1 scores provided by Meyer et al. for global management and usage of crops and adjusted them to take into account our specific knowledge on management and use in Africa. An initial crude principal coordinate analysis of the data using PAST software and a Euclidean distance measure (Hammer et al., 2001) was then undertaken in which each of the above categories of information was treated as a single independent variable. The results of our preliminary analysis were plotted in Figure 6.

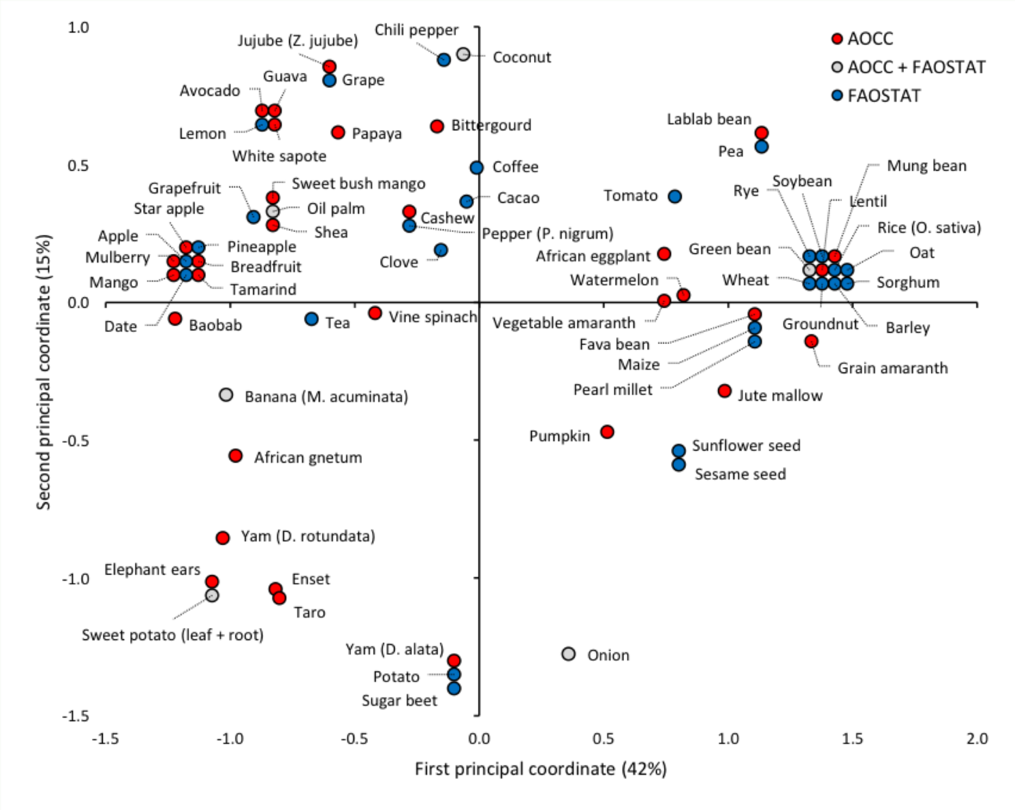

Figure 6. Preliminary principal coordinate analysis of biological features of a range of 66 crops to identify possible improvement pathways for AOCC species. Other better-researched (FAOSTAT) crops that group with AOCC species may be exemplars. Data on biological features were from Meyer et al. (2012). Where species occupy coincident positions is analysis, some points have been offset for visualisation purposes.

Results revealed clear groupings of AOCC species around major crops in most cases, indicating possible major crop models for devising NOC improvement approaches. However, there were no clear major crop models for some AOCC species (e.g., African gnetum, yam [*D. rotundata*]), suggesting the definition of exemplars may be more difficult in these cases. In some cases, individual NOC clustered with more than one possible reference crop; the most useful exemplar may then be the reference crop that has shown the greatest contribution from yield to output changes over time (see analysis in Box 2).

3.2. The activities of the African Orphan Crops Consortium

3.2.1. Sequencing and resequencing of the Consortium's new and orphan crops

The Consortium seeks to assemble genome and transcriptome sequences of the 101 chosen NOC, and then to resequence germplasm panels of 100 accessions of each species, as illustrated in Figure 7[2]. The assembly of germplasm panels is specific to each crop, depending on the importance of particular categories of genetic material (wild, landrace, breeding line, formally-bred cultivar, etc.) in improvement programmes, the environmental and geographic ranges of the plant, if wild material is easily accessible, and the existence or not of phenotypically characterised germplasm, among other factors. The aim of the panels is to explore both important and representative genetic diversity for each species based on assembly of material around a set of standards for sampling that have to be applied pragmatically to the germplasm that is available or can realistically be newly accessed.

After resequencing, sequences are annotated, SNPs identified, genotyping platforms assembled and databases curated to provide a library of genomic information for each NOC. This information is then made freely available as a public good through open access web portals, from where it can be accessed by African plant breeders to support crop improvement. Breeders are able to combine this genomic information with phenotypic data on NOC to identify phenotype-SNP correlations that can be employed for selection purposes. Combining genomic data with phenotypic data is a crucial step in the use of genomic information, so AOCC supports breeders in the development of initiatives to establish phenotyping trials that include the initial resequenced germplasm panels of NOC.

The Consortium also collects associated information that can be used to support NOC genetic improvement, such as environmental data from geo-referenced germplasm sample points that can be used to explore genotype-environment associations and the processes of crop adaptation (e.g., as in Russell et al., 2016 for the case of a major crop, barley). Such 'landscape genomic' approaches to genetic improvement may be particularly relevant for new crops including several perennial AOCC entries that essentially exist currently as wild populations that have adapted over many generations to their current locations (Bragg et al., 2015). For example, if through such analysis genetic markers associated with dry sample site conditions are identified, these markers may be applied as at least a quasi-indicator for drought tolerance. Another reason to use landscape-based approaches for trees is that the time and effort required to evaluate them in formal field trials may be much greater than for annuals. This is especially so if the product of interest is fruit that depends therefore on tree maturation, which may only be a number of years (or decades) after first planting. An assessment of adaptation for AOCC NOC will eventually extend to a meta-analysis of resequence data across the species to determine if there are general patterns of relevance (although it can be hard to make generalisations across species; see Ćalić et al., 2016).

At the same time as supporting genetic improvement directly, genome sequencing provides valuable molecular markers that support more general diversity analysis of the 101 NOC, building up knowledge on the biology and evolutionary history of each species that informs

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[2] As of September 2017, genome sequencing by BGI and other Consortium partners was underway for 60 of the 101 AOCC NOC; of these, the genomes of 10 species were being finalised for release. At the same date, transcriptome sequencing by ARC in South Africa had begun for 20 NOC, while significant resequencing had been carried out for three species in the AOCC laboratory at ICRAF in Nairobi; a further 10 NOC were ready for resequencing in Nairobi.

use. The same markers support the rationalisation of germplasm collections and indicate through gap analysis where new collections are necessary to sample diversity comprehensively.

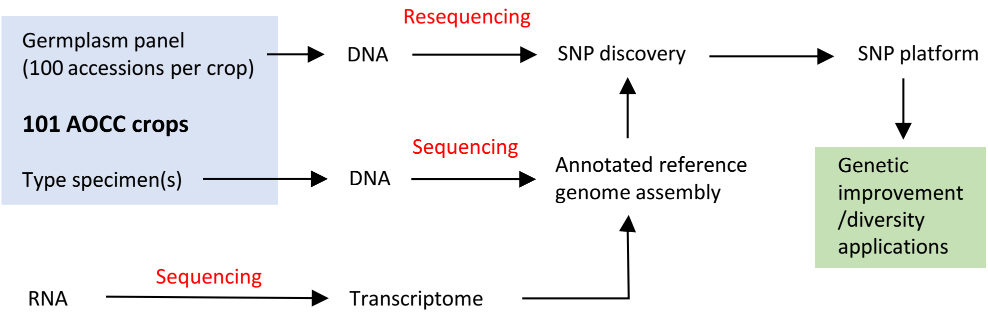

Figure 7. *Schematic of the assembly of genomic information for the 101 species of the AOCC initiative.*

3.2.2. The African Plant Breeding Academy

In parallel with the work outlined in section 3.2.1, the Consortium collaborates with the African Plant Breeding Academy (AfPBA) to train practicing African plant breeders on how to apply genomic information in advanced breeding programmes (AfPBA, 2017). The AfPBA, coordinated by the University of California Davis, covers the principles and most recent advances in plant breeding theory and practice[3]. In enabling African plant breeders to apply advanced breeding approaches, AfPBA supports the integration of these methods with conventional and participatory crop improvement techniques.

Other related initiatives that train plant breeders also exist elsewhere in SSA (e.g., WACCI, 2018). Together with the AfPBA, these have contributed to increasing the region's plant breeding capacity, which can be used to drive production improvements in NOC. The developing network of AfPBA alumni also supports the phenotypic evaluation of NOC that is essential for making progress in breeding.

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[3] The AfPBA held its first session in 2013. It is currently conducting its third class. Each class is composed of three two-week teaching sessions at ICRAF in Nairobi. After the third class completes in 2018, more than 80 African plant breeders will be alumni, with Ethiopia the country with the highest number of alumni (13 breeders).

4. Conclusions and quick win activities to support the African Orphan Crops Consortium

The aim of this Working Paper has been to outline a broad research programme for NOC integration into African food systems and to demonstrate how the AOCC initiative fits within this. The required interventions to ensure NOC integration are certainly much wider than the advanced crop improvement measures that are the focus of the AOCC initiative, but if these improvement measures are placed appropriately within the wider context presented here, they have the potential for significant impact.

Based on our analysis of research needs in section 2 and the description of AOCC in section 3, six useful ‘quick win’ knowledge-generating activities are evident that should be undertaken in the near future to support AOCC. These activities, which will help build business models for work on NOC, are discussed below.

Drivers of integration and exclusion: as noted in section 2.2.1, understanding what makes some crops winners and others losers in food systems over time is essential for targeting interventions that support future opportunities for NOC. In Box 2, an initial trend analysis of global FAOSTAT crop data sets was presented, but formal meta-analysis of these data at global, continental, regional and country levels is required, comparing consumption and production metrics with a wider range of longitudinal measurements (data on investments in research, economic development, demographic shifts, etc.) that are routinely reported by national governments and that may influence consumption and production patterns. Such analysis will provide a better picture of the types of market- and production-based measures that are required to support NOC integration into food systems in African countries, and where the balance lies between the different types of measure in different locations as economies and societies continue to evolve. As a starting point, country-specific analysis could focus on nations where AOCC species richness is highest (Figure 5).

Modelling species distributions: as noted in section 3.1.3, sufficient African point location data already exist in public geo-spatial data sets such as GBIF to support ENM of many of the distributions of AOCC NOC. Modelling under current climate conditions would identify geographic areas from where to seek material when assembling representative germplasm panels for resequencing and for testing of species in field trials, to cover environmental and geographic variation. When this present-day modelling is combined with modelling for predicted future climates, guidance will be provided on the likely different responses of AOCC species to global warming, with implications for research and crop deployment approaches, and for the resilience of the production systems of which they are part.

Prioritising NOC by geographic location: which of the AOCC species to focus on in specific locations in SSA to most optimally support human diets depends on a wide range of factors. These factors include the geographic locations in which the species can grow (see previous paragraph), context-specific production systems, and the particular nutritional needs and preferences of consumers. As has been indicated (see especially section 2.3.1), there are a range of geo-spatial maps and other spatially explicit data sets available that provide the opportunity for developing a geographically-based decision-support tool for NOC priorities in the SSA region. The construction of a basic tool to inform national governments on research investment decisions for specific NOC would therefore be relatively straightforward.

Trait definition for genetic improvement: as outlined in section 2.3.2, defining key traits for genetic improvement for AOCC species involves understanding consumers', food processors' and retailers' needs, as well as the crop production constraints that farmers face. An excellent starting point to meet the need for trait information would be to consult the plant breeders who are alumni of the AfPBA (see section 3.2.2) that is linked to the AOCC initiative. Their perceptions on the genetic constraints of NOC production and the important traits for improvement – for individual species and for groups of NOC more widely – can then be refined through further surveys of other stakeholders. Fuller trait definition will support more effective targeting of AOCC discovery activities and will ensure better alignment between improvement objectives and breeding approaches (e.g., using breeding approaches appropriate for the expected genetic architecture of key traits; section 2.3.3).

Testing genetic improvement approaches: a few annual African NOC are already being bred using advanced methods as well as conventional approaches. For these species, formal model-based comparison of the costs versus benefits of different breeding methods to reach a given level of field-validated genetic gain would be relatively straightforward to carry out and could be very informative. A good crop option for study is finger millet, for which both conventional and genomic selection approaches for breeding are already in place in East Africa as part of ICRISAT's research with national and international partners. Such analysis should use a common framework to describe the pathway to impact for each breeding approach. Included should be the steps involved in translating breeding actions into actual crops in farmers' fields and foods in consumers' diets, which means considering seed delivery systems and product value chains among other issues.

Comparing the biologies of NOC and exemplar crop models: as noted in section 3.1.4, devising approaches for NOC domestication should take account of the methods used for better-researched crops with similar production biologies. In an initial assessment of biologies presented in Box 6, a subset of AOCC species was compared against a range of more researched crops for a small number of biological characteristics using a crude principal coordinate analysis. Additional important data sources on the biologies of orphan crops are available in the literature, and an extended analysis to that presented in Box 6, including all AOCC species and more detailed biological information, would therefore be relatively straightforward for scoping possible domestication pathways. Extended analysis should also include information on desired product profiles (see *Trait definition for genetic improvement* above) as well as on genetic relatedness among species (section 3.1.4).

The six activities described above can be carried out quickly. Looking further into the future, these activities can help guide the more comprehensive and detailed research outlined in section 2 of this Working Paper. Because of its fundamental importance in understanding current food systems and food system trajectories, a particular need for future research is the collection of food consumption and production data sets at a sub-national level, including the collection of long-term recall data and constraints to NOC use and cultivation (see section 2.1.1). Such surveys should therefore be a priority.

The breadth of the research required on NOC to support their integration into SSA food systems requires a research platform that extends beyond production considerations and involves broad multidisciplinary teams of scientists and development specialists. Current efforts to raise funds for research on NOC are therefore being targeted to this end.

Insights revealed by research on NOC integration into African food systems will also be relevant for supporting human nutrition globally, but particularly so for low-income nations where opportunities for crop and food diversification are high because countries are centres of crop diversity (Jamnadass et al., 2011). This diversity is, however, being lost rapidly from some of these nations (Clay, 2004), meaning attention to its collection and safeguarding – and demonstrating its potential for use – is crucial.

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Appendices

Appendix 1. Trend analysis of global FAOSTAT crop data sets

Our initial analysis of global crop data sets to explore appropriate NOC promotion approaches (Box 2) was based on a panel of 35 annual and perennial crops (or crop groups) of varying importance in food systems for which production, trade and food balance information is available at FAOSTAT (2016) for the last half century. Global-level data extracted from the production domain of FAOSTAT for the current analysis, and the derivation of crop farm gate value per unit output (as a proxy for consumer access) and crop farm gate value per hectare (as a proxy for farmer profitability) metrics, are summarised in the table below.

Data extracted from FAOSTAT (production domain)	**Notes**
Yield (hg/ha), annual data, 1961-2013	Apart from the use of annual data, mean values were calculated for the 1961-1965 and 2009-2013 periods to generate the derived metric of crop farm gate value per hectare
Area (ha), annual data, 1961-2013	Area harvested
Production quantity (tonnes), annual data, 1961-1965 and 2009-2013	Total output, yield*area. Mean values were calculated for the 1961-1965 and 2009-2013 periods and compared
Gross production value (constant 2004-2006 million USD), annual data, 1961-1965 and 2009-2013	This is an indication of total crop value to farmers, corrected to a baseline to allow real comparisons over a time series. Mean values were calculated for the 1961-1965 and 2009-2013 periods and compared. Mean value for 2009-2013 was used as point size for Figure 2
Derived metrics	
Crop farm gate value per unit output	Calculated by dividing gross production value by production quantity (total output). Mean values were calculated for the 1961-1965 and 2009-2013 periods and compared
Crop farm gate value per hectare	Calculated from multiplying crop farm gate value per unit output by yield. Mean values were calculated for the 1961-1965 and 2009-2013 periods and compared

Crops (crop groups) for which data were extracted from FAOSTAT were as follows (crop labels shown exactly as given in the FAOSTAT production domain data set): Apples; Bananas; Barley; Beans, dry; Chillies and peppers, dry; Cloves; Cocoa, beans; Coconuts; Coffee, green; Dates; Grapefruit (inc. pomelos); Grapes; Groundnuts, with shell; Lemons and limes; Maize; Millet; Oats; Oil, palm fruit; Onions, dry; Peas, dry; Pepper (piper spp.); Pineapples; Plantains; Potatoes; Rice, paddy; Rye; Sesame seed; Sorghum; Soybeans; Sugar beet; Sunflower seed; Sweet potatoes; Tea; Tomatoes; Wheat.

To explore changes in the relative contributions of crop yield and area to total output over the time period we devised the following index:

$$\log_{10}(((Y_T/Y_B)*(Y_T/Y_B)) / ((Y_T/Y_B)*(A_T/A_B))),$$

where for each crop Y = yield and A = area, both for time T (each year, 1961 to 2013) and time B (baseline, mean value 1961-1965).

For each crop, application of a linear regression of index values against time (the year 1961 set as time = 0) in Excel provided a gradient value for the relative role of yield and area to output over the period (Figure 1). The gradient values for all 35 assessed crop were then regressed, again using a linear equation in Excel, against log_{10} value of changes in output comparing the start and end of the time period (Figure 2).

Finally, log_{10} values of the change in crop farm gate value per unit output and crop farm gate value per hectare comparing the start and end of the time period for all 35 assessed crops were also regressed against log_{10} value of changes in output comparing the start and end of the time period, again using a linear equation in Excel (Figure 3).

It should be noted that the utility of crop farm gate value per unit output as a proxy for consumer access assumes there has been no major change in margins or efficiency in delivering food to markets over the period, while the utility of crop farm gate value per hectare as a proxy for farmer profitability assumes there has been no major change in farm input levels over the period. Both these assumptions are highly questionable, indicating further and more sophisticated research is needed on this topic.

Appendix 2. Compiled database information on 101 AOCC crops

Please use the link below to access detailed information on the 101 AOCC crops:

http://africanorphancrops.org/wp-content/uploads/2018/02/New-and-Orphan-Crop-Working-Paper-Appendix-2.xlsx

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