# Intercropping and crop rotations in cassava cultivation: a production systems approach

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## 1 Introduction

Cassava is the sixth most important food crop globally (Burns et al., 2010) and it is grown in a highly diverse array of cropping systems. This diversity, which reflects the versatility of cassava, includes smallholder farming systems, but also larger-scale plantations (for animal feed, biofuels). Cassava does not have a specific and determined maturity period and it can therefore be harvested over a range of ages, depending on cropping system and socio-economic conditions. In general the cropping cycle of sweet cassava, especially on the fertile dark Amazonian soils, is much shorter than that of bitter cassava, which usually grows on oxisols and ultisols, in the same area (Fraser et al., 2012; Jakovac et al., 2016). There is a tendency in Africa towards shorter cycles of cassava in conjunction with increased commercialization of the crop (Fermont et al., 2010a).

In this chapter we will review the current knowledge on mixed cropping systems (both intercropping and crop rotations) in which cassava plays a prominent role. We will discuss yield benefits of such mixed cropping and evaluate mechanisms that have been proposed

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to explain superior yields of such systems. We will also list the functional traits of different cassava varieties that likely explain why cassava performs well in intercropping.

# 2 Advantages of cassava as a crop

The cultivation of cassava is a major activity for many smallholder farmers in the tropics. Benefits of cassava cultivation for resource-constrained smallholder farmers are given by (Adjei-Nsiah et al., 2004, 2007, 2017).

## 2.1 High productivity

Cassava is highly productive relative to other crops, especially on soils of low fertility (Fresco, 1986; Dixon and Ssemakula, 2002). This productivity on poor soils has given rise to the faulty understanding that cassava is a major cause for soil fertility decline (Sitompul et al., 1992). The fact that cassava grows well on poor soils and that cassava cultivation area is increasing has led Hillocks (2002) to link both phenomena to declining soil fertility levels in Africa. Fermont et al. (2010a,b) argued that declining levels of soil fertility, rather than labour shortage or food shortage, drove the transformation towards cassava-based systems in Uganda.

## 2.2 Low fertilizer demand

Cassava seems to need little or no mineral fertilizer, except K (but see Howeler, Chapter xx); in fact, cassava does not always respond to nitrogen (N) fertilizer and sometimes shifts carbon allocation towards above-ground tissues, making it excessively leafy (Mutsaers et al., 1993) after N fertilization, with reduced yields of storage roots.

## 2.3 Drought tolerance

Cassava is drought tolerant, and can withstand several dry months after it has become well established in the first critical months. Cassava cultivation therefore may be part of a risk management strategy. The increasing likelihood of drier periods as a consequence of climate change could also make cassava a crop of increasing importance (Burns et al., 2010; Jarvis et al., 2012). As many other staple foods are likely to be negatively impacted by climate change, the importance of cassava as a major food will likely increase. However, higher temperatures could negatively impact cassava productivity (Adjei-Nsiah and Kermah, 2012). The increase in atmospheric $CO_2$ may have divergent effects on cassava – its high nutrient use efficiency may cause an increased yield (Fernandez et al., 2002), but with potentially lower nutritive value (Gleadow et al., 2009).

## 2.4 Low labour demand

Cassava is claimed to have a low labour demand. Before canopy closure (the first 3–6 months) intensive management is required, which makes cassava not as labour-extensive as often claimed (Fermont et al., 2010b). In the early stages labour demand can in fact even be higher than that for other crops. Harvesting can also be labour intensive.

Cassava allows a very flexible harvesting calendar, although planting needs to be done during the rainy season, or under irrigation. Staggered planting and harvesting may not only reduce constraints on labour availability, but also allow harvesting of small amounts any time it is needed over a long period, even up to two to three years.

## 2.5 Income generation

Income from cassava can be high. In Ghana, Adjei-Nsiah et al. (2007) showed that cassava rotation with maize had the highest return on investment. This beneficial effect was more due to the high monetary value generated by cassava than by the yield increases of subsequent maize. Also Fermont et al. (2010a) showed for Uganda that cassava generated higher income than other crops. In that study, wealthier farmers tended towards cassava mono-cropping, whereas the less well-endowed farmers maintained a larger part of their cassava fields as intercrop. Cassava also can be used as animal feed (Thailand) or biofuel (Brazil) or for local beers (Ghana). Currently, however, market linkages in Africa are underdeveloped for cassava, despite its potential as raw material for starch and ethanol (Adjei-Nsiah and Sakyi-Dawson, 2012). But with increasing urbanization, cassava may become (depending on relative food prices and food cultural preferences) a major product for the rapidly increasing urban populations (Kamau et al., 2011).

## 2.6 Suitability for female households

Cassava often has a prominent role in female-dominated households relative to other crops (Berry, 1993; Nweke et al., 2002); also the processing of cassava is a female-dominated activity (Chiwona-Karltun et al., 1998).

## 2.7 Options for intercropping

Widely spaced cassava cuttings create options for intercropping, which is intended either to suppress weeds or to grow food crops among cassava plants. If the plant stays longer in the field than the other crops, further photosynthetic carbon can be allocated below-ground until storage capacity is saturated. This factor explains why cassava, as a perennial plant, can be integrated into annual cropping systems, but can also form part of cross-year systems. It is easier to keep cassava in the field than to harvest and store the roots, especially since the roots begin to show physiological deterioration within a few days of harvest. In that sense, apart from being a source of daily food, a field of cassava is like money put in the bank – where some plants can be harvested when needs for cash increase. Other crops must be harvested at specific periods of maturity; without adequate storage there are periods of high availability (with low prices) and periods of low availability (when food reserves have run low).

By this combination of beneficial properties, even relatively poor households with not more than one or two hectares of agricultural land can achieve food security almost across the year, something that cereals are far less likely to achieve. These benefits explain why an exotic crop has now become the second-most important source of calories in Africa (after maize), with more than 500 million Africans deriving a major portion of their calorie intake from cassava (Nweke and Haggblade, 2010). Cassava has not always been popular among R&D institutions, nor a priority for national policies. Not being an export-oriented cash crop for most countries, such crops have often been neglected by policy and academia (Scott et al., 2000). However, times are changing. A book by Nweke et al. (2002) was one of the early works to reflect the increased interest in cassava as a flexible crop that could make major contributions to both food security and income generation in Africa.

However, it has been suggested that some generalizations on cassava cropping do not have sufficient empirical support. Fermont et al. (2010a) investigated five such beliefs: (1) cassava is a subsistence crop grown to avoid hunger; (2) cassava is grown by poor farmers; (3) cassava is mainly grown as intercrop, and less so as monocrop; (4) cassava cultivation is less labour demanding than most other crops; and (5) cassava requires no nutrient inputs due to its ability to grow on the poorest soils. The persistence of these beliefs, without empirical validation, could be problematical for understanding the changing role of cassava in agriculture (see Future trends and conclusion).

# 3 Crop rotations in cassava

Crop rotation is recommended in cassava cultivation to minimize nutrient exhaustion, weed pressure, disease build-up, and soil loss. Rotation may also result in soil organic matter build-up and promote biological soil activity. Rotation therefore maintains cassava productivity. In Colombia, Leihner and Lopez (1988) reported that within a nine-year period, fresh cassava root yield dropped from 37 to 12 t $ha^{-1}$ when cassava was sole-cropped. In the same experiment, after five-year farmer-managed cassava sole-crop cycles, moderate fertilization did not result in increased productivity. However, when cassava was rotated with *Crotalaria juncea* (Fabaceae) as green manure, maize, cassava, maize, common bean, sorghum and cassava again, cassava yield returned to 30 t $ha^{-1}$. They reported that soil nutrients were not depleted under continuous cropping of cassava but that biological soil degradation resulting from continuous cropping had rendered the soil nutrients unusable by cassava. Soil organic matter under continuous cropping of cassava showed a tendency to decline. After four years of rotation, soil organic matter increased again. Spore counts of arbuscular mycorrhizal fungi were 36% higher than in continuous cassava cropping.

In rotations involving cassava it is not only the yield of cassava that is positively influenced by the system but also the yield of the crops in rotation with cassava. In a 12 years' rotational experiment in Northern Ghana, Agyare et al. (2006) reported that the best preceding crops for maize in descending order were: groundnut (3.8 t $ha^{-1}$), cassava (3.5 t $ha^{-1}$), soybean (3.4 t $ha^{-1}$), cowpea (3.2 t $ha^{-1}$), and sorghum (1.9 t $ha^{-1}$). They reported that a cassava-maize rotation gave the highest total energy value, indicating that cassava was the most compatible crop with maize. In the Guinea/savanna transitional agro-ecological zone of Ghana, Adjei-Nsiah et al. (2007) reported a higher maize grain yield when cassava preceded maize than when grain legumes such as pigeonpea, cowpea and groundnut preceded maize. They attributed the higher maize grain yield after cassava to the amount of nutrients returned to the soil after cassava through litter fall and green leafy biomass that was incorporated in the soil after the cassava harvest. In a rotational system involving maize with other crops such as cassava, pigeonpea, cowpea, groundnut and maize, in the semi-deciduous agro-ecological zone of Ghana, Adjei-Nsiah (2010, 2012) reported that the best preceding crops for maize in descending order were: pigeonpea, cassava, groundnut, cowpea and maize.

## 4 Cassava intercropping

While the literature often proposes a clear separation between crop rotations and intercropping, such a dichotomy is not always applicable in the case of cassava. Due to its long duration (12–24 months) several companion crops can be grown with cassava, either simultaneously or sequentially.

Since the review on cassava-based intercropping by Mutsaers et al. (1993) more than two decades ago, no new synthesis seems to have been published. The review concluded that in cassava intercropping the relative yield total (RYT) or land equivalent ratio (LER) is usually above 1, a phenomenon known as overyielding. However, mechanistic understanding of the benefits of cassava intercropping has made little progress.

Cassava has been intercropped in many different combinations:

- With other tuber crops (yam or sweet potato)
- With cereals (maize, upland rice)
- With pulses (cowpea, common bean, groundnut, soybean, pigeonpea)
- With maize and pulses (common bean; cowpea (but used for weed control and as green manure); groundnut; soybean)
- With commercial vegetable crops (egusi melon, pumpkin, okra, pepper, cotton, sunflower)
- With cover crops (or forage leguminous crops) as an additional contribution to weed suppression (*Crotalaria spectabilis*, *Pueraria phaseoloides*, *Canavalia ensiformis*, *Mucuna pruriens*, *Stylosanthes guianensis, Centrosema pubescens*)
- With fruit plants and trees (banana, pineapple, passionfruit, coffee, oil palm, coconut)
- With fruits (as above) and maize and cover crops
- With agroforestry trees (*Gliricidia sepium*, *Leucaena leucocephala*) that provide N-rich mulch in alley-cropping systems.
- With a diversity of crops as in traditional polycultures, that is intercropping arrangements without a predefined spatial arrangement
- With tree species to enhance revegetation or natural restoration on small farms in order to generate income in the first stages of afforestation (Martinotto et al., 2012).
- With any fallow plant (jachère de manioc, cassava fallow – see below).
- Cropping systems with two or more cassava varieties of different architecture also constitute a form of intercropping.

This list of intercrop combinations shows the versatility of cassava. In many, though not all cases, the intercrop is of a much shorter duration than cassava. But late-maturing crops can also be combined with cassava, and arrangements of both early- and late-maturing crops in combination with cassava have been recorded from Africa (Mutsaers et al., 1981).

## 5 Yield increases through cassava intercropping

Benefits or disadvantages of intercropping can be expressed in absolute or relative terms. Because of the very different nature of the harvested products, expressing benefits in relative terms is preferred. The most common parameter is RYT or LER, a parameter that expresses the sum of the relative yields of all crops when grown together compared to the summed yields when grown separately. An RYT larger than 1 is an indication of a relative yield advantage of intercropping compared to mono-cropping, but does not specify which crop benefits, or benefits more, from the intercropping arrangement.

Farmers, however, do not intercrop with the intention to increase RYT, irrespective of the crops concerned, but are specifically interested in the yield benefits or disadvantages of specific intercropping arrangements. For that reason the design of experiments by ecologists to study the underlying mechanisms of overyielding differs from the ways farmers intercrop. In ecological experiments, benefits of intercropping are usually studied in *a substitutive design*, whereby total plant density is held constant. Cassava intercropping under farmer conditions usually follows an *additive design*. In this design, cassava density is held constant at 10 000 plants $ha^{-1}$, with no difference in density between cassava monocrop and cassava intercrop; the other intercrop is then planted in variable densities. Farmers evaluate the extent to which their cassava harvest is reduced in this intercropping arrangement, and how this reduction is or is not compensated for by the yield of the second crop. The prevalence of additive intercropping designs with cassava follows from the fact that cassava yield in farmers' fields usually does not exceed that density of 10 000 plants $ha^{-1}$; at that density there is substantial unused space and light in the first months of cassava growth. Depending on the duration of the intercropping phase, the competitive interactions of cassava with the intercrop(s) and the ability of cassava to recover from initial competitive interference, the cassava yield is usually (somewhat) decreased, but the beneficial effect of the yield of the companion crop compensates for that yield loss. In exceptional cases cassava produces more as an intercrop than as sole crop. Cenukdee and Fukai (1992a) reported the intercrop combinations of soybean and small-statured cassava. The underlying mechanism was not described.

The literature abounds with data on RYT in cassava intercropping. Mutsaers et al. (1993) provided an extended table with RYT from various intercropping experiments. From their table RYT was almost always higher than 1, and reached values slightly above 2 in several cases. Modern studies have reported even higher RYTs, especially in cases of multiple-crop intercropping. The currently highest reported RYT is 3.12 for a system with cassava, maize, cowpea and melon (Udoh and Ndaeyo, 2000) in south-eastern Nigeria. In a Ghanaian intercropping system with maize, soybean, cowpea and cassava, RYTs up to 2.83 were reported (Ennin et al., 2001; Dapaah et al., 2003). In Brazil, Neto et al. (2014) described a polyculture of cassava, maize, passionfruit and pineapple, to which green manures from legumes were added, and reported RYT between 2.45 and 2.77.

A complication with the use of RYT as an indicator for intercropping benefits is the unequal period that both crops remain on the land. Considering combinations of a short-growing annual crop (cereals, legumes) with a long-duration cassava, the standard way of calculating RYT might be biased towards intercrop combinations that show large differences in phenology (temporal niche differentiation). For that reason Mutsaers et al. (1993) introduced the Area $\times$ Time Equivalency ratio (ATER). Applying ATER for cassava intercropping results in lower values than for RYT, although values still remain above unity. However, applying the correction for differential crop growth duration is not without problems, especially in cases of extended dry periods, where ATER may give low values. Subtracting the dry season can generate problems, especially in regions with a bimodal rainfall pattern. Here, including or excluding the short rainy season from ATER produces different results. With the human impact on climate, it is likely that many tropical and sub-tropical sites will receive less and less predictable rainfall; and claims on the benefits of cassava intercropping may then rely strongly on the way in which changes in dry periods are or are not discounted in ATER. Since RTY and ATER are usually correlated, we will therefore continue to use the RYT, but with the caveat that the absolute values should be interpreted with caution.

# 6 Achieving yield increases in cassava intercropping

While many studies have described yield increases in cassava intercropping, only very few tested specific mechanisms are responsible for that yield increase. From the literature on yield increases in intercropping (Li et al., 2014; Brooker et al., 2015) various mechanisms have been proposed. The relative importance of these mechanisms has not yet been evaluated. Our list is therefore descriptive and should be considered as an invitation for mechanistic research (as is currently taking place at IITA), in which plant traits (see below) as causal factor should be incorporated. Mechanisms for benefits with cassava intercropping include the following.

## 6.1 Vertical niche differentiation

Cassava has been reported to have the ability to form deep roots, thereby avoiding competition with companion (annual) crops by vertical niche differentiation. Cassava could also be able to regenerate nutrients that have leached to deeper soil layers.

## 6.2 Temporal niche differentiation

When cassava cuttings are planted, a certain time period is needed for adjustment of their shoot to root ratio. In this initial period light interception is low and there is substantial unused space for leaf development by companion plants. If such plants can complete their cycle before cassava forms a closed canopy, more complete light utilization can be achieved. But cassava can suffer from light limitation in intercropping. The negative relation between cassava yield and growth period of the associated soybean suggests that the temporal window to escape from competition for light becomes smaller, the longer the period of crop overlap. A major conclusion from intercropping studies is that RYT is better correlated with cassava yield than with the yield of the companion crop, implying that efficient intercropping combinations are those that have only small impacts on cassava yield. Apparently there is competition for resources as long as both crops grow together, but after harvest of the companion crop, cassava has the ability to recover. It is this ability to recover from competition that makes intercropping successful, but the mechanism of recovery and the conditions under which recovery is likely need further study. Unfortunately there are no published studies where competitive dynamics in intercropping (in terms of light capture or nutrient acquisition) have been studied, following the protocol of Trinder et al. (2013). Mutsaers et al. (1993) suggested that there is a threshold beyond which maize is too competitive to allow recovery by cassava; unfortunately, this concept of a competitive threshold has not yet been fully tested experimentally. The existence of a threshold is consistent with a hypothesis of a *temporally limited plasticity* of cassava to recover from competition for light. Because the threshold is different with legumes or cereals (Mutsaers et al., 1993), it may be possible that next to competition for light, competition for below-ground resources (including space) is important. Possibly a systematic comparison of different legumes of different statures (ranging from short-cycle cowpea to longer-cycle pigeonpea), planted prior to, simultaneously with, or one or several weeks later than cassava, will help resolve the issues of competition for light and for below-ground resources in relation to temporal niche differentiation.

## 6.3 Complementarity with other crops

Complementarity has been described from cropping systems with cereals and legumes. Due to their ability to fix atmospheric $N_2$, legumes do not compete with cereals for N, thereby leaving a larger N pool for cereals. Comparison of RYT in various intercropping combinations indicates that maize–cassava combinations are on average more productive than maize–legume combinations. That difference would suggest that below-ground niche differentiation is due rather to P or K than to N. Only two studies have suggested a cassava benefit due to $N_2$ fixation by a legume (Njoku et al., 2010; Umeh and Mbah, 2010). Whereas cassava takes little N and P from the soil, it takes up substantial amounts of K and cassava cropping can become K-limited, as shown by fertilizer trials (Fermont et al., 2009). A recent study by Ezui et al. (2016) indicated that for yields of up 8 ton $ha^{-1}$ dry weight (equivalent to 20–25 ton fresh weight), the main limiting nutrient is K.

## 6.4 Facilitation

Facilitation describes situations whereby one plant increases the availability of a limiting nutrient in a way that benefits not only itself, but also its companion species. Facilitation has also been noted in legume–cereal interactions, with legumes producing organic anions (carboxylates) that increase phosphorus availability for the cereal; and for iron, whereby the ability of grasses to enhance iron availability in calcareous soils increases iron uptake by the legumes. The literature on cassava intercropping has not yet provided clear examples of facilitation.

## 6.5 Weed suppression

Intercropping may be a way to reduce weed pressure. In the initial growth stages of cassava, competition with weeds, especially rhizomatous grasses like speargrass (*Imperata cylindrica*), can result in substantial cassava yield reductions (Fermont et al., 2010a). Under these conditions cover crops can be beneficial (Ekeleme et al., 2003; Chikoye et al., 2001), although some cover crops can also result in cassava yield reductions (Chikoye et al., 2002). Weed suppression may be beneficial in cassava–pepper intercropping (Olasantan et al., 2007), resulting in higher pepper yields. A study in Brazil used cowpea to manage weeds in a cassava–cowpea intercropping system. The cowpea was not harvested, indicating the dual nature of various cowpea varieties to suppress weeds, to impact soil fertility and/or to yield grains (cf. Vissoh et al., 2008).

## 6.6 Reduction of erosion

Although cassava is frequently believed to contribute to erosion (Howeler, 1991), Hulugalle and Ezumah (1991) noted that cassava protected the soil against run-off due to its extensive canopy development. On the other hand a study in Nigeria by Odemerho and Avwunudiogba (1993) indicated substantial increases in erosion when polycultures with cassava were replaced by cassava monocultures. They also noted that traditional planting practices against erosion were more successful with polycultures than with monocultures. Ijima et al. (2004) noted from Indonesia that cassava mono-cropping resulted in the highest erosion rates. Ardjasa et al. (2001) found high erosion under cassava mono-cropping, especially during the first months when soil cover was still low; 90% of the annual soil loss happened during the first four months.

## 6.7 Enhancement of beneficial soil microbiota

Cassava is a crop that is highly dependent on and responsive to the arbuscular mycorrhizal symbiosis (Habte and Byappanahalli, 1994). Cassava could therefore build-up and maintain mycorrhizal inoculum from which the companion crop(s) benefit. Conversely, the build-up of mycorrhizal inoculum by the intercrops could also be beneficial for cassava. Enhancement of beneficial soil biota (e.g. earthworms) could also be due to microclimate improvement, such as lower soil temperatures and higher soil moisture (Olasantan et al., 1996).

In conclusion this list suggests many potential mechanisms for overyielding, but the relevance of these has in most cases not been assessed experimentally. Our interpretation from the literature suggests that more complete light use (temporal niche differentiation), weed suppression and enhanced soil biological activity likely constitute the more important mechanisms. Data from Benin (Saïdou et al., 2004) indicate that farmers mention similar mechanisms for soil fertility enhancement, including the closed canopy (less soil erosion, moderated soil temperatures, enhanced soil moisture and increased biological activity).

# 7 Soil fertility enhancement through cassava intercropping

Claims that cassava regenerates soil fertility (and therefore fulfils the same role as trees in bush fallow) are widespread in Africa (Saïdou et al., 2004; Adjei-Nsiah et al., 2004, 2007; Fermont et al., 2008). For that reason cassava not only is intercropped, but can also remain in the cropping cycle at the end when the land would otherwise be laid fallow. In West Africa this system is known as *cassava fallow* or, in French, *jachère de manioc*. In Benin the system was first described by Daane et al. (1997) and Totongon et al. (2000). Most descriptions of cassava fallow are from West Africa (Ghana, Benin, Nigeria), but a similar system is known from Uganda under the name *imitation fallow* (Fermont et al., 2010a). The term *cassava fallow* has also been used for indigenous agricultural systems in Honduras (House, 1997). It is likely that similar systems occur in parts of Amazonia, to judge from studies by Hecht and Posey (1990).

At first sight, the term *cassava fallow* seems an oxymoron – fallows being considered the period when no crops are grown. For that reason Fermont et al. (2010a) replaced the term *cassava fallow* with that of *imitation fallow*. We do not consider this a terminological improvement, mainly because the alternative terminology assumes an absolute distinction between the agricultural period and the fallow period. But a strict separation may be artificial – when useful crops continue to grow after the land has been abandoned and soil tillage comes to a stop before planting of new crops takes place. As cassava can remain on the land for up to 24 months, there may still be cassava after the end of what would otherwise be considered the cropping phase. And when weed pressure remains low, the cassava on that land may produce food while contributing to soil fertility recovery. In that respect cassava has partly replaced bush fallow. A benefit of cassava fallow over bush fallow is that it can shorten the fallow period; Vanlauwe et al. (2013) noted for Congo an alternation of cassava growth of 1–2 years and a subsequent fallow period of only 2–4 years. Soil data indicating recovery under two-year cassava fallow were provided by Okore et al. (2007). They noted increased labile soil organic C and N and higher microbial biomass C and N in a cassava fallow compared to a continuous cropping system. Unfortunately, the paper did not provide data on cassava planting density, nor on cassava yield.

The use of cassava fallow is not accessible to all farmers. In the areas of West Africa where cassava is commonly grown, a major influx of people from neighbouring regions and countries has taken place. Although these new immigrants are integrated in agriculture, a study by Adjei-Nsiah et al. (2008) indicated that cassava growing as part of soil fertility regeneration was much more widespread among native farmers (82%) than among immigrant farmers (44%). For bush fallow the differences are even larger, suggesting that land tenure regulations are the basis of access to such soil fertility management practices. Differences in valuation of cassava fallow have also been noted for Benin (Saïdou et al., 2004).

A question that has not been addressed is the extent to which different cassava varieties are more or less preferred by farmers for cassava fallow. Considering the high planting density (17 000 plants $ha^{-1}$) in cassava fallow, it is possible that certain varieties with specific traits are preferred.

## 8 Farmer experimentation during cassava cropping

One interesting benefit of cassava cropping systems, with their continuous harvesting times over a longer period, is that they provide opportunities for farmer experimentation that most annual cropping systems do not easily provide. For example, although rarely practised on a global basis, farmers have an opportunity to generate new genetic diversity through propagation of true seed. This will in theory allow new options for variety traits that best fit into farmers' preferred cropping systems. Basically the on-farm *breeding* system consists of farmers allowing certain plants to flower and be pollinated by natural means. (Many cassava varieties flower and set seed, but neither flowers and fruits nor dried seeds typically have value to the farmer.) When seeds set, they fall to the soil and generate new genotypes (all other cassava plants are reproduced clonally). These volunteer seedlings are then allowed to grow and are harvested at the end of the cropping season. If such volunteers are considered by farmers to have desirable traits, these new genotypes are subsequently reproduced through cuttings. By this intended (but poorly controlled process, since fertilization is random) novel genotypes are generated that allow farmers to adapt to changing conditions.

Such systems have been extensively described from the Amazon region, where farmers use an elaborate technology to balance risks of inbreeding and outbreeding (Duputié et al., 2009), but they also occur in western Africa (Manu-Aduening et al., 2005). In cassava fallow there are possibly more chances for volunteer seedlings and some of these could be tested and actually incorporated in next cycles.

# 9 Cassava functional traits

The benefits of intercropping for cassava yield show large differences between different cassava varieties. Classification of cassava varieties with relevant functional traits as a basis for understanding this differential performance is currently under study. Functional traits have received only little attention in the agro-ecological literature (Garnier and Navas, 2012; Martin and Isaac, 2015).

Literature on cassava in the early 1990s includes several papers that compare large numbers of cassava varieties. Descriptions of those varieties in terms of relevant functional traits are often so brief that we cannot yet link this literature to a trait-based framework. A directly selected trait like cyanogenic potential (the contrast of bitter and sweet cassava) may affect diverse characteristics such as leaf N content, leaf decomposability and N cycling (Zhao et al., 2015). They showed that linamarin (the cyanogenic glucoside from which HCN is released) is important for N resorption under drought.

From the perspective of cassava intercropping, relevant cassava traits include both those that determine the ability of cassava to yield well (exhibit only small yield reductions) in competition with intercrops, and those that determine the intercrops that yield well in competition with cassava. Clearly both sets of traits have trade-offs, for example, high competitive ability of one intercrop reduces the performance of the other. In this review we focus on potentially important cassava functional traits for intercropping.

## 9.1 Leaf nutrient content and leaf litter quality

Cassava leaves are rich in N, and leaf litter retains high amounts of N. According to Borin and Frankow-Lindberg (2005) cassava leaves contain 35–50 mg N $g^{-1}$. Cassava leaves are poor in lignin, and the combination of both traits results in high decomposition and hence high N flux rates that are likely beneficial for subsequent crops in rotation (Adjei-Nsiah et al., 2007). The actual sources for this high N content are currently unknown. Possible mechanisms include $N_2$ fixation by asymbiotic, free-living bacteria, the ability to prevent leaching through a deep-rooting system and/or the ability to acquire N from deep-water sources. The occurrence of $N_2$-fixing bacteria has been reported (Balota et al., 1999; Teixeira et al., 2007). No $^{15}N$ data are available to unambiguously demonstrate significant $N_2$ fixation by cassava. Cassava leaf litter also recycles substantial amounts of P and K (Fermont et al., 2010b).

## 9.2 Leaf retention and longevity

Both leaf N and leaf longevity form part of the leaf economics spectrum (Reich, 2014). The two traits (leaf N and leaf longevity) should logically be negatively correlated; however, Lenis et al. (2006) showed evidence that leaf retention was not negatively correlated with other useful agronomic traits. Cock et al. (1979), in their study of the ideal cassava phenotype, noted that higher cassava yields would be achieved with longer leaf life span. Leaf longevity determines not only the timing and the amount of N returned to the soil, but also the extent to which cassava can adapt to drought in more seasonal climates. The existence of genetic variation in that trait indicates potential for genetic improvement (Kawuki et al., 2011). The fate of N in periods of drought (e.g. resorption before senescence) seems also unknown, but it has been suggested that linamarin is important in N resorption (Zhao et al., 2015). The fact that cassava leaves are rich in N allows substantial N returns to the soil in terms of easily decomposable, N-rich litter. It is therefore not surprising that cereal crops such as maize, whose growth limitation in the West African savanna is usually N, show high productivity after a cassava fallow.

## 9.3 Plant architecture

Plant architecture is determined by three fundamental parameters: total plant height, height of the first branching point, and number of branching levels. Plant architecture determines the extent to which cassava can outshadow other plants, intercrops and weeds (and the extent to which it can create a suitable microclimate for more shade-tolerant intercrops and a more favourable microclimate for soil fauna). Next to variation in architecture there may be variation in the degree of plasticity. Cassava plants may change their branching after the intercrop has been harvested and light availability increases, resulting in recovery from competitive suppression. Branching habit (as well as architecture of the root system) could also be partly controlled by the arbuscular mycorrhizal symbiosis. Branching pattern and height have been mentioned as important traits by Mutsaers et al. (1993).

## 9.4 Timing of carbon allocation to fine and storage roots

This timing determines when the first storage roots are formed and how long storage roots continue to increase in mass. This timing is likely affected by stoichiometric relations, the relative conversion of photosynthetic carbon and nutrients into storage roots, and therefore correlated with leaf (N content, leaf longevity) and stem traits (maximum canopy height, branching architecture). A study by El-Sharkawy and De Tafur (2010) indicated that canopy height and the time after planting that cassava begins to form storage roots are positively correlated. Both are also positively correlated with total leaf area and total yield of storage roots. A corollary of their study was the suggestion that in short and in short-duration (early bulking) varieties, leaf area was less than optimal for maximum yield (although harvest index was higher in varieties of shorter stature, as also shown by Egesi et al., 2007). However, other short-duration varieties have been stated to be higher yielding than the more traditional varieties (Kamau et al., 2011).

## 9.5 Rooting depth

Cassava is generally considered a species with relatively superficial roots, with the largest part of the root system being in the uppermost 60 cm (Iijima et al., 2004). In a study by Subere et al. (2009) genetic variation in rooting depth was small. A study by Muhr et al. (1995a) equally indicated that, depending on variety, 58–74% of cassava root length was in the uppermost 30 cm. In intercropping there was little or no vertical niche differentiation between cassava and the intercrop (an observation that is consistent with other reports that the importance of vertical niche differentiation as an explanation for overyielding has been overestimated). A subsequent report by the same authors (Muhr et al., 1995b) indicated both the potential and the actual occurrence of severe competition during early stages of cassava growth. There are reports that cassava roots can go much deeper, up to 200 cm (El-Sharkawy et al., 1992; El-Sharkawy, 2004) or 260 cm (Connor et al., 1981). However, on acid soils, most cassava roots are likely to remain in the upper soil layers where soil organic matter levels are higher and Al toxicity is less of a problem. Deep rooting more likely occurs in coarse-textured soils than in the clayey oxisols and ultisols. Deep roots could allow cassava to acquire water from layers inaccessible to other plants, which might contribute to its higher drought tolerance (El-Sharkawy, 2007); deep roots could also be important as a safety net against N leaching. To the best of our knowledge there are no isotopic data that demonstrate that cassava has access to deep-water sources. Also the drought tolerance of cassava is not clearly linked to its deep-rooting habit. Cassava drought sensitivity (and risk of substantial yield reductions) in the first months after planting may be related to its still relatively sparse and shallow root system (Baker et al., 1989; Bakayoko et al., 2009). Its remarkable capacity to recover from drought (El-Sharkawy, 1993) is not evidently related to its ability to produce deep roots. Whether there is also hydraulic redistribution of water (as a mechanism of facilitation to explain high RYT in intercropping) is currently unknown.

## 9.6 Root extension and root branching

Subere et al. (2009) reported genetic variation in lateral root development and root branching, but how this variation can be harnessed for productive intercropping systems needs more attention.

## 9.7 Interaction with arbuscular mycorrhizal fungi

Cassava is a highly mycotrophic plant that shows large biomass increases due to arbuscular mycorrhiza (Ceballos et al., 2013; Rodriguez and Sanders, 2015). Genetic variation in mycorrhizal responsiveness of different cassava varieties has been reported by Sieverding and Galvez (1988) and Carretero et al. (2009), while genetic variation in mycorrhizal colonization was reported by Saïdou et al. (2009, 2012). Peña-Venegas (2015) reported small differences in fungal species composition between bitter and sweet cassava, when grown in the same field in the upper Amazon near Leticia, Colombia. In that area, at least 126 different species of arbuscular mycorrhizal fungi were identified with molecular methods in cassava plots. Many of these species can also form common mycorrhizal networks with other crops in intercropping systems (Cardoso and Kuyper, 2006). The mycorrhizal symbiosis also impacts on the production of strigolactones, a class of hormones that have a major impact on shoot and root branching.

## 9.8 Compatibility with other crops

Cassava varieties that produce most above-ground biomass in monoculture are both most successful in suppressing weeds and competitively superior to other intercropped plants. It goes without saying that the functional traits of the companion intercrop in terms of compatibility need equally to be studied – as it may ultimately be the match or mismatch of traits that determines the conditions under which intercropping results in increased relative yields of cassava and/or the intercrop. Compatibility is also relevant in cases where different cassava varieties are intercropped (Daellenbach et al., 2005). Okoli et al. (1996) compared three different cassava varieties with two different cowpea varieties. Both cowpea varieties reduced cassava height, but this resulted in different yield reductions for the different cassava varieties. Cenpukdee and Fukai (1992c) compared above-ground competition between cassava and pigeonpea, using two different cassava varieties with different growth architecture. Their study showed the importance of planting dates (as a means for temporal niche differentiation) and cassava architecture (as related to differential

### Box 1 A typical cassava intercropping system within smallholder farming system in forest/savanna transitional agro-ecological zone of Ghana

Within the root-crop farming system in the forest/savanna transitional agro-ecological zone of Ghana, a typical cassava intercropping system consists of three main crops: yam, cassava and maize. The first crop to be planted after land preparation is yam. However, after preparation of the yam mounds and before the yam sets are planted, cassava cuttings are first planted in the mounds at the periphery of the field. After the yam has sprouted, maize is planted followed by cassava on the lower portions of the mound in the main part of the field. Sometimes, pigeonpea may be planted after the cassava and maize have been planted. The yam is harvested first, usually after a 9- to 10-month growing period followed by maize, and then cassava is planted at the periphery of the field. This is the first cassava crop that is harvested to fill the hunger gap before the main cassava crop is harvested later. Where pigeonpea is included in the system, it is harvested during the dry season. After the pigeonpea is harvested it is cut back to reduce competition with the cassava. Upon harvesting the cassava, the field is reverted to fallow under pigeonpea for one or two years before the field is cropped again.

ability to capture light depending on canopy height). Their study concluded that the highest RYTs were achieved by the taller cassava variety. These authors also studied seven cassava varieties in combination with soybean and pigeonpea (Cenpukdee and Fukai, 1992a). Potential height of cassava, in relation to sowing dates, was a major determinant of cassava competitive ability and hence final yield of storage roots. This suggests that breeding smaller-stature cassava may select against ability to grow in certain intercrop combinations. A third study with 18 cassava varieties and two legumes indicated that cassava canopy height was a main determinant of final cassava yield and intercrop compatibility (Cenpukdee and Fukai, 1992b). Unfortunately apart from stature, cassava traits were not analysed in detail.

## 10 Future trends and conclusion

This chapter documented various benefits that cassava, when grown as an intercrop or in crop rotations, can provide. However, cassava is not only grown as an intercrop in Africa. Fermont et al. (2010b) indicated that in Uganda and Kenya cassava was also grown as a monocrop and suggested that a shift towards cassava mono-cropping was taking place. This shift likely reflects the increased potential of cassava as a cash crop – either for food, or for feed or biofuel. It goes beyond the scope of this paper to analyse this shift. Shifts are likely to be driven by market conditions, where increased yields due to external inputs make mono-cropping more attractive. Also labour shortage may contribute to this shift. With shorter-duration varieties new options arise for alternative cropping arrangements, including newer forms of rotations that include cassava. New arrangements may well result in higher cassava yields. Suja and Sreekumar (2015) compared cassava yield in a rotational cycle and as intercrop (with cowpea) and noted significantly higher yields (root weight of

26 ton ha$^{-1}$) in a rotation than in the intercrop (20 ton ha$^{-1}$). A mechanism for increased cassava yield was not provided.

# 11 Where to look for further information

The versatility of cassava as a crop that fits in a very large diversity of agro-ecosystems has been well known. However, the knowledge has not moved much beyond the descriptive phase. The standard reference on cassava intercropping is still the review by Mutsaers et al. (1993). Many of the ideas in that paper are still highly pertinent. However, at the time of that review most studies on cassava intercropping lacked tests of specific mechanisms. Mechanistic understanding of the benefits of intercropping, through a variety of causes, is provided in the review by Li et al. (2014) and Brooker et al. (2015), although cassava is not represented in these papers. Also, understanding the specific traits of cassava (and its companion crops) was at that time in its infancy. An outline of the importance of traits in agro-ecosystems (even though the paper does not provide specific information about cassava) is provided by Martin and Isaac (2015). Next to biological studies on cassava cropping, research efforts should be geared towards understanding the socio-economic context in which cassava functions. Persistent myths about cassava were analysed and partly refuted by Fermont et al. (2010a).

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