



The role of mycorrhizas in more sustainable oil palm cultivation

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ABSTRACT

Oil palm is a significant and developing crop in many developing countries. The introduction of oil palm puts pressure on natural resources because it is often planted in cleared-cut land that previously supported other crops or was forested. This has led to environmental concerns which require attention. Hence it is important that new plantations are managed in a sustainable way to reduce the impact of oil palm cultivation on ecosystems whilst maximising yield and productivity to farmers. The application of arbuscular mycorrhizal fungi (AMF) technology is one option that can benefit both agronomic plant health and ecosystems. AMF have the potential to increase conventional agricultural productivity and are crucial for the sustainable functioning of agricultural ecosystems. This paper provides an insight into how AMF application might benefit oil palm cultivation through more sustainable management and the practical use of AMF for oil palm plantations.

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1. Introduction

Palm oil, obtained from the African Oil Palm *Elaeis guineensis* (Jacq.), is an important world commodity. It is the world's third most produced edible oil, following closely behind soya and rapeseed oil. Along with its use in food, it is also used in a wide array of cosmetics and pharmaceuticals and increasingly for bio-diesel production. Despite a short-term economic dip, diesel fuel prices are likely to continue to increase over the next decades and so will the demand for alternative sources. The world market for palm oil has been growing steadily at about 8% per annum (Carter et al., 2007). Thus, oil palm is considered as a multipurpose and economically significant crop in many developing countries. The area under oil palm cultivation is likely to greatly increase over the next two decades. In Thailand, for example, the Royal Thai Government has a policy of a 5-fold expansion in the area under oil palm cultivation over the next 20 years. The company PT Central Palm Plantation intend to invest an additional US \$280 million to further develop oil palm plantations in Indonesia (Anonymous, 2008). In South America, Colombia's agricultural policy includes an enormous increase in the area under cultivation; particularly in post-conflict regions such as the Eastern Plains. Whilst the Brazilian government had signed a deal with Malaysia's land

development to establish 100,000 hectares of oil palm plantations on forest land near Tefe in the Brazilian state of Amazonas.

This unprecedented growth in demand has led to environmental concerns. In particular, massive deforestation and destruction of peatlands when previously unplanted lands are given over to oil palm, leading to loss of biodiversity. These issues need attention and more sustainable practices introduced for all farmers and business sectors. In many cases, virgin sites are not necessary and former crop areas can be turned over successfully to oil palm. The conversion of coconut plantations to oil palm in Papua New Guinea is a good example and the transformation of poor grazing pasture into plantation in Colombia. Many players in the oil palm industry are anxious about the environmental concerns and promote good practice through the Roundtable on Sustainable Palm Oil (RSPO). The RSPO have published their principles (Roundtable on Sustainable Palm Oil, 2007), with criteria for sustainable management of oil palm plantations. At present, only 4% of palm oil is certified sustainable by the RSPO, but many palm oil companies are discussing moving to more sustainable practices with their suppliers. One criterion (Principle 5) requires companies to provide management plans and operations for conservation of natural resources and biodiversity. Soil microbiology is often neglected in such plans and a key component involves mycorrhizal associations. Arbuscular mycorrhizas are key components of sustainable plant–soil ecosystems because they play an essential role in plant nutrient acquisition, in plant diversity and nutrient cycling (Jeffries and Barea, 2000). Due to its biology the African oil palm can potentially benefit greatly from mycorrhizal associations.

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If used correctly, the management of these associations could make oil palm production more sustainable and greatly cut investment in the establishment of new plantations. In this review we consider the potential impacts of mycorrhizal management in oil palm cultivation. We indicate where they are likely to be most useful for improving sustainability, but also where they may lead to more economic oil palm production. Because one of our conclusions is that application of mycorrhizal inoculum could be considerable in the establishment of new plantations on existing agricultural land with poor soil fertility. These principles are more easily illustrated in the context of one particular country but many of the same issues may apply elsewhere. We discuss, herein, the rationale for application of AMF in the development of new plantations in the Eastern Plains region of Colombia and in Central and Southern Thailand.

2. Arbuscular mycorrhizas

Arbuscular mycorrhizal fungi (AMF) are abundant and ubiquitous in almost all natural communities and can form associations with over 80% of vascular plants (Harley and Smith, 1983; Smith and Read, 1997). This is the most ancient mycorrhizal type and their history dates back to the Ordovician era at least 450 million year ago (Redecker et al., 2000). It is apparent that these symbiotic soil fungi have become an integral component of plant communities in both natural and agricultural ecosystems. The symbiosis confers numerous benefits to host plants including improved plant growth and mineral nutrition, tolerance to diseases and stresses such as drought, temperature fluctuation, metal toxicity and salinity (Meharg and Cairney, 2000; Borowicz, 2001). Furthermore, AMF may play a role in the formation of stable soil aggregates, building up a macroporous structure of soil that allows penetration of water and air and prevents erosion (Miller and Jastrow, 1992; Jeffries et al., 2003). All of these beneficial effects on plant health and soil fitness mean that AMF are crucial for the sustainable functioning of terrestrial ecosystems. The benefits of inoculating a wide array of agronomic plant species with AMF have been documented in numerous studies (Menge and Timmer, 1982; Harley and Smith, 1983; Sylvia et al., 1993).

3. Mycorrhizas and oil palm

Most plant species form mycorrhizal symbioses and, therefore, many crops could potentially benefit from inoculation with the correct AMF inoculum. However, plants vary greatly in the degree to which they benefit. This ranges from those that benefit little to those that are strongly mycorrhizal dependent (Janos, 2007). In fact, many of the world's major food plants do not respond strongly to inoculation with AMF and applications where they are clearly beneficial are limited. In the case of oil palm, the limited development of the root system, along with field observations of high levels of mycorrhizal colonisation, suggest that they benefit greatly from the symbiosis.

The establishment of oil palm plantations puts pressure on natural resources. In several countries oil palm is often planted into cleared-cut land that previously supported other crops, or was forested. The clearing of land to plant oil palm has resulted in erosion of top soils by rain and severe leaching of the soil. It can also result in loss of indigenous mycorrhizal fungi that reside in the top soil. The combination of erosion and the nutrient depletion means that the land has a limited capacity to support the growth of either native or agricultural plants without the addition of significant amounts of fertilizer. AMF have the potential to make oil palm cultivation more sustainable and reduce the effects that oil palm cultivation may have on ecosystems outside of the plantation itself. Enormous amounts of P and N inorganic fertilizers

are applied in the nursery or during planting in the field, where much of the P may not be taken up and thus large amounts escape into the water running out of plantations into natural ecosystems. There are environmental concerns when excessive amounts of P reach surface water. In most cases an influx of fertilizer into these areas will alter natural biodiversity. This is a challenge to producers and agriculturalists who need not only to increase agricultural profitability but also to protect environmental quality.

Mycorrhizal fungi that could promote and sustain oil palm growth may not necessarily be present, but pre-plantation mycorrhizal management can ensure that new crops establish quickly and do not exhaust soil nutrients rapidly. Hence, it is important that new plantations are managed in such a way as to maximise yield and productivity whilst integrating sustainable practices. Undoubtedly mycorrhizal technology will play a vital role in sustainable plant–soil ecosystems (Jeffries and Barea, 2000; Gianinazzi et al., 2002) and needs to be considered in conserving natural resources and for reducing fertilizer inputs in favour of more natural, environmentally sustainable practices for oil palm.

Given the unusual morphology of the oil palm root systems and the results from experimental studies it appears that oil palms are strongly mycorrhizal dependent. Well-established field-grown oil palm roots are naturally heavily colonised by arbuscular mycorrhizal fungi (Nadarajah, 1980; Blal and Gianinazzi-Pearson, 1990 and Fig. 1A and B). Both the African and American oil palms (*Elaeis oleifera*) produce thick cylindrical adventitious roots and do not produce root hairs (Corner, 1966). Root hairs are used by most plants for efficient water and nutrient uptake and, therefore, oil palms are probably functionally dependent on AMF to obtain their nutrition (Corley and Tinker, 2003). If plants are grown in unsterilized soils then it is to be expected that the roots will pick up natural symbioses with indigenous populations of AMF (providing sufficient inoculum is present). This has led to the established view that the only practical use of AM inoculum for oil palm is in artificial situations where potential plant hosts are being grown in sterilized soil or other media (Corley and Tinker, 2003). However, this needs to be re-addressed in view of the interaction between fertilizer application and mycorrhizal colonisation, as explained in the next section. Furthermore, Corley and Tinker (2003) also assert that it can be assumed that all experimentation in field soil will have been done with infected palms—a view that can be challenged without data on percentage of root colonisation by AMF. It has also been suggested that inoculation of these deficient substrates is best achieved through addition of a small amount of almost any unsterile soil, especially if it has previously supported oil palms (Corley, 1993). However, experiments documented below indicate that the identity of the AMF inoculum could be extremely important for determining whether it is economically viable to use AMF in oil palm cultivation. Despite this view, some producers have advocated the use of AMF inoculum. Commercial products are available for field use in Malaysia, whilst some other producers have collaborated with Small and Medium Enterprises (SMEs) involved in inoculum production. The quality of inoculum and expertise has been very variable and without the correct management practice, particularly fertilization regimes, its application may be futile. Through our recent interviews with growers, we know that several have had a bad experience with ill-informed advisors. Inappropriate inoculation schemes have been promoted when an informed view would have advised against intervention in established field plantations. For this reason, the role of AM fungi in oil palm cultivation needs re-assessment.

4. Negative effects of fertilizers on mycorrhizal formation

Fresh, young roots collected from around well-established, mature oil palms are usually extensively colonised by AM fungi

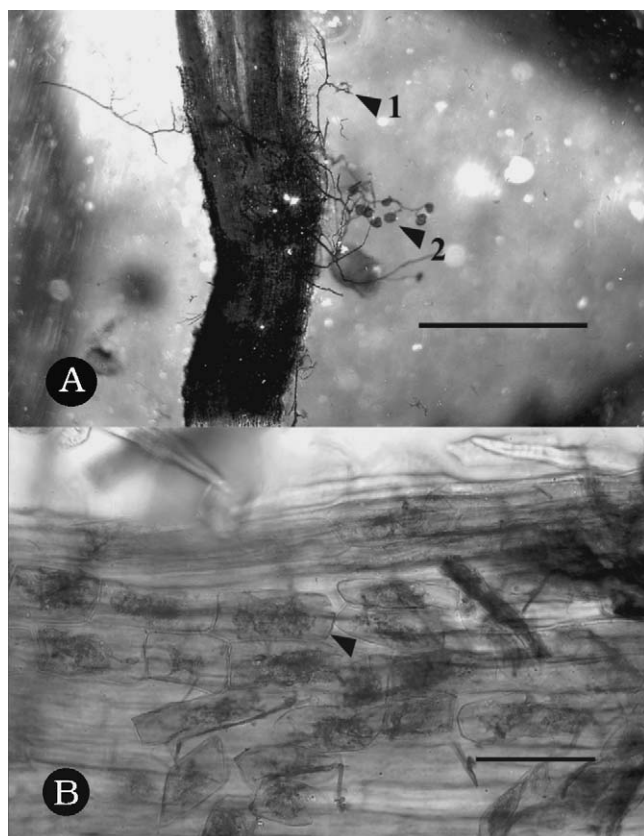


Fig. 1. (A) Roots of oil palm collected from plantation in Papua New Guinea showing stained root with associated soil mycelium (arrow 1) and spores (arrow 2) of AMF, bar = 1 mm. (B) Fine roots of oil palm collected from surface soil of plantation in Papua New Guinea showing stained root with intercellular mycelium and arbuscules (arrow) of AMF, bar = 100 μ m.

(Fig. 1A and B). This contrasts markedly with the situation where oil palm seedlings are propagated in the nursery in field-collected soil. Here infection levels are negligible or absent. This is probably because of the interaction between available P levels and development of the symbiosis. Oil palm seedlings receive high levels of fertilizer, especially P. Representative figures for fertilization of nursery stage seedlings are 41.9 g/palm (as P_2O_5) or after transplanting from 65 to 120 kg/ha/year (as triple superphosphate) in major growing areas such as Malaysia. In many cases, the initial P content of the substrate used for seedling production may be high prior to fertilizer addition (see Table 1).

It is well documented that high P levels inhibit mycorrhizal formation (Bolan et al., 1984) and that in some plants the mycorrhizal benefits can be negated provided P applications are high. Black and Tinker (1977) showed that application of 481 kg/ha superphosphate reduced AM infection levels in potato to negligible amounts despite inoculum being supplied and negated

the mycorrhizal effect shown in unfertilized plots. Clarke and Mosse (1981) noted that 83 kg P/ha eliminated the growth response of barley to mycorrhizas in a low phosphate (10 ppm Olsen P) soil. For citrus, Menge (1983) estimated that between 112 and 556 kg/ha P negated the mycorrhizal benefit, leading to a prediction that soils would benefit from AM inoculation if Olsen P was less than 34 ppm. For apple, Hoepfner et al. (1983) showed no effects of AMF in a more fertile soil (60 ppm Olsen) and estimated that 70 kg/ha of P negated the mycorrhizal benefits in a less fertile soil. Wood (1992) took a more cautious view and suggested 5 ppm Olsen P as a general minimum for plants in general to benefit from mycorrhizal effects, and showed that mycorrhizal colonisation of roots decreased rapidly as P levels rose from 5 to 10 ppm. However, dose-response curves presented by Stribley et al. (1980) suggest that the mycorrhizal effect in the highly mycorrhizal dependent leek plant was not negated until around 200 ppm Olsen P in the soil solution. Other examples of P applications that compensate for the mycorrhizal effect are given in Table 2. These results obviously vary considerably depending on the inherent P content of the soil, its P-fixing capacity and the crop dependency on P. Other results where P is less available in the soil solution indicate that the presence of AM can still have beneficial effects even in the presence of standard fertilizer treatments (Table 3).

5. How might mycorrhizas benefit oil palm?

In less intensive agricultural situations, involving cash crops such as corn, coffee, sugarcane and soybean, many farmers are unwilling to risk low yields as a result of reduced fertilizer inputs. Hence a combination of AMF inoculation with reduced P inputs is not attractive. This is especially true in oil palm which has high nutrient demands, particularly during the early stages of plantation growth. Thus, a typical management practice is to apply high rates of P fertilizer. Most of the above experiments in P fertilization and mycorrhizal benefit have been conducted with crops that can have well-developed root systems with root hairs. Because oil palms have a poorly developed root system with no root hairs, it is possible that oil palm would not be able to adequately take up enough P without mycorrhizal assistance. This is supported by results of experiments conducted by Blal and Gianinazzi-Pearson (1990). They showed that when micropropagated oil palm is planted into tropical acidic soils, the plants cannot grow well or efficiently use phosphate fertilizer unless AMF are present. In their study, AMF inoculation resulted in a 2.7–5.6-fold increase in fertilizer use efficiency. Furthermore, mycorrhizal benefits are not restricted to traditional fertilizer sources. Blal et al. (1990) reported that the coefficient of fertilizer utilization in micropropagated oil palms, was increased 4–5-fold after mycorrhization, particularly when using rock phosphate. Thus, in the nursery situation, the interaction between P application and mycorrhizal inhibition may lead to unnecessary levels of P fertilization. Oil palm growers may initiate plant growth with high levels of P fertilizer, inhibiting the

Table 1

Characteristics of field-collected soil from different oil palm plantations in Thailand.

Provinces	pH	OM (%)	N (%)	P (ppm)	K (ppm)	Ca (ppm)	Mg (ppm)
Chacherngsao	5.8	1.0	0.06	79 ^{VH}	70	480	70
Chiang Rai	5.0	3.3	0.16	57 ^{VH}	260	1000	80
Nan	5.4	3.5	0.26	656 ^{VH}	300	2160	300
Nongkai	4.4	2.2	0.12	42 ^H	320	720	110
Trad	4.3	5.3	0.23	449 ^{VH}	120	520	100

Remark: According to Land Development Department, Thailand.

P < 10 ppm means Low (L).

P ranging between 11 and 25 ppm means Medium (M).

P ranging between 26 and 45 ppm means High (H).

P > 45 ppm means Very High (VH).

Table 2

Application rates of P fertilizer that negate the mycorrhizal effect in field studies.

Crop	P application rate	Soil type/origin	References
Apple	70 kg/ha	Various soils/USA	Hoepfner et al. (1983)
Barley	83 kg/ha	Heavy clay loam/UK	Clarke and Mosse (1981)
Citrus	112–356 kg/ha	Loamy sand/USA	Menge (1983)
Finger millet	38 kg/ha	Sandy loam/India	Govinda Rao et al. (1983)
Maize	50 kg/ha	No soil data/Canada	McGonigle et al. (1990)
Soyabean	176 kg/ha	Sandy loam/USA	Ross (1971)

Table 3

Application rates of fertilizer that still show beneficial effects from AMF.

Crop	Fertilizer application rate	Soil type/origin	References
Bamboo	44 kg P/ha	Alfisol/India	Muthukumar and Udaian (2006)
Clover	44 kg P/ha 90 kg P/ha	Dystric Cambisol/Norway Ferric stagnopodzol/UK	Joner (2000) Hayman and Mosse (1979)
Coffee	85 kg P/ha	Oxisol/Brazil	Siqueira et al. (1998)
Maize	7 kg P/ha 30 kg P/ha 180 kg P/ha	Silt loam, Typic Hapludalf/Canada Sandy loam/Canada Silt loam/USA	Gravito and Miller (1998) Bittman et al. (2006) Anderson et al. (1987)
Oil palm	90 kg P/ha (hydroxyapatite)	Native soil + sand (1:1)/Indonesia	Schultz (2001)
Wheat	20 kg P/ha	Sandy loam/Canada	Xavier and Germida (1997)

development of the mycorrhizal symbiosis. As a result the plants grow poorly and cannot efficiently utilize the applied P leading to application of more P, much of which cannot be taken up by the plant. In Thailand, present recommendations for P fertilizer in major growing areas for young, mature palms (4–10 years old) range from 33 to 130 kg/ha/year. Thus, the environments where oil palm is grown are unlikely to exhibit the low levels of soil P conducive to mycorrhizal development and, thus, a growth benefit. In the nursery, oil palms are usually propagated in containers with substrates containing unsterilized natural soils which will have an indigenous AMF population. However, containerised seedlings are fertilized at application rates of 41.9 P g/palm P_2O_5 and, hence, do not become colonised by these fungi. In cases where non-soil based substrates are used (e.g. the use of composted oilseed fruit bunch wastes), no indigenous AMF are likely be present but good growth will be encouraged by the addition of the high levels of P. In such situations, there is an opportunity to reduce P inputs and maximise the mycorrhizal benefits via inoculation at the seeding stage. However, the relative benefit analysis in terms of both cost and environmental sustainability needs to be experimentally evaluated.

5.1. Previous studies where benefits have been reported

Despite the significance of the crop, there are relatively few published reports of the interaction of AMF and oil palms. Motta and Munévar (2005) reported low inherent colonisation of young palms in the field. They showed that inoculation of oil palm seedlings in the nursery resulted in a 3-fold growth increase over uninoculated plants after 570 days in natural soil substrate with no fertilizer addition. Raja et al. (1999) have shown that inoculation with AMF prolonged the productivity of palms infected with *Ganoderma* but the mechanism for this protective effect is unclear. In micropropagated oil palms, Blal et al. (1990) reported that the coefficient of fertilizer utilization was increased four to 5-fold after mycorrhization, particularly for rock phosphate. In South East Asia, a survey of soil from oil palm plantations in Malaysia revealed AMF species comprising six genera of the Glomales (Nadarajah, 1980) and was the first to describe a beneficial effect of mycorrhizal inoculation on oil palm. In fertilizer-controlled trials, Widiastuti

and Tahardi (1993) showed that inoculation of oil palm seedlings with AMF increased plant growth and nutrient uptake of oil palm plantlets; P uptake in particular increased by 37–44%. Inoculation also enhanced the survival and development of the plantlets during the acclimatization phase. Further work by Widiastuti and Tahardi (1993) showed that palm seedlings growing in sterilized soil required much less phosphorus fertilizer if they were inoculated with *Gigaspora margarita* and other AMF strains. Similarly, Blal et al. (1990) reported inoculation increased fertilizer use 2.7–5.6-fold by outplanted oil palm. Mycorrhizal benefits are not restricted to traditional propagation techniques: Blal et al. (1990) reported that the coefficient of fertilizer utilization in micropropagated oil palms, was increased 4–5-fold after mycorrhization, particularly when using rock phosphate. Tests have shown that enhanced growth of seedlings was obtained during the nursery phase in seedlings inoculated with MYCOgold (LR Agricare, Malaysia) such that they reached the stage suitable for transplanting 4 months earlier than the conventional method (Zakaria, 2006). Presumably, in these trials, the mycorrhizal inoculum potential of the original substrate must have been very low.

Given the results of these experiments, the rationale for AMF application in the nursery situation seems highly warranted coupled with a reduction in the amounts of P given to the seedlings. There is a potential that through AMF application, a reduction in P fertilizer application could be significant and therefore, highly compatible with some of the principles of the RSPO.

5.2. Economic considerations of AMF application in nurseries and plantation establishment, with reference to the Eastern Plains region of Colombia

Several countries have proposed to greatly increase the area under oil palm cultivation. Whilst the extension of oil palm cultivation in some of those countries threatens to destroy natural forest ecosystems, and in others reduces the area of land that will be used for food production, regional plans in some countries have proposed converting agricultural land that, through poor existing management has resulted in poor soil fertility and low agricultural productivity. One of those regions is the Eastern Plains of Colombia.

A cooperative study involving expertise from CORPOICA (former governmental Institute for Agricultural Research in Colombia); “Agroecosystems National Program” (Programa Nacional de Agroecosistemas de CORPOICA) and technical information from the oil palm sector (FEDEPALMA—The National Federation of Oil Palm Growers) established that Colombia has 3.5 million hectares with no climatic or edaphic limitations for oil palm cultivation. Of these, 70% are located in the Eastern Plains Region (Romero et al., 1999). The Eastern Plains covers approximately 104 million hectares which represents about 17% of the Colombian land mass (Cochrane and Sánchez, 1981). Soils are characterized as highly acidic and infertile Oxisols and Ultisols, dominated by kaolinite and the oxides and hydrous oxides of iron and aluminium, with large P-fixation rates (Bartoli et al., 1992). Current agriculture mostly comprises pasture of low nutritive value (Alvarez and Lascano, 1987) and low animal productivity (Paladines and Leal, 1979; Kleinheisterkamp and Häbich, 1985). Studies have reported that the productivity and nutritional value of grasslands at the Eastern Plains is low and that management practices for both short-cycle cropping and/or cattle raising are highly detrimental to soil and environmental quality, e.g. the high use of machinery, no incorporation of organic residues in the soil and use of fire for establishing or renewing grasslands (Rippstein et al., 2001; Espina et al., 2005). Thus, replacing short-cycle crops and cattle farming with oil palm is considered as a potentially positive feature in the development of the region. This view is shared by a number of authors who emphasize the positive ecological characteristics of the oil palm crop in comparison with short-cycle crops and cattle rearing (Abraham, 1992). Additionally, the region has been badly affected by the conflict in Colombia. It is recognized that employment is the key stabilizing factor for the region. Within this context, a sustainable productive agricultural activity, like oil palm production, is part of the Colombian government strategy for resolving the conflict on a regional scale. According to the national report on human development *El conflicto callejón con salida*, 2003 (United Nations Development Programme, 2003), “The Conflict, A Way Out of the Impasse”, oil palm plantations are part of the so-called Colombian enclave economies, which have the possibility to help solve problems such as poverty and social disintegration. There are also on-going plans to develop farmer associations and reinsert former rebel fighters as employees in some oil palm companies. The overall aim is that new types of oil palm companies would be able to contribute to peace building and help eradicate poverty. It is clear that given the correct policy, development of the oil palm industry in the Eastern Plains represents an opportunity to achieve oil palm production in a sustainable and sound socio-economic management regime.

Such an ambitious regional development and extension of oil palm cultivation as that proposed in the Eastern Plains can only be achieved with enormous investment. One of the heaviest initial investments is the production of oil palm plants in the nursery and even after plantation establishment, nurseries are constantly required to provide plants for areas that are replanted on a 25-year cycle. The proposed extension of oil palm plantation in the Eastern Plains (Los llanos) region by up to 3 million hectares over the next 10 years means that 480 million oil palms will have to be established in plantations (plantation tree density 160 palms ha⁻¹). However, nurseries in Colombia typically lose 30% of plants because they either die in the nursery, die during transplantation or do not reach the correct developmental stage at the right time for transplantation into the field because of the enormous size inequality among nursery plants. In other countries, losses in nurseries are similar. In the Eastern Plains region, given the 30% loss at the nursery stage, this would require growing approximately 685 million nursery palms at an estimated cost of between approximately 3420

million and 4800 million Euros. Thus, if application of AMF could reduce costs by 1 Euro per plant then this would result in a saving in investment of approximately 685 million Euros. The lower estimate of the cost in Euros of the 30% loss of nursery plants is 1025 million Euros.

A key and an extensive study conducted in Indonesia by Schultz (2001), indicated that application of AMF could considerably reduce losses in the nursery. Schultz (2001) used 12 selected AMF isolates in an attempt to improve the survival and *post vitro* development of oil palm plantlets during micropropagation. Eleven AMF isolates significantly improved the survival rate (83–100%), by helping the plantlets resist environmental stress induced at transplanting from axenic conditions to normal cultivation in open pots. In contrast, only 55% of the non-inoculated control plants survived during the 3-month experimental period. The isolates used were also highly effective in promoting plant growth. The shoot dry weights of plantlets which were inoculated with these fungal isolates significantly increased compared to the non-inoculated plants. Schultz (2001) concluded that inoculation at the nursery stage would be beneficial as she demonstrated that, in tropical soils, seedlings were frequently grown in substrates with low pH (typically between 4 and 6). Under these conditions, inoculation with AMF was an important factor in facilitating plant acquisition of P from any fertilizers applied in conjunction with inoculum.

Other than the study by Schultz (2001) on AMF effects on survival, most experimental work on AMF effects on oil palm have concentrated on whether AMF improve oil palm growth. From the economic perspective, increases in growth may reduce costs but the potential saving by improving survival is greater. This has been largely overlooked by researchers. The effects on survival seen by Schultz (2001) could lead to enormous savings in investment in the nursery.

The study by Schultz (2001) also highlights another misunderstood aspect of AMF effects on plant growth that has also been overlooked when considering AMF application. Numerous studies show that different AMF species have highly variable effects on plant growth (Van der Heijden et al., 1998a,b; Bever et al., 2001; Vogelsang et al., 2006). The largest variation in plant growth is often seen in those plant species that are the most dependent on AMF for their growth (Van der Heijden et al., 1998a). The available data indicate that the African oil palm is highly dependent on AMF for its growth (Blal et al., 1990; Schultz, 2001). At first glance, it would seem, therefore, that taking any AMF inoculum, irrespective of its identity, would probably improve oil palm growth. However, the study by Schultz (2001) shows that enormous variation in oil palm growth can occur according to the isolate of AMF used for inoculation. In that study, eleven AMF species were shown to have positive effects on palm growth, development and nutrition for the variables shoot length, leaf development, relative growth rate, root and shoot fresh and dry weights, total P uptake per plant, N concentration and total N uptake per plant. However, the effect on all of these growth and nutritional measurements varied greatly among AMF species. This means that there is a very good rationale to isolate AMF that will have particularly large growth and nutritional effects on oil palm in the local soil type as they could lead to a much more efficient production than simply selecting any AMF inoculum that is commercially available or relying on that already present in the unsterilized soil.

Schultz (2001) also observed that the four AMF isolates that improved palm growth the most also had positive effects on palm post-transplant survival. However, there was 17% variation in effects on survival showing that the biggest economic effect of AMF application would require selection of isolates with a combination of beneficial growth effects, as well as post-transplant survival. Given the high costs in terms of loss of nursery plants, a 17%

variation in survival represents a minimum investment saving of 580 million Euros in the regional plan for the Eastern Plains. However, more experiments are needed to accurately address the potential saving made by inoculation. Furthermore, for realistic and efficient commercial production of the isolates for use in oil palm nurseries, the isolates would also have to be selected for, not only beneficial effects, but also for rapid growth in the system designed for inoculum production. Therefore, in order to use AMF efficiently in oil palm production, a clear research goal is to isolate AMF from local soils that have the combined characteristics of growth and nutritional effects on oil palm, effects on post-transplant survival and efficient growth in the culture conditions for inoculum production.

5.3. The role of oil palm genetics and oil palm response to AMF application

Many plants show a growth response to AMF. However, recent studies have shown that genetic variation within a given plant species also results in considerable variation in mycorrhizal responsiveness. Mycorrhizal responsiveness has also been shown to vary among cultivars of crop plants including *Zea mays* (Kaeppeler et al., 2000), *Avena sativa* (Koide et al., 1988), *Hordeum vulgare* (Zhu et al., 2003), *Triticum aestivum* (Zhu et al., 2001; Li et al., 2006), tomato (Bryla and Koide, 1990a, 1990b), soya (Bethlenfalvay et al., 1989). The variation in mycorrhizal responsiveness with genetically different oil palm has not been previously investigated and is certainly justified. It is quite possible that certain varieties of oil palm would be much more responsive to AMF inoculation than others. A combined plant and fungal genetics approach is certainly warranted to identify optimal combinations of mycorrhizal responsive oil palm varieties with the most beneficial AMF isolates from local soils. In Colombia and other parts of South America, there is good potential for using the American oil palm and hybrids might represent a better candidate as a source of oil. The use of hybrids would increase yields per unit area, in addition to increasing oil quality, which is higher in the American than the African oil palm. There are a growing number of new plantations and re-planting of existing plantations being carried out with an inter-specific hybrid between *E. guineensis* and *E. oleifera*. To date, there are no published studies that have investigated the mycorrhizal responsiveness of either the American oil palm or American $\times$ African oil palm hybrids. Native Colombian AMF inoculants could potentially play a key role in the use of the American or hybrid palm for palm oil production in Colombia and investigation of the mycorrhizal responsiveness of these plants is certainly warranted.

5.4. Application of AMF in existing oil palm plantations

When seedlings have matured and are transplanted to the field, the benefits of mycorrhizal inoculation become much less apparent. Planting holes are often heavily fertilized and hence may inhibit any mycorrhizal infection established in the outplants from developing with the growing roots. However, as the P levels drop as the plant grows and matures indigenous mycorrhizal fungi from the surrounding soil will begin to colonise and develop in the growing root system thus negating the need for inoculum. Cultural practices already established in plantations may aid this process. For example, the interplanting of *Pueraria* between rows of outplanted oil palm as practised in Univanich, Thailand (Palat, pers. comm.) will stimulate natural populations of AM fungi in the soil around the outplanted oil palm and improve efficiency of N-use in following crop. Similar practices are used in Colombia. However, many of the anecdotal reports about failure of a growth response in oil palm following inoculation has been carried out in

plantations where the benefits of inoculation are clearly less easy to achieve than in the nursery situation.

6. Conclusions

There are certainly doubts as to whether mycorrhizal inocula have a real potential to improve oil palm productivity in established plantations and especially if growers continue high P inputs. Nevertheless, the fact that oil palm is very responsive to mycorrhizas means that there is potential to exploit this symbiosis. If the grower has no concerns about the economic costs or environmental downside of using high levels of P fertilizer, then there are probably few benefits from introducing arbuscular mycorrhizal fungi into plantations. However, there is a clear rationale for their use in the nursery, given the cost of producing nursery plants and the levels of fertilizer used that almost certainly inhibit development of the symbiosis. One barrier to increasing the percentage of palm oil certified as sustainable by the RSPO is the increased costs. Using AMF to reduce fertilizer applications in the nursery to help meet RSPO criteria for sustainable production, coupled with the enormous potential reduction in costs by addressing the issue of mortality and poor growth in the nursery and subsequent survival during transplantation, could result in overall cost benefits and certainly warrants further investigation.

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