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REVIEW

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Acacia mangium Willd: benefits and threats associated with its increasing use around the world

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Abstract

Background: *Acacia mangium*, a fast-growing tree native to parts of Indonesia, Papua New Guinea and Australia, has been cultivated outside its native environment and introduced into humid tropical lowland regions of Asia, South America and Africa over the last few decades. It is a multipurpose tree used in agroforestry, forestry and for restoration of degraded lands. It is also highly invasive in many regions where it has been introduced outside its native range. This paper reviews evidence of its obvious benefits and its negative impacts on biodiversity.

Methods: A literature review on Australian acacias and especially on *A. mangium* was undertaken to highlight both benefits and threats associated with their increasing worldwide use outside their native ranges.

Results: Through N_2 fixed from the atmosphere, *A. mangium* improves soil fertility, especially by increasing N status and soil C accretion when introduced to N-limited areas; it thus has the potential to restore nutrient cycling in degraded systems. No studies have, however, been done to assess the effectiveness of *A. mangium* in restoring biodiversity of degraded lands. Most Australian acacias have traits that facilitate invasiveness, and 23 species have been recorded as invasive to date. *A. mangium* has been reported as invasive in Asia, Indonesia, Pacific Islands, Indian Ocean Islands, southern Africa and Brazil. Research on other invasive Australian acacias in several parts of the world has elucidated the types of impacts that are likely in different types of ecosystems and key options for mitigating impacts.

Conclusions: *A. mangium* has the potential to restore nutrient cycling in degraded systems, but is highly invasive wherever it is planted. Many parts of the world have a large invasion debt for this species. Experience with other invasive acacias around the world suggests a suite of interventions that could be used to reduce invasions and mitigate impacts. Careful risk assessments should be undertaken prior to any new plantings of this species.

Keywords: Biodiversity, Biological invasions, C sequestration, Soil N status, Tree invasions

Background

Due to their diverse uses, tropical Australian acacias are widely planted around the world – in Asia where they were first introduced (Midgley and Turnbull 2003; Inagaki et al. 2011; Richardson et al. 2011), Africa (Bernhard-Reversat 1993; Tassin et al. 2012; Dubliez et al. 2018) and South America (Franco and de Faria, 1997; Chaer et al. 2011; Attias et al. 2013). They are used in agriculture, forestry and agroforestry to improve soil fertility (especially soil nitrogen), to sequester carbon and potentially to restore nutrient cycling in degraded lands and forests, but also for commercial forestry, for ornamental purposes, and to supply wood and charcoal (Bernhard-Reversat 1993; Franco et al. 1994; Parrotta and Knowles, 1999; Fuentes-Ramírez et al. 2011; Bouillet et al. 2013; Sitters et al. 2013; Permadi et al., 2017). Forest productivity or crop yields usually increase on N-limited sites in the presence of N-fixing species (NFS) such as Australian acacias (Binkley 1992; Khanna 1998; Bouillet et al. 2013; Nambiar and Harwood 2014; Paula et al. 2015; Dubliez et al. 2018), as does soil N status (Sanginga et al. 1986; Binkley 1992; Parrotta, 1999; Kaye et al. 2000; Resh et al. 2002; Ludwig

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et al. 2004; Hagos and Smit 2005; Sitters et al. 2013). Most Australian acacias have the capacity to sequester C in both soil and biota which also addresses goals associated with climate-change mitigation (Binkley 1992; Kaye et al. 2000; Resh et al. 2002; Lee et al. 2015; Forrester et al. 2013), though soil C storage may not occur in some cases (Voigtlaender et al. 2012; Oelofse et al. 2016).

Most Australian acacias have traits associated with invasiveness. Twenty-three species have been recorded as invasive to date, and some are major invasive species in many geographical areas (Richardson and Rejmánek 2011; Gibson et al. 2011; Rejmánek and Richardson 2013; Richardson et al. 2015). In documenting the global biogeography and invasion ecology of Australian acacias, Richardson et al. (2011) showed that all species that have been widely planted for forestry or other uses have become invasive. Whether an alien species becomes invasive depends on many factors, including life-history traits and the extent, level, and duration of species usage in the new environment. Considerable work has been done in this regard on Australian acacias. Interactions between traits, human usage, and residence time explain the extent of invasiveness for acacias (Castro-Díez et al. 2011). There is usually a long time lag between introduction and planting and the start of invasive spread; this results in a substantial 'invasion debt' in many areas where the widespread planting of alien species has occurred recently (Rouget et al. 2016).

A. mangium, one of the Australian acacias that is widely planted in many parts of the world, has clear benefits in agricultural, agroforestry and forestry ecosystems (Bernhard-Reversat 1993; Franco et al. 1994; Parrotta and Knowles, 1999; Richardson et al. 2004; Kull et al. 2011; Epron et al. 2013). Key reasons for the widespread planting of *A. mangium*, in commercial monoculture plantations or in mixed plantings with other tree species or crops in areas with infertile soils, are its capacity to improve soil fertility (Wang et al. 2010; Forrester et al. 2013; Koutika et al. 2014; Machado et al. 2017; Tchichelle et al. 2017), change the soil faunal, microbial and bacterial communities (Bernhard-Reversat 1993; Bini et al. 2012, 2013; Huang et al. 2014; Pereira et al. 2017), and to stimulate crop or tree growth and forest productivity (Bouillet et al. 2013; Epron et al. 2013; Paula et al. 2015). The species is considered useful for these purposes due to the enhanced nutrient cycling, higher nutrient availability and microbial activities that accrue from its presence (Khanna 1998; Bini et al. 2012; Rachid et al. 2013; Santos et al., 2017a, b). Introduction of *A. mangium* to agricultural, agroforestry or large open areas is, however, increasingly being shown to trigger major biological invasions. The number of publications documenting the invasive spread of *A. mangium* from planting sites is increasing rapidly; the species is currently recorded as an invasive species in Asia, Indonesia, southern Africa and South America (Richardson and Rejmánek 2011; Ismael and Metali 2014; Aguiar et al. 2014; Meira-Neto et al. 2018; Souza et al. 2018). Such invasions are reducing the overall benefit from using the species and is creating conflicts of interest between (agro) foresters on the one hand and conservationists and natural resource managers on the other. Such conflicts are arising in many temperate regions of the world where other Australian *Acacia* species (and other legume trees) have been planted outside their native range. Management initiatives are underway in many areas to reduce such conflicts (e.g. Kull and Rangan 2008; Dickie et al. 2014; van Wilgen and Richardson 2014; Shackleton et al. 2018 and references therein).

Australian acacias are favoured for planting because of their high adaptability; climatic modelling shows that roughly a third of the world's land areas are suitable for growth of Australian acacias (Richardson et al. 2011). The largest area of plantations of tropical Australian acacias is in South East Asia where plantings cover about 2 Mha (Midgley and Turnbull 2003; Arisman and Hardiyanto 2006; Kull and Rangan 2008). *A. mangium* Willd., a large tree which can reach 30 m in height, is native to parts of Indonesia, Papua New Guinea and Australia. The species produces many flowers and is mainly pollinated by bees (Midgley and Turnbull 2003). It grows in coastal, tropical lowlands (at altitudes below 300 m) and in a range of forest types (rainforests to open forests), but also in woodlands disturbed by fire (Midgley and Turnbull 2003). The natural distribution of *A. mangium* overlaps with the warm and hot tropical climatic zones where the temperatures are high and equable throughout the year, with the mean maximum temperature during the hottest month between 31 °C and 34 °C and the mean minimum temperature during the coolest month between 15 °C and 22 °C (Otsamo et al. 1997; Midgley and Turnbull 2003). Mean annual rainfall across its natural range is between 1500 and 3000 mm, with summer (January to March) being the wettest period. This fast-growing species prefers well-drained soils of moderate to low fertility (Franco et al. 1994; Cole et al. 1996; Bouillet et al. 2013; Aguiar et al. 2014). Extended dry season and sandy and nutrient-poor soils outside its native range may, however, trigger growth during the first year (Koutika et al. 2018). Like many acacia species, *A. mangium* is adapted to acidic soils, and grows in soils with pH below 4 (Franco and de Faria, 1997; Midgley and Turnbull 2003).

This paper reviews the benefits and threats of *A. mangium* in areas where it is planted outside its native range, and discusses whether it is feasible to promote planting of the species to encourage the benefits it provides while reducing current and potential future negative impacts due to invasiveness.

Methods

Literature review

Using keywords associated with 'Australian acacias' and '*A. mangium*' we undertook a detailed review of peer-reviewed papers, books, book chapters, conference proceedings, online publications and the grey literature. We used Google, Google Scholar, Web of Science, and the databases of research institutions, notably EMBRAPA (Brazilian Agricultural Research Corporation), CIMMYT (The International Maize and Wheat Improvement Center), Université de Lorraine (France), and the Centre for Invasion Biology (Stellenbosch University) to source information on the benefits and impacts associated with the use of Australian acacias, and particularly *A. mangium*, outside their native ranges.

Acacia mangium and its changing global distribution

A. mangium is widely used in commercial plantations to provide products such as pulp, firewood, charcoal, construction material; it is also used for soil protection and ecological restoration purposes and as a food source for bees (Awang and Taylor 1993; Franco and de Faria, 1997; Otsamo et al. 1997; Midgley and Turnbull 2003; Eyles et al. 2008; Kull and Rangan 2008; Coetzee et al. 2011; Hai et al. 2015). Key life-history traits of the species are its rapid growth, prolific production of hard-coated, heat-tolerant and long-lived seeds with the capacity for long dormancy and long-distance dispersal by birds (Awang and Taylor 1993; Franco et al. 1994; Gibson et al. 2011; Low 2012). *A. mangium* has been widely cultivated outside its native range in the last century, mainly in the humid tropical lowlands of Asia, South America and Africa (Bernhard-Reversat 1993; Otsamo et al. 1997; Franco and de Faria, 1997; Kull et al. 2007; Hai et al. 2015; Oelofse et al. 2016, Table 1). The species was first introduced to Malaysia in 1966 where it was initially planted for firebreaks and to protect pine plantations, but its rapid growth suggested potential for wood

Table 1 First introduction of *Acacia mangium* and current levels of planting in some countries around the world. Seeds of *A. mangium* were also dispatched from Australian Tree Seed Centre to the following countries for which detailed planting details are not available (decade that seeds were first dispatched in brackets): Cambodia (1980s), Central African Republic (2000s), Colombia (1980s), Cote d'Ivoire (1980s), India (1980s), Laos (1980s), Mexico (1980s), Mozambique (1980s), Myanmar (1980s), Sri Lanka (1980s), Tanzania (1980s), Thailand (1980s), Uganda (1980s) and Venezuela (1980s)(Australian Tree Seed Centre, unpublished data)

Countries / Time	First introduction & purpose(s)	Initial planted areas	Current level of plantings	Key references
Asia				
China	1979	NA	NA	Yang et al. 2009
Indonesia	Native (eastern part) 1960s	NA	300,000–500,000 ha (2013)	Midgley and Turnbull 2003; Nambiar & Harwood 2014; Nambiar et al. 2018
Malaysia	1966, Forestry& restoration	15,000 ha degraded lands	250,000 ha (2013)	National Research Council 1983; Midgley and Turnbull 2003; Nambiar & Harwood 2014; Nambiar et al. 2018
Philippines	1977	NA	NA	National Research Council 1983
Vietnam	1960s (southern part), 1980s (northern part), Genetic improvement, reforestation, reclamation	580,000 ha	600,000 ha (2013)	Kull et al. 2011; Nambiar et al. 2014; Nambiar & Harwood 2014; Frey et al. 2018
Africa				
Cameroon	1980, Planting program	NA	NA	National Research Council 1983
DR Congo	1980s, Agroforestry	NA	NA	Tassin et al. 2012
Kenya	1980s	NA	NA	Kenya Forestry Research Organization (KEFRI)
Republic of the Congo	1990s, Experimental plantations	NA	NA	Bernhard-Reversat 1993
America				
Brazil (Roraima)	1990s, Commercial forestry	30,000 ha	NA	Souza et al. 2018
Costa Rica	1980, Planting program	NA	NA	National Research Council 1983
Dominican Republic	1980s, Social forestry	NA	NA	Kull et al. 2011
Hawaii	1979, Planting program	NA	NA	National Research Council 1983

NA Not Available

production (Midgley and Turnbull 2003). Kull and Rangan (2008) reported that in the 2000s, both Malaysia and Indonesia had nearly 850,000 ha of commercial plantations of *A. mangium*. In South America, *A. mangium* has been introduced for different purposes. Commercial cultivation for pulpwood production and tannin and plantings for the reclamation of degraded lands were main reasons for the introduction of *A. mangium* to Brazil (Franco and de Faria, 1997; Attias et al. 2013), while in northeastern Costa Rica the species has been used mainly for restoration plantations (Chazdon 2008).

In South East Asia, species such as *A. mangium* and *A. auriculiformis* are used mainly for solid wood production and short-rotation fibre (Midgley and Turnbull 2003). Due to their large canopies and ability to increase soil N and soil organic matter (SOM), to improve conditions for photosynthesis, and to buffer air and soil temperatures, *A. auriculiformis* and *A. mangium* have been widely planted in degraded areas to serve as nurse trees for understorey plants in South China (Yang et al. 2009). In Central Africa, *A. auriculiformis* and *A. mangium* have been planted as part of Project Makala (http://makala.cirad.fr/le_projet_makala) for fuel and wood energy e.g., in DR Congo and the Republic of the Congo. Both species were also planted for agroforestry and forestry in the two countries. *A. auriculiformis* is valued by farmers for both agricultural and wood-energy production in agroforestry or forestry systems in DR Congo (Kasongo et al. 2009; Shure et al. 2010; Dubliez et al. 2018), while *A. mangium* is mainly used to sustain eucalypt plantations to provide pulp, fuel and wood energy in the Congolese coastal plains of the Republic of the Congo (Shure et al. 2010; Bouillet et al. 2013; Epron et al. 2013; Tchichelle et al. 2017).

History and extent of invasiveness of *A. mangium*

In some countries, *A. mangium* is considered an invasive tree species (Richardson and Rejmánek 2011; Low 2012; Rejmánek and Richardson 2013; Attias et al. 2013; Aguiar et al. 2014; Sampaio and Schmidt 2013; Richardson et al. 2015; Witt 2017; Souza et al. 2018). We could find no statistics on the extent of invasions or the area invaded in different regions. In northeastern Roraima State, Brazilian Amazonia, invasions commenced within a decade of the establishment of large plantations, and invading plants were recorded up to 900 m from the plantation edge (Aguiar et al. 2014). Table 1 shows that introductions and major plantings of *A. mangium* are recent in most parts of the world; experience in South Africa has shown that major invasions of Australian acacias typically occur only several decades after major plantings began (Richardson et al. 2015). This means that most of the countries mentioned in Table 1 have a major invasion debt (Rouget et al. 2016) for *A. mangium* and that large-scale invasions are likely to occur over the next few decades.

Benefits of using *A. mangium* for ecosystems and the environment

Improving soil nitrogen status

Nitrogen-fixing species (NFS) have the ability to improve soil N status. For example, *Leucaena leucocephala* (Lam.) de Wit, a NFS, provided more than 500 kg of N $ha{\cdot}y^{-1}$ (Sanginga et al. 1986). Parrotta (1999) reported higher N accretion in *L. leucocephala* stands relative to pure eucalypt stands or when grown in association with another NFS, *Casuarina equisetifolia* L. *Acacia auriculiformis*, established as fallow in the mixed crop food systems on sandy arenosols in DR Congo, increases soil N (Kasongo et al. 2009). *A. auriculiformis* and *A. mangium* were planted to serve as nurse trees for understorey plants in degraded soils in South China (Yang et al. 2009). Higher soil N status was found in *A. mangium* relative to *A. auriculiformis* - a total soil nitrogen of 0.103 ± 0.02% vs. 0.092 ± 0.01% and a hydrolysed nitrogen of 105.7 ± 16.9 $mg{\cdot}kg^{-1}$ vs 89.3 ± 3.78 $mg{\cdot}kg^{-1}$ (Table 2). Soil N status improved in the pure *A. mangium* relative to pure eucalypt stands with the cumulative net production of mineral N over the two first years in the second rotation of 7 years i.e., 343 $kg{\cdot}ha^{-1}$ in acacia and only 189 $kg{\cdot}ha^{-1}$ in eucalypt stands in the Congolese coastal plains (Tchichelle et al. 2017). This has been confirmed by the 30% higher N concentration in coarse particulate organic matter (POM, 4000–250 μm), an active part of soil organic matter, in pure *A. mangium* stands compared to pure eucalypt stands at year 2 of the second rotation (Koutika et al. 2017). These findings are in accordance with the reduction in N-limitation to growth shown by an increase in N: P ratio of eucalypt leaves from 9.4 ± 0.5 (end of the 7 first year rotation) to 13.1 ± 0.6 (year 2 of the second rotation) (Koutika et al. 2016), and the improvement in soil N status of afforested stands containing acacias compared to natural savannas (Koutika and Mareschal 2017).

Potential to restore degraded lands

We found no published evidence to support the contention that the planting of Australian acacias aids in restoring biodiversity levels or the conservation value of degraded ecosystems. Several Australian acacias do, however, have the potential to restore elements of nutrient cycling in degraded ecosystems (Franco and de Faria, 1997; Yang et al. 2009; Sang et al. 2013; Machado et al. 2017). NFS, including *A. mangium*, have the potential to rehabilitate degraded lands (Otsamo et al. 1997; Wang et al. 2010; Richardson et al. 2015; Permadi et al., 2017, Table 2), unmanaged secondary forests (Sang et al. 2013) and understorey plants (Yang et al. 2009). The ability to

Table 2 Benefits of planting *Acacia mangium* in terms of land restoration, C sequestration, soil fertility and tree production in different ecosystems

Original ecosystem / habitat	Current ecosystem	Country	Soil type	Soil fertility				Tree productivity	Reference
				Nitrogen status	Phosphorus status	Carbon status	Soil fauna/ microbial status		
Savannas	Acacia plantations	Republic of Congo	Arenosols	NA	NA	NA	Higher activity of macroar-thropods, incl. Cockroaches	NA	Bernhard-Reversat 1993
Degraded areas	Revegetating tailing tanks	Brazil	Tropical soils	Increased (190 kg of N $ha^{-1}\cdot y^{-1}$)	NA	Increased	NA	NA	Franco and de Faria, 1997
Eucalyptus siebiri	Mixed-species plantations	Australia	Sandy clay loam	+	NA	Increased soil C	NA	Increased	Forrester et al. 2013
Pinus massoniana plantation	Eucalypt and acacia plantations (1978)	China	Oxisol	Increase in NH_4-N, NO_3-N, and total N in the mixed species plantations	NA	Increase in total C	Changes in microbial communities	NA	Huang et al. 2014
Plantations	Mixed-species plantations with *A. mangium*	Malaysia	Haplic Alisols	More N in the litterfall	Less P in the litterfall	NA	NA	NA	Inagaki et al. 2011
Savannas/ Eucalypt plantations (1984)	Eucalypt and acacia plantations (2004)	Republic of Congo	Arenosols	Increase in N stocks (0–0.25 m)/ Increase in N contents of coarse POM (4–0.25 mm) Increase in N mineralization in pure acacia	Decrease in available P in the mixed species stands (0–0.15 m)	Increase in C stocks (0–0.25 m)	NA	Eucalypt benefits from N_2 fixed by acacia	Koutika et al. 2014; Koutika et al. 2017; Epron et al. 2013; Tchichelle et al. 2017
Degraded lands with low fertility	*A. mangium* plantations	Malaysia		NA	NA	Increased	NA	Increased	Lee et al. 2015
Eucalyptus	Eucalypt and acacia plantations	Brazil	Ferralsol	–	–	–	Higher activity of microbial and bacterial communities	–	Pereira et al. 2017, Pereira et al. 2018
Degraded tropical lands	*A. mangium*	Vietnam	–	Increased	NA	NA	NA	NA	Sang et al. 2013
Fallow for more than 15 years	Eucalypt and acacia plantations	Brazil	Haplic Planosol	More N in the litterfall of acacia vs eucalypt	More P in the litterfall of eucalypt vs acacia	NA	NA High microbial activity	Eucalypt benefits from N_2 fixed by acacia	Santos et al. 2017a; Santos et al. 2017b;
Disturbed evergreen broadleaved forest	Restored forest with *A. mangium* and *A. auriculiformis*	China	Red soil	+	NA	+	+	Good nurse plants for understory species	Yang et al. 2009

Table 2 Benefits of planting *Acacia mangium* in terms of land restoration, C sequestration, soil fertility and tree production in different ecosystems *(Continued)*

Original ecosystem / habitat	Current ecosystem	Country	Soil type	Soil fertility				Tree productivity	Reference
				Nitrogen status	Phosphorus status	Carbon status	Soil fauna/ microbial status		
Degraded lands	Mixed species plantations	China	–	20%–50% higher N than non-N-fixers counterpart	–	40%–50% higher SOM than non-N-fixers counter-part	NA	Land restoration	Wang et al. 2010

NA Not Available
"+" and "-" indicate positive and negative effects, respectively

form symbioses with nodulating N_2-fixing bacteria and arbuscular mycorrhizal fungi of leguminous trees is key in this regard (Chaer et al. 2011). Franco and de Faria (1997) showed that *A. mangium* may provide around 12 tons of dry litter and 190 kg of N $ha^{-1} \cdot y^{-1}$ to restore degraded lands in Brazil. The effects of monospecific plantations of *A. mangium*, *Dipteryx odorata*, *Jacaranda copaia*, *Parkia decussata*, and *Swietenia macrophylla* established in pasture areas on soil chemical properties were evaluated in the Brazilian state of Amazonas (Machado et al. 2017). These authors advised planting *A. mangium* and *S. macrophylla* to rehabilitate degraded areas because of their important role in cycling of N and P, the most limiting nutrients in the soil for tropical forest productivity. Re-establishment of soil C and N cycling processes were reported after planting of *A. auricu liformis* and *A. mangium* in southern China (Wang et al. 2010). For economic reasons (e.g., low cost of reforestation, the positive correlation between C sequestration, N and P amounts and aboveground biomass production) *A. mangium* is considered superior to *Eucalyptus urophylla* across edaphic and climate gradients in Vietnam (Sang et al. 2013).

Enhancing carbon sequestration

NFS often have beneficial impacts on climate change mitigation in reducing atmospheric CO_2 by sequestering C in both soil and biota (Binkley 1992; Chen et al. 2011; Sang et al. 2013). In most cases, carbon sequestration in soil and biomass occurs when NFS are introduced to agricultural, agroforestry, and forestry systems (Binkley 1992; Resh et al. 2002; Kasongo et al. 2009; Chen et al. 2011; Forrester et al. 2013; Sang et al. 2013; Dubliez et al. 2018). C sequestration occurred in both soil and aboveground biomass in *A. mangium* plantations in Malaysia, with higher soil C stocks, ranging between 52.2% to 87.5% of the total C (soil and biomass) stocks, while the overall C stocks were 74.9, 89.9 and 138.9 $t \cdot ha^{-1}$ for 1-, 3-, and 5-year-old stands (Lee et al. 2015). C accretion has been reported down to 25 cm in the mixed-species (50% acacia and 50% eucalypt) stands ($17.8 \pm 0.7\ t \cdot ha^{-1}$) compared to pure acacia ($16.7\ t \cdot ha^{-1}$) and eucalypt stands ($15.9\ t \cdot ha^{-1}$) at the end of the first 7-year rotation in the Congo (Koutika et al. 2014). This may be attributed to both the lower turnover of old C and a higher accretion of new C (Resh et al. 2002). Another beneficial impact of *A. mangium* is its ability to contribute to climate-change mitigation goals, since emissions of N_2O, one of the main greenhouse gases, may be reduced by the application of its bark tannins in water-saturated soil (Matsubara and Ohta 2015).

Stimulating microbial activity and P availability

Accrual in nutrients as soil N, P and C in *A. mangium* monocultures or in *A. mangium* mixed with non-N-fixing species is due to more effective and higher nutrient cycling and availability (Santos et al. 2017a) and greater stimulation of microbial activity and dynamics in the litter (Bini et al. 2012; Pereira et al. 2018, Table 2). Distinct microbial communities have been reported in mixed *A. mangium*/*E. urograndis* plantations, which specific role for each species e.g., inducing an increase in nitrate amounts in the pure *A. mangium* stands (Rachid et al. 2013). Microbiological and chemical changes occurring in soil due to leaf litter accumulation in the intercropped plantations of eucalypt and *A. mangium* stimulate and favour plant growth (Bini et al. 2013). Litter decomposition depended on C quality i.e., water soluble compounds and lignin content, but also on the activity of decomposers, which may be limited by energy starvation and by P deficiency, common in most tropical planted forests (Bachega et al. 2016). This common P deficiency may be partly alleviated by introducing tree NFS and non-fixing species in nutrient poor ecosystems such as savannas or grasslands (Sitters et al. 2013; Koutika and Mareschal 2017). Planting acacias and eucalypts in nutrient-poor savanna soils in the coastal Congolese plains, induced an increase in soil available P in the coarse particulate organic matter (4000–250 μm) relative to savannas (Koutika and Mareschal 2017).

Sustaining forest productivity

A. mangium has a positive impact on tree growth and forest productivity (Epron et al. 2013; Forrester et al. 2013; Nambiar and Harwood, 2014; Santos et al. 2017a). At the end of the first 7-year rotation of *A. mangium* and *Eucalyptus urophylla* × *grandis* plantations established in the Congolese coastal plains, eucalypt growth had benefitted from the N_2 fixed by *A. mangium,* as shown by the higher wood biomass in the mixed-species than in pure eucalypt stands (Epron et al. 2013). Using ^{15}N pulse-labelling, Paula et al. (2015) demonstrated the below-ground transfer of N from *A. mangium* to *Eucalyptus grandis* trees in the field in the first few days after labelling in a Brazilian planted forest, revealing the facilitation process which may ensure a significant amount of required N to neighbour trees. *A. mangium* increased the capacity of forest plantations to exploit soil deep layers when introduced alone or in mixtures with non-fixing species trees (Germon et al. 2018). Since *A. mangium* is not only renowned for its commercial uses for wood (pulp and solid) and energy, but also for its capacity to establish easily and grow rapidly in marginal land, it has been adopted and is widely preferred over other acacia species and other NFS for enhancing afforestation strategies and for improving the social welfare of smallholders in various forest transition stages in Indonesia (Permadi et al., 2017).

Limitations of *A. mangium*: From benefits to threats

The multipurpose tree *A. mangium* has shown many benefits outside its native range as described above. *A. mangium* may, however, have limitations for improving soil fertility and forest productivity, sequestering C, and driving land restoration. Monospecific plantations of four native species (*Dipteryx odorata*, *Jacaranda copaia*, *Parkia decussata*, and *Swietenia macrophylla*) and the exotic *A. mangium* established to restore pasture areas, have shown a decline in silvicultural performance e.g., biometric data, crown projection area, total height, commercial cylinder volume etc. of *A. mangium* compared to other species (Machado et al. 2018). These authors did not recommend *A. mangium* for restoration because of its limited performance in relation to most of the variables that were assessed. Similarly, Parrotta and Knowles (1999) reported poor performance of fast-growing species (i.e. eucalypt and acacia species) in facilitating the rehabilitation of mined areas in Brazil. *A. mangium* does not benefit the successional processes in Amazonian forest, compared to other restoration criteria. Although tree basal-area development of mixed commercial species was superior to all other species, they had low species richness (Parrotta and Knowles, 1999). Similarly, *A. mangium* did not sequester C in an experimental plantation at Itatinga in Sao Paulo State, Brazil; soil C stocks were 44% lower in the forest floor of *A. mangium* stands than in eucalypt stands (Voigtlaender et al. 2012).

Large plantations of fast-growing exotic species on the Congolese coastal plains may exclude colonial breeding bird species such as rosy bee-eater *Merops malimbicus* and Congo River martin *Pseudochelidon eurystomina* which rely on large open grassy plains on the coast for their breeding colonies (Hugo Rainey, Wildlife Conservation Society, pers. comm.). Such findings reinforce the concerns that have been expressed regarding the widespread planting of Australian acacias outside their native range (Richardson and Rejmánek 2011; Wilson et al. 2011; Aguiar et al. 2014; Ismael and Metali 2014).

In the absence of empirical evidence of significant long-term benefits to native biodiversity levels following the introduction of *A. mangium*, recommendations regarding its use for the purpose of 'rehabilitation' in areas where the conservation of biodiversity is the primary objective should be informed by the 'Precautionary Principle' as outlined in the Rio Declaration in 1992 (Raffensberger and Tickner 1999). Principle 15 of this Declaration states that 'in order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall be not used as a reason for postponing cost-effective measures to prevent environmental degradation'. In practice, the 'Postcautionary Principle' which is states as 'Where there are threats of serious or irreversible damage, the lack of full scientific certainty shall be used as a reason for not implementing cost-effective measures until after the environmental degradation has actually occurred' (Paull 2007), is often applied in ecological impact assessments.

Threats to ecosystems and the environment from introducing *A. mangium*

Negative impacts on biodiversity

Despite the many reported benefits of *A. mangium* in agricultural, agroforestry and forestry systems, there is increasing evidence that because of its invasive properties, this species can exert profound negative impacts on soil, biodiversity, and human wellbeing. Commercial forestry plantations are mostly established in large open areas which are highly susceptible to invasions of alien trees (Richardson and Rejmánek 2011; Attias et al. 2013; Aguiar et al. 2014; Rundel et al. 2014). Osunkoya et al. (2005) argued that Australian acacias can easily invade disturbed and degraded forests, especially those that experience drought and fire. $\delta^{15}N$ isoscapes, a useful framework for evaluating the impacts of an invasive N_2-fixing species on the surrounding plants, has provided the means for quantifying the impact of invasive

NFS by combining range, abundance and per-capita effects (Rascher et al. 2012). Aguiar et al. (2014) documented that *A. mangium* may rapidly threaten the biodiversity of Amazonian savannas surrounding large-scale plantations, based on experiments conducted around five plantations in Roraima, Brazil. According to these authors, one of the reasons for its wide expansion in Brazil is its use in large commercial plantations in Amazonian savannas in the 1990s without a prior assessment of the risk of invasiveness. This is also the case in some Asian countries, notably Malaysia and Vietnam (Richardson and Rejmánek 2011; Richardson et al. 2015).

Invasions of *A. mangium* started only recently, and no detailed assessment has been done to determine the types of impacts that these invasions have on aspects of biodiversity and ecosystem functioning. However, Le Maitre et al. (2011) reviewed the types of impacts ascribed to other invasive Australian acacias in many parts of the world. They found that acacias have a wide range of impacts on ecosystems that increase with time and disturbance, and frequently transform ecosystem functioning, thereby altering and reducing the delivery of ecosystem services. The accumulation of massive stores of long-lived acacia seeds in the soil ensures persistence of the invader even with frequent and severe disturbances. This is the fundamental mediator of thresholds that facilitate major biotic and abiotic impacts (Gaertner et al. 2014). Widespread invasions of Australian acacias in many parts of the world have led to increasing conflicts of interest regarding the benefits and negative impacts of the species (Kull and Rangan 2008; Richardson and Rejmánek 2011; Wilson et al. 2011; Tassin et al. 2012; Ismael and Metali 2014; Aguiar et al. 2014; Kull et al. 2018; Souza et al. 2018).

Threats to human wellbeing

Research on the negative impacts of *A. mangium* invasions on human wellbeing began only very recently. In savanna areas surrounding indigenous lands in Roraima State, Brazil where 30,000 ha of *A. mangium* were planted for commercial purposes, Souza et al. (2018) undertook interviews in three communities. They found that *A. mangium* was perceived to have negative effects on the natural environment and on human livelihoods in the subsistence of their communities.

Negative impacts on soils

Changes in the functional diversity of soil microorganisms (mycorrhizal fungi and rhizobia) inhibited the growth of the native tree species *Faidherbia albida* and *Quercus suber* while restoring degraded lands in Senegal and Algeria with two Australian acacias, *A. holosericea* and *A. mearnsii* (Duponnois et al. 2013). Another Australian acacia, *A. dealbata*, established positive plant-soil feedbacks which are important mechanisms for its further invasion (Gaertner et al. 2014), and showed a strong competitive ability relative to the native trees (Rodriguez-Echeverria et al. 2013). *A. mangium* may have negative impacts on the concentrations of soil nutrients and neighbouring plants (Liu et al. 2017; Meira-Neto et al. 2018). In its early invasion stage, *A. mangium* is able to alter both soil and leaf nitrogen, increase shade and enable a wider range of light variation, which is facilitated by the nitrogen taken up and transferred to neighbouring plants (Meira-Neto et al. 2018). In plantations of acacia and eucalypt in the Congolese coastal plains, soil resin P availability decreased in the top soil in the mixed-species (50% acacia and 50% eucalypt) compared to pure eucalypt stands at the end of the first 7-year rotation (Koutika et al. 2014). This change in P was noticed further by a decrease in soil readily available inorganic P (resin and Pi-HCO_3) in acacia relative to pure eucalypt stands at year 2 of the second rotation compared to the end of the first rotation (Koutika et al. 2016). In the eucalypt and acacia plantations located in Rio de Janeiro state, Brazil, Santos et al. (2017b) demonstrated that eucalypt deposited greater quantities of P via litter, but little N, while acacia did the opposite. In subtropical China, Liu et al. (2017) showed that NFS (*A. mangium* and *Ormosia pinnata*) had higher P uptake capacity than non-NFS under ambient N deposition. These findings may reveal a possible risk of shifting from N-limitation to soil P limitation in the longer term involving a decrease in forest productivity. This may occur in pure acacia stands in the Congolese coastal plains (Koutika et al. 2016), or when N deposition continue since high amounts of N may decrease soil microbial activity of NFS in subtropical China (Liu et al. 2017). It has to be noted that *A. mangium* is mostly introduced in the tropical climates and nutrient-poor soils, where N is the most limited nutrient, and also where P availability is reduced by strong adsorption due to the large amounts of Al and Fe oxide surfaces in most of tropical soils (Sanchez and Uehara 1980).

Negative effects on water availability

In some dry or water-limited areas, introducing alien NFS such as Australian acacias may change seasonal water use patterns (Rascher et al. 2011; Siddiq and Cao 2016). Siddiq and Cao (2016) evaluated the seasonal water use and stand-level transpiration of eight, evergreen, dipterocarps in tropical Southwest China during the wet and dry seasons with six species in monoculture and two species in mixture. The introduced fast-growing species, such as eucalypts and *A. mangium*, consumed much more water than dipterocarp trees and forests, which are more suitable as plantation timber crops for the region (Siddiq and Cao 2016).

Can potential negative impacts of *A. mangium* due to invasiveness be mitigated?

Is it possible to plan for the sustainable use of *A. mangium* i.e., reaping benefits yet limiting negative impacts? The threats of *A. mangium* on ecosystems and biodiversity outside its native environment are obvious (Wilson et al. 2011; Low 2012; Attias et al. 2013; Sampaio and Schmidt 2013; Aguiar et al. 2014; Richardson et al. 2015; Nambiar et al. 2018). From experience in parts of the world with a long history of plantings of Australian acacias, three main issues warrant careful attention when considering issues relating to invasiveness and management of invasive acacias: 1) the role of residence time and invasion debt; 2) massive seed production; and 3) biological control (van Wilgen et al. 2011; Richardson et al. 2015).

Residence time and invasion debt

All species of Australian acacias that have been widely planted outside their native range over decades have become invasive and have caused negative impacts. Invasions and associated impacts typically manifest only several decades after large-scale plantings (Richardson et al. 2011; Richardson et al. 2015). Given the relatively recent expansion of *A. mangium* plantings (Table 1), the lack of major problems with invasiveness until now in some areas has probably led to the assumption that the species poses limited problems with invasiveness. As far as we know, little or no attention was given to issues pertaining to invasiveness when planning major plantings in any of the areas listed in Table 1. Several life-history traits of *A. mangium* are strongly associated with invasiveness in woody plants: these include rapid growth, and the capacity to produce very large numbers of hard-coated, heat-tolerant and long-lived seeds that are adapted for long-distance dispersal by birds (Awang and Taylor; 1993; Franco et al. 1994; Gibson et al. 2011). Suhaili et al. (2015) argued that invasions of *A. mangium* into tropical heath forests of Borneo may be controlled by a proper management of plantations and monitoring of soil seed banks, but we could find no evidence that this has been attempted or is likely to be practical.

The massive seed production of *A. mangium* in the absence of native enemies is the fundamental driver of invasions. Research on plantings and invasions of other Australian acacias has shown that the type and configuration of plantings is important for determining the trajectory of invasions (Donaldson et al. 2014). Biological invasions proceed more quickly and are more likely to result in landscape-scale invasions when plantings take the form of large commercial plantations which provide a massive propagule source. In most cases, such plantations are situated in open vegetation (grassland or scrublands) and/or in areas adjoining natural vegetation which ensures large areas of habitat that are open to invasion. Plantings for ornamentation or for other purposes generally provide smaller propagule sources and have less chance of seeding massive invasions (Donaldson et al. 2014). *A. mangium* has been mainly introduced for pulpwood, soil fertility improvement and land restoration in Asia, Africa and South America (Franco and de Faria, 1997; Epron et al. 2013; Permadi et al., 2017). This may partly explain the rapid and widespread spread.

Biological control

The use of seed-attacking insects and fungi for biological control is a key component of integrated control strategies against Australian acacias, especially in South Africa (Richardson and Kluge 2008; Impson et al. 2009). These efforts have, over several decades, significantly reduced seed production of several invasive acacias, have reduced the density of some invasive populations, and seem to be reducing the spread rates, thereby contributing to overall control aims. Many other types of control are also being used to deal with current and potential future problems with invasive Australian acacias. These include: risk assessment (to help identify highly invasive species that are not yet in the country); eradication (to totally remove populations of those species that still occur over small areas and at low densities, e.g. Kaplan et al. 2012, 2014); containment using mechanical and chemical control; exploitative harvesting of invasive populations (e.g. for fire wood); research to develop of sterile cultivars of commercially important species (Wilson et al. 2011; Harbard et al. 2012;); spatial prioritization of control operations (Roura-Pascual et al. 2009); education and raising awareness; the use of legislation to assign responsibility of control and legislation to prohibit cultivation (Aguiar et al. 2014), prohibition of trade of some species in certain areas (van Wilgen et al. 2011). All of these components of management could reduce problems associated with invasiveness of *A. mangium* and should be considered when assessing risks associated with plantings and in compiling management plans for reducing problems that already exist.

Conclusions

A. mangium has obvious benefits for improving soil fertility in agriculture, agroforestry and forestry in areas with nutrient-poor soils, and for restoring degraded lands and ecosystems. However, the species has the potential to cause major negative impacts to biodiversity and ecosystem functioning when it becomes invasive. The ecology of the species in most parts of its introduced range remains poorly understood. Experience in those parts of the world with long histories of planting *A. mangium* and other Australian acacias provide useful previews of future problems, and such insights must be considered when evaluating costs and benefits of new plantings.

Abbreviations
NFS: Nitrogen fixing species; POM: Particulate organic matter; SOM: Soil organic matter

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Authors' contributions
LSK planned the project, undertook most of the literature review, and wrote the first draft. DMR contributed additional literature and contributed substantially to interpretation and writing. Both authors read and approved the final manuscript.

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The authors declare that they have no competing interests.

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