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Global analysis of yield benefits and risks from integrating trees with rice and implications for agroforestry research in Africa

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ABSTRACT

While agroforestry is a well-established approach for agroecological intensification, rice is less often integrated with trees than other annual staple crops. The benefits and risks from rice agroforestry practices have not been systematically explored. Considering the need for strategies that may address low fertility and high degradation of arable soils and contribute to smallholder farm productivity, livelihoods and climate resilience, such exploration would both be timely and relevant. This study, therefore, reviews the published literature on integrating trees in rice production worldwide and provides perspectives for future research, with special attention to Africa, where the potential for sustainable productivity enhancement is deemed highest. Worldwide, six improved rice agroforestry practices are distinguished: hedgerow alley-cropping, short-term (0.5–4 years) improved fallows, pre-rice green manuring, biomass transfer, systematically arranged rice – tree intercropping and irregularly dispersed trees in fields. The rice agroforestry practices in the 87 publications reviewed were associated with 204 woody perennial species world-wide. Rice agroforestry practices provide a range of products and services to farmers but rice yield is the only quantitative performance indicator reported widely enough to enable meta-analysis. Frequently reported comparative or additional effects of fertilizer application, made it possible to include this aspect in the analyses. Across all types of agroforestry practices enumerated, the average effect of adding trees compared to a no-fertilizer and no-tree control is + 38%. The most beneficial practices in terms of enhancing rice yield were biomass transfer, pre-rice green manuring (100% of data points showing positive responses for both practices) and hedgerow alley-cropping (21% positive cases overall but 64% where fertilizer was not applied). Yield reductions occurred with fertilized intercropping compared to a fertilized mono-crop (in 95% of cases) and with the unfertilized short fallow practice (50% of data points showed yield reduction due to competition in the relay intercropping stage). Tree species that combined rice yield enhancements (alongside other products and services) with wide environmental adaptability across the African continent, include *Sesbania rostrata, Aeschynomene afraspera*, *Acacia auriculiformis*, *Gliricidia sepium* and *Gmelia arborea*. Yield benefits and risks from integrating trees with smallholder rice cropping depend on the type of agroforestry practice used and how each practice interacts with fertilizer application. Further research is needed to investigate the impact of different ways of integrating trees with rice cropping on wider environmental, social and economic sustainability aspects, that are driving increasing interest in rice agroforestry.

1. Introduction

Rice is predominantly produced on smallholder family farms in the tropics (Seck et al., 2012) and significant yield gaps exist, particularly in Africa (e.g., Stuart et al., 2016; Niang et al., 2017; Senthilkumar et al., 2020). Agroecological intensification of smallholder rice production, including compatible forms of sustainable intensification and climate smart agriculture, are urgently needed as a means to increase yields while avoiding as much as possible negative environmental externalities (Wezel et al., 2020) and enhancing the adaptability of food systems to climate change (Freed et al., 2020). Integrating useful trees with annual crop production is increasingly advocated as an agroecological intensification option (Garrity et al., 2010; Pretty et al., 2011; Glover et al., 2012) that could reduce dependency on external inputs such as mineral

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fertilizers (e.g. Carsan et al., 2014). In general, rice is less often observed in an agroforestry context than other tropical annual crops. This is partly because rice is a particularly weak competitor (van Heemst, 1985) making it less suitable to be intercropped with taller and more competitive species (Akanvou et al., 2001), and partly because rice is often perceived to be associated with flooded and anaerobic soil conditions, that are less favourable for many tree species (Kramer and Kozlowski, 1979). However, rice is a versatile crop that is grown in different environments, predominantly irrigated and rainfed lowlands and rainfed uplands (Andriesse and Fresco, 1991). Upland environments are characterised by free-draining soils that are suitable for a much wider range of tree species than the water-logged soils of the 'lowlands'. In addition, crop-, tree- and soil-management practices could address some of the environmental constraints to tree growth in the lowlands.

While rice may be a less obvious crop for agroforestry in general, there are regional differences in how trees are integrated with rice. In Asia, farm trees have been commonly integrated in rice production systems (Belsky, 1993; Wangpakapattanawong et al., 2017), while purposeful tree integration in rice systems is only sporadically observed or overlooked in Africa. This is not only remarkable in view of the large area share of uplands in this region, estimated at 32% of the total area under rice (Diagne et al., 2013b), but also in view of the aforementioned yield gaps, the associated need for agricultural intensification strategies that address the low fertility and high degradation of African arable soils and the contribution farm trees could offer to smallholder rice farmers' crops, lands and livelihoods.

Households of smallholder rice farmers may benefit from trees in economic, food security and nutritional terms, through the production of timber, firewood, fuel, fruits and fodder (Rajasekaran and Warren, 1994; Roder et al., 1995) and in terms of ecosystem services provided by trees (Sinclair and Hitinayake, 2000). The rice crop may benefit from trees by: (1) increased soil moisture availability through either hydraulic lift (e.g., Hirota et al., 2004) or reduced evaporation caused by shade or mulch from pruned tree biomass (e.g., Schroth et al., 1995a); (2) reduction of winds and thereby evapotranspiration of (irrigated) upland rice in semi-arid and arid regions (Thevs et al., 2019); (3) decreased weed pressure through mulching with tree biomass (e.g., Kamara et al., 2000; MacLean et al., 2003), as a result of allelopathic effects (e.g., Parvez et al., 2004; Xuan et al., 2004; Khaliq et al., 2012), or more directly through shade provided by the tree canopy (e.g., Roder and Maniphone, 1998); (4) sourcing of botanicals for integrated pest management (e.g., Nathan et al., 2005); (5) improved soil fertility through nitrogen fixation (e.g., Amara et al., 1996), recycling of nutrients from below the crop rooting zone to the soil surface and organic matter inputs through tree leaf and root turnover (Barrios et al., 2012) which increase soil carbon contents (e.g., Spaccini et al., 2004; Budiadi and Ishii, 2010); (6) protection from erosion by acting as physical runoff barriers and by providing a cover to the soil composed of living and dead (litter, mulch) biomass (Pansak et al., 2010), which in turn reduce rain drop impact (Thapa et al., 1995); and (7) protection from yield reduction caused by high temperatures through provision of shade (Matthews et al., 1997; Oh-e et al., 2007). Shading and other competition effects, however, also impose prominent production constraints, so that integrating trees with rice may involve risks as well.

Given these potential benefits and risks of integrating trees across the range of contexts in which rice is grown, there is an immediate need to evaluate what information is available about trees in smallholder rice production systems in the tropics and which practices and tree species are most compatible, in particular for Africa, where yield gaps are largest and sustainable intensification strategies are most needed. This review is part of the Special Issue on sustainable productivity enhancement of rice-based farming systems in Africa, 50 years after the establishment of the Africa Rice Center (AfricaRice, formerly known as the West African Rice Development Association -WARDA-), presenting the current state of rice agronomy research on the continent and determining the way forward. The objectives of this study were, on the basis of published literature, to: (1) characterise the types of extant and experimentally tested rice-agroforestry practices worldwide, (2) provide an overview of the tree species that are being combined with rice production, (3) analyse and discuss rice yield benefits and risks associated with agroforestry practices relative to monoculture rice, (4) understand interactions between fertilizer application and the performance of rice-agroforestry practices in terms of rice yield, and (5) suggest future research and development priorities for integrating trees in smallholder rice cropping systems in Africa.

2. Literature analyses

A systematic literature search was done to identify relevant sources from which information on the integration of trees in rice production systems was extracted. We adopted a scale-neutral definition of agroforestry, referring to a class of practices where trees (referring to all woody perennials, thus including shrubs) interact with agriculture at field, farm or landscape scale (Sinclair, 1999) in the short-, medium or long-term. On 3 November 2020, a systematic search was conducted in Web of Science, using the search terms (1) Rice OR "*Oryza sativa*" OR "*O. sativa*" OR "*Oryza glaberrima*" OR "*O. glaberrima*" combined with (2) tree* OR agroforestry, as topic, or combined with (3) Agroforestry Systems, as publication name. The search output was then refined to the Web of Science category "Agronomy" and document type "Article". In addition, annual reports and strategic plans of AfricaRice (WARDA before 2009), over the time period 1970–2019, were reviewed to determine the role of trees and agroforestry in rice research and development in Africa.

The Web of Science literature search yielded 81 Science Citation Indexed (SCI) studies. An additional 18 relevant research papers (all exclusively SCI) were found through a systematic review of the references cited by these 81. Studies on conservation agriculture using woody perennial species (e.g. *Stylosanthes* spp.) were excluded because they involved a number of other prominent components, such as no-till, which would complicate analyses and comparisons. The total number of relevant research papers on rice agroforestry was, therefore, 99. The above systematic review approach, while explicit does not preclude the existence of relevant papers that were not identified. Agroforestry practices and tree species reported in these 99 sources were reviewed and 12 of the sources were deemed less relevant for the current paper as they were not reporting on improved rice agroforestry practices (see Section 3). The remaining 87 papers were then analysed.

Seasonal rice yield was the only measure reported widely enough to allow for a quantitative comparison across a large number of studies. The number of studies documenting economic benefits was limited and these studies used different methodologies, indicators and expressions, so these benefits were reported on a case-by-case basis. All other criteria relevant for assessing the performance of agroforestry practices, were more qualitatively discussed as a function of what was reported in the literature. Reported evidence of benefits and drawbacks of tree species and agroforestry practices is summarised in Appendix A.

Based on the specific association between trees and rice, the agroforestry practices were grouped into six practices (see Section 3.1). Rice yields were analysed for each agroforestry practice and fertilizer treatment (with or without additional fertilizer) and data plotted using the ggplot2 library within R version 3.5.1 (Wickham, 2016; R-Core-Team, 2018). The smooth curve in Fig. 2 was estimated by loess (Cleveland et al., 1992). Yields were reported in 42 out of the 87 studies, but only 33 studies included a suitable control without trees allowing assessment of the impact of tree integration on rice yield.

In 17 of these, trees occupied land at the expense of the rice cropping area (i.e., in hedgerow alley-cropping and other rice-tree intercropping practices). Rice yields per hectare explicitly corrected for the total land area used by the crop and the trees were only reported in three out of these 17 studies. Among these three, only Agus et al. (1998) and Hoang Fagerström et al. (2001) provided an indication of the area occupied by the tree. They estimated the hedgerow to take up 15–20% of the total land area. As the yield statistics presented in the current paper are based on yields reported in the original studies, for these two agroforestry practices (i.e., hedgerow alley-cropping and intercropping) this could imply an overestimation by a minimum of 15%.

3. Results

3.1. Global characterisation of rice agroforestry

A total of 204 different tree species were reported to be grown as part of rice-based cropping systems (Appendix A). The most frequently cited tree species were *Sesbania rostrata* (14 studies), *Gliricidia sepium* (13), *Mangifera indica* (10), *Azadirachta indica* and *Leucaena leucocephala* (9), *Samanea saman* (8) and *Acacia nilotica, Eucalyptus tereticornis* and *Senna siamea* (7). Integration of trees with rice was documented in all three major rice growing environments: rainfed upland, rainfed lowland and irrigated lowland.

The majority of papers reported on practices tested or used in Asia (Fig. 1). Fewer studies originated from Africa and Latin America. In upland rice growing environments the most frequently observed practices were (1) hedgerow intercropping, mostly along contours on sloping lands, (2) improved short fallows with (often leguminous) tree species, and (3) tree – rice intercropping in regular planting patterns. In lowland rice growing environments the documented agroforestry practices comprise (1) trees that are growing dispersed in rice fields, (2) trees allowed to grow for a short while before the rice season, and (3) situations where biomass from trees growing outside rice fields is transferred to the rice field (also applicable to upland rice). In the first practice trees are observed to grow (a) on bunds, (b) on raised beds and (c) in the field under temporary water-logged conditions. The first (1) and third (3) lowland rice agroforestry practices described above may make use of natural regeneration (remnants of clearances), spontaneous emerging or deliberately planted trees.

Based on the components involved and their arrangement and interactions in space and time (following Sinclair, 1999), we classified the various ways that trees are integrated with rice production as described in the literature, into the following six practices: hedgerow intercropping (Hedgerow), short, improved fallow (S Fallow), pre-rice green manuring (Pre-Rice), biomass transfer (Biomass), systematically arranged rice-tree intercropping (Intercrop) and irregularly dispersed trees in fields (Dispersed). Practices that involve long-term rotations of planted trees followed by clearance and rice crop cultivation, or shifting cultivation with long term fallows after one or two years of rice cultivation, are not considered improved agroforestry practices and no rice yield assessments were available for them and so they were not further considered in this review (12 studies).

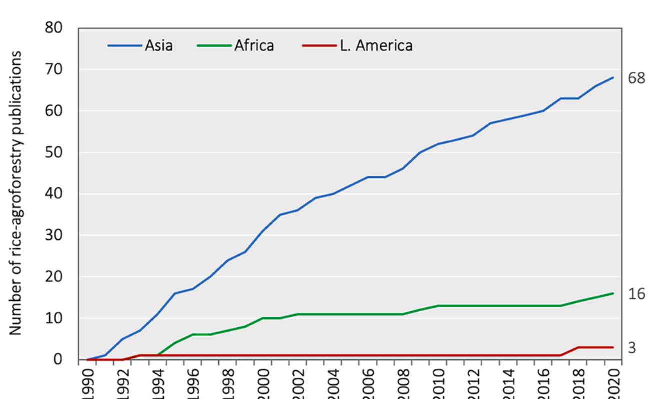

Fig. 1. Cumulative number of relevant research articles on rice-agroforestry over the past three decades, per continent (totals: Asia: 68, Africa: 16, L. America: 3) as found in Web of Science (Accessed: 03/11/2020).

3.1.1. Hedgerow alley-cropping (Hedgerow)

In the Hedgerow practice rice is grown in the alleys between hedgerows composed of (single or multiple) tree species. Alley spaces may vary but are usually 5–10 times the width of the hedge. In the reviewed hedgerow rice alley-cropping studies, the average distance between hedgerows is 4.8 m (median: 5; range: 4–6 m). The average age of hedgerow trees at the first rice yield assessment is 20.5 months (median:20; range: 5–40). Hedgerow may be associated with a range of management practices including: hedgerow pruning, where pruned biomass can be used as mulch; and cropping practices including crop rotations, that result in either more simultaneous or sequential interactions between the hedgerow and the annual crop. This practice is restricted to rainfed upland rice systems.

Contour hedgerows in upland rice are used to control soil erosion and increase crop yield (Samsuzzaman et al., 1999). For instance, *G. sepium* contour hedgerows have been shown to increase rice yield and N supply to crops (Amara et al., 1996; Agus et al., 1998) although the advantages (i.e., N fixation) do not always compensate the disadvantages (i.e., light reduction from tree shading) for a crop like rice (Hairiah et al., 2000; Whitmore et al., 2000). Other species used as hedgerows include *S. siamea*, formerly *Cassia siamea*, (e.g. Danso and Morgan, 1993), *Gmelina arborea* (Amara et al., 1996), *L. leucocephala* (Salazar et al., 1993), *Tephrosia candida* (Hoang Fägerstrom et al., 2001), *Flemingia congesta* and *Peltophorum dasyrrachis* (Hairiah et al., 2000; Whitmore et al., 2000). In the semi-deciduous rainforest zone of Côte d'Ivoire, rice has been rotated with groundnut in-between regularly coppiced *G. sepium* hedgerows. The hedgerow derived biomass, used as mulch, increases annual crop production particularly in drier years, by reducing disease incidence and improving soil water availability for the crop (Schroth et al., 1995a).

3.1.2. Short-term improved fallow (S Fallow)

The S Fallow practice comprises an improved fallow with a fast-growing, perennial shrub or tree species (preferably an N-fixing legume). There are two types of S Fallow practices, depending on the length of the fallow. In an annually grown crop (rice-rice, or rice-rotation crop) the shrub or tree can be either relay sown into the rice during the preceding cropping season or sown right after the rice harvest. The fallow period then covers the period till the next cropping season (Akanvou et al., 2002). In the second type of S Fallow practice, the fallow is extended by one or even two or more years.

Before sowing of the new rice crop, the improved fallow vegetation needs to be cleared. The vegetation can be (1) slashed and removed, (2) slashed (dried) and burnt, (3) slashed and mulched or (4) slashed and incorporated in the soil (Becker and Johnson, 1998, 1999; Akanvou et al., 2000; Saito et al., 2008). The latter two options may require specialised farm equipment (e.g., cutter-rollers, shredders). Killing of the fallow species may also involve application of a broad-spectrum herbicide like glyphosate. Rice sowing can then be done with the remnants of the fallow legume used as mulch, burnt or incorporated, and the legume allowed to grow back from seeds or resprouts. In the second type of S. Fallow, where the improved fallow species may be grown for more than 1 year (up to 4), the trees are either cleared (by slash-and-burn) or thinned. Rice is then grown in the cleared field or intercropped in the thinned tree stand (Hoang Fägerstrom et al., 2001; Saito et al., 2009). The S Fallow practices are mainly applied in rainfed upland rice systems and have similarities with the Intercrop practice (see below) as they may involve stages of (relay) intercropping of rice with trees. The S Fallow practice however always involves timely clearance, or at least thinning, of trees whereas in Intercrop trees are maintained.

Species commonly used include *Stylosanthes guianensis* (Samsuzzaman et al., 1999; Saito et al., 2006, 2010) or *S. hamata* (Roder et al., 1998; Akanvou et al., 2002) as well as *C. cajan*, *Calliandra calothyrsus*, *Flemingia congesta*, *L. leucocephala* and *Sesbania sesban* (Roder and Maniphone, 1998). S Fallow practices with leguminous tree species suppress weeds compared to a natural fallow, when applied during the dry season only (Saito et al., 2010), as well as with longer (e.g., 1-yr) improved fallows (Becker and Johnson, 1998; Roder et al., 1998; Saito et al., 2006) and may also benefit soil available nitrogen content (Becker and Johnson, 1998; Saito et al., 2006, 2008).

3.1.3. Pre-rice green manuring (Pre-Rice)

In the Pre-Rice practice, fast-growing (N-fixing) leguminous trees are grown for a very short time span (i.e., 5–9 weeks) before rice in the same season. The tree saplings are slashed and ploughed or harrowed into the soil as green manure before rice planting. This practice is most adapted to irrigated lowland rice growing environments as it requires some level of water management. If adapted mechanisation (i.e., hydrotiller) is not available it will steeply increase labour demands to attain good soil incorporation. *Sesbania rostrata* and comparable species like *Aeschynomene afraspera* are often used as Pre-Rice species (Bar et al., 2000). *Sesbania rostrata* can produce 5000–7000 kg dry mass ha^{-1} within six weeks (Ndoye et al., 1996) and has been shown to increase nitrogen availability to the crop (Buresh et al., 1993a, 1993b).

3.1.4. Biomass transfer (Biomass)

In the biomass transfer practice, above-ground biomass pruned from trees growing outside the rice field is transferred to the rice crop and distributed over the soil surface as mulch or chopped and incorporated in the soil before crop establishment. This provides organic matter and nitrogen to the crop with positive effects on rice yields extending for a number of years after application (Pandey and Sharma, 2003). Leguminous tree species, such as *A. nilotica* (Singh et al., 2008; Bargali et al., 2009) and *S. saman* (Sae-lee et al., 1992; Pham et al., 2015; Watanabe et al., 2017) provide good biomass for this practice. Leaf litter from *Acacia auriculiformis* and *S. saman*, have been shown to raise soil fertility and rice yields (by>20%) when applied as green manure to rainfed rice (Whitbread et al., 1999). In lowlands, soil fertility improvements may be further enhanced by soil aeration (Vityakon and Dangthaisong, 2005). The increases in soil fertility, mainly relate to N and C, although leaves of some species, such as *Tithonia diversifolia*, are also valued for high P and K contents (Jama et al., 2000). This practice is suitable for both upland and lowland rice.

3.1.5. Rice – tree intercropping (Intercrop)

The Intercrop practice involves rice – tree intercropping where trees are planted in regular arrangements (excluding hedgerows). In this practice, trees are grown for several years and rice is grown in between, with or without other annual crops in rotation. In the reviewed rice - tree intercropping studies the average age of the trees at the first rice yield assessments is 29.4 months (median: 28; range: 5–52). The average tree density is 2766 trees ha^{-1} (median: 1250; range: 100–12,346).

The taungya reforestation method is a well-known example of intercropping, in which cleared land is replanted with desirable trees that are intercropped for the first few years of tree growth with food crops (Menzies, 1988). Taungya practices that include upland rice and teak trees (*Tectona grandis*) are observed in Thailand (Watanabe et al., 1988). Another example is sericulture-based intercropping where mulberry (*Morus alba*) is combined with annual crops including rice (Dhyani et al., 1996). In Intercrop practices, trees are often annually pruned to reduce negative shade effects on the rice (e.g., Khybri et al., 1992; Dhyani et al., 1996).

Tree species that have been intercropped with rice include *A. nilotica*, *Populus deltoides*, *Eucalyptus tereticornis, Salvadora persica*, *Hevea brasiliensis*, *Elaeis guineensis, Terminalia arjuna*, *Grewia optiva*, *Morus alba*, as well as fruit trees like *Citrus lemon*, *Psidium guajava* and *Punica granatum* (Appendix A).

In upland rice, tree intercropping has been shown to improve crop productivity, soil fertility and overall economic outcomes (Singh et al., 1997). The main economic benefit may come from high-value tree products, like fruits, nuts, oil, timber, rubber and silk (e.g. Khybri et al., 1992; Dhyani et al., 1996; Bhatt and Misra, 2003). Rice may be grown during the first few years of tree establishment in some rotations, notably with rubber (*Hevea brasiliensis*), to provide economic returns to the farmer during the initial unproductive period of the tree component (e.g. Hondrade et al., 2017). Tree – rice intercropping may be viable even in lowland conditions, if trees are grown on raised beds or bunds and rice and other annual crops in sunken beds in between (Dagar et al., 2001, 2016).

3.1.6. Irregularly dispersed-trees in rice fields (Dispersed)

Both in upland and lowland rice growing environments, trees may also be grown dispersed in rice fields. They may be naturally occurring, purposely planted or both. Trees are traditionally grown on bunds of paddies in Asia, particularly in India, Bangladesh, Indonesia, Thailand and Laos (e.g. Kosaka et al., 2006; Miyagawa et al., 2013; Pham et al., 2015; Miyagawa et al., 2017; Dumrongrojwatthana et al., 2020). Trees need to be pruned to mitigate competition with the crop (Evensen et al., 1994; Semwal et al., 2002). Frequently used tree species in this agroforestry practice include *A. nilotica* (Viswanath et al., 2000; Singh et al., 2008; Bargali et al., 2009), *A. catechu* (Hocking et al., 1997), *S. saman* (Sae-lee et al., 1992; Watanabe et al., 2017), *Eucalyptus* sp., *Mangifera indica, Azadirachta indica*, *Dipterocarpus tuberculatus* and *Tamarindus indica* (Kosaka et al., 2006; Pham et al., 2015; Miyagawa et al., 2017; Watanabe et al., 2017; Appendix A).

In Africa, trees are also frequently encountered in rice where farmers maintain, manage and use beneficial trees in their fields (Rodenburg et al., 2012), in the higher parts of the lowland – upland continuum of inland valleys, where high-value fruit trees such as mango and cashew (*Anacardium occidentale*) are common (Balasubramanian et al., 2007) or in traditional agroforests in the forest zones of West Africa where several palm species (e.g. *Raphia ruffia*, *Elaeis dura*) are common (Camara et al., 2009). Cases like the latter three examples may not always be classified as agroforestry in the literature resulting in underestimation of the extent to which trees are integrated in rice systems in Africa, but also other regions, as has been previously suggested (Zomer et al., 2016).

3.2. Productivity and profitability of rice – agroforestry practices

3.2.1. Agronomic benefits and challenges of tree – rice integration

The benefits reported from integrating trees with rice production are numerous and diverse (Appendix A). Apart from rice yields (discussed in 3.2.2.) and products derived from trees (e.g., fodder, timber, oil, fuel wood, fruits, nuts and silk; mostly derived from practices categorised as Hedgerow, Intercrop and Dispersed), a key benefit of agroforestry that was often mentioned was the increase in soil nitrogen content, resulting from biological N-fixation associated with leguminous tree species. While this was observed across agroforestry practices, it is most explicitly reported following the Biomass, S Fallow and Pre-Rice practices. Positive effects of trees, in particular for soil N and C, have been reported for a great number of tree species reviewed, and across agroforestry practices (Appendix A) but this may require careful tree and crop residue management to avoid net nutrient outflows, in particular for soil P, as well as additional fertilizer application (e.g. Salazar et al., 1993).

A number of tree species were reported to suppress weeds (MacLean et al., 2003; Saito et al., 2008), including parasitic weeds of the *Striga* genus (Randrianjafizanaka et al., 2018). This is one of the main benefits from the S Fallow practice. Weed suppression is an important trait for rice production, as weeds are among the most important production constraints (Diagne et al., 2013a) and smallholder rice farmers have limited options for weed control (Rodenburg et al., 2019).

Several disadvantages of integrating trees with rice production were also reported (Appendix A). Additional inputs were often required. The need for additional fertilizers was often reported for the agroforestry practices Hedgerow, S Fallow and Dispersed. The S Fallow practice may need a broad-spectrum herbicide such as glyphosate to kill the fallow vegetation. All agroforestry practices required additional labour, for pruning (Hedgerow, Intercrop, Dispersed, Biomass) or slashing, mulching and soil incorporation of tree biomass (S Fallow, Pre-Rice, Biomass). Farmers practising Hedgerow with rice in the Philippines cited tree-crop competition and the additional labour required to prune the hedgerows as major constraints (Fujisaka et al., 1994).

A disadvantage of integrating trees in rice systems, is the possible reduction in rice yields due to several factors. In the Intercrop and Dispersed practices, some species were reported to have negative allelopathic effects on the crop: e.g., *Michelia oblonga*, *M. champaca* and *Tectona grandis* (Bhatt et al., 2009) as well as *Dalbergia sissoo* (Akhtar et al., 2010). High water use of *Eucalyptus* sp. has been reported to negatively affect rice yields in drought prone rainfed lowlands (Pham et al., 2015; Miyagawa et al., 2017). Increased incidences of insect pests or diseases like rice blast, were reported with *G. sepium* and *Acacia spectabilis* (MacLean et al., 2003).

Shade and space requirements are important disadvantages of trees in rice production systems, in particular in Hedgerow, Intercrop and Dispersed agroforestry practices. Compared to monoculture, rice yields may increase in the central part of the alleys in Hedgerow, for instance, but this positive effect may be cancelled out by the land area occupied by the trees or yield losses close to the trees caused by competition for light (Schroth et al., 1995b). Because rice is a weak competitor (van Heemst, 1985), competition for light is the main yield reducing factor in rice-based agroforestry where water is often not limiting (e.g., Sae-lee et al., 1992; Hocking et al., 1997; Singh et al., 2008; Bargali et al., 2009). Tree height, crown width, age and species are important in determining understory crop yield, and the competition can be mitigated by optimizing the species choice, spatial arrangements and in particular by tree pruning. In some arrangements as much as 75% of the tree crown needs to be pruned to mitigate competition (Semwal et al., 2002). Often pruning has the additional advantage that the pruned material can be used as fodder or firewood or be applied to the crop as mulch to suppress weeds and increase soil fertility (as described above), in particular when combined with application of inorganic fertilizer. For this reason high biomass production is an important trait for trees that are primarily integrated because of their nitrogen fixation (Samsuzzaman et al., 1999) although this has to be traded-off against the abovementioned competitive effects (Barrios et al., 2012) as well as increased labour demands.

Another challenge in rice agroforestry is that rice is often grown under temporary or continuous flooding and thus anaerobic soil conditions, which are unfavourable to many tree species. For lowland systems, where these anaerobic soil conditions are likely to occur during at least part of the season, either a flood-tolerant tree species such as *A. nilotica* can be used or, species that cannot tolerate water-logging, can be grown on bunds (e.g. Singh et al., 2008; Bargali et al., 2009) or on raised beds (e.g. Dagar et al., 2001).

3.2.2. *Effect of rice-agroforestry practices on rice grain yields*

From the literature on integrated rice – tree practices that we identified, 42 studies reported on field-based rice yields. For the analysis of these yield data, we focused on five of the six rice agroforestry practices, leaving out Dispersed because yield comparisons reported in this practice were not comparable to the plot-level yield comparisons of other practices. Studies in the Dispersed practice predominantly compared yields of rice plants under a single tree to those of plants growing at a distance from that same tree, or they used a (single) 100% lopped tree or the first year of a time series as the no-tree control. Of the studies reporting field-obtained yield, 33 included a monoculture rice control allowing calculation of a tree effect (difference in yield with and without trees). Differentiation was made between tree effects measured where additional (mineral) fertilizers were applied to tree and monoculture plots and those without any fertilizer, to investigate whether positive or negative tree effects depend on fertilizer management.

Histograms of tree effects with and without fertilizer suggest little evidence of publication bias in the rice yield data (Fig. 2), typically revealed by the distribution of effects being truncated at or near zero. Rice yields across rice growing conditions and agroforestry practices range from close to zero to nearly 5000 kg ha^{-1}, showing that the data come from very heterogeneous contexts. Rice yields with trees plotted against rice yields without trees with and without additional mineral fertilizer show heterogeneity of response to trees indicated by the scatter around the 1:1 line (Fig. 3). Some overall trends can, however, be observed. Without fertilizer, there is on average an increase in rice yield from incorporating trees across all levels of baseline yield, so that trees generally increase rice yield in high and low yielding contexts. The average effect of trees, without fertilizers, is to increase yield by 624 kg ha^{-1}, equivalent to a mean increase of 38% across conditions and practices (Fig. 3) but ranging from − 1187 to + 2320 kg ha^{-1} in specific cases. When fertilised rice without trees is compared to fertilised rice with trees, at low baseline yields (< 1500 kg ha^{-1}) the average tree effect is to increase yield by 261 kg ha^{-1}, equivalent to a 23% increase with a range from − 390 to + 813 kg ha^{-1}, but when the baseline yield is higher (>1500 kg ha^{-1}), the average effect of trees is to decrease rice yield by 519 kg ha^{-1}, equivalent to a decrease of 12% with a range from

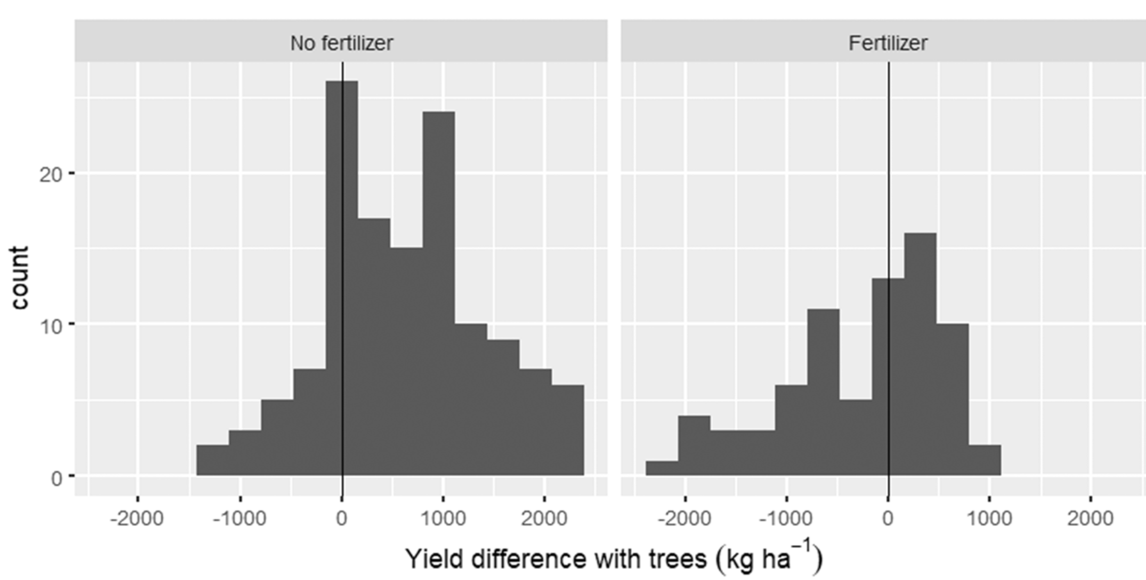

Fig. 2. Distribution of data on yield differences (with trees – without trees) for observations with and without fertilizer (total of 33 studies).

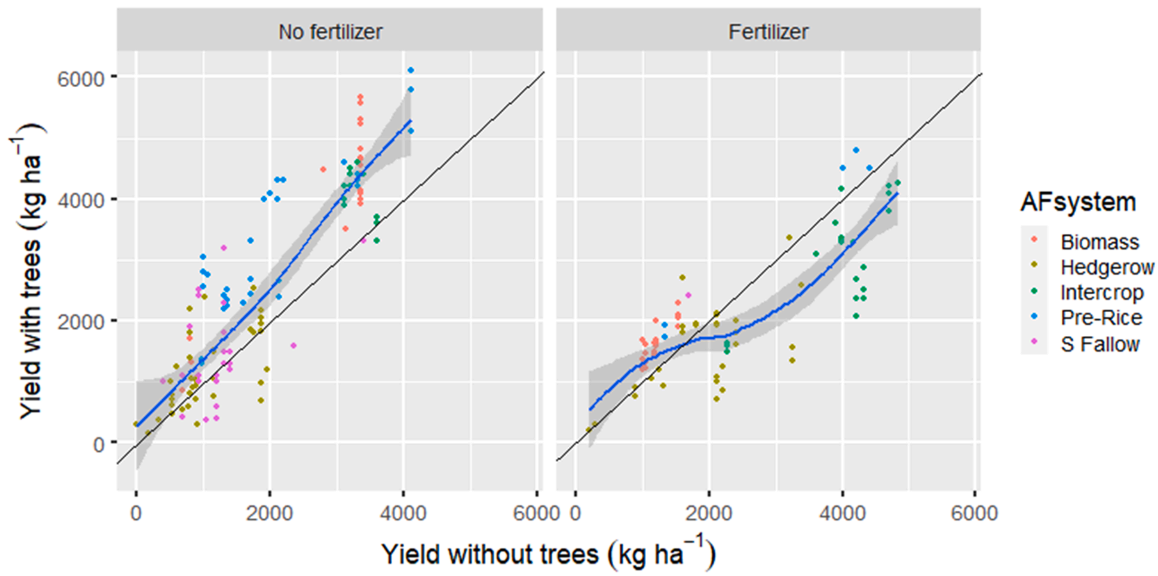

Fig. 3. Yield with trees plotted against the corresponding yield without trees from the same study, for observations with and without fertilizer. The 1:1 line (black) indicates equality between yield with and without trees. The mean yield with trees conditional on yield without (blue line) is a smoothing curve with approximate 95% confidence interval (grey band). Total of 33 studies. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

− 2140 to + 1100 kg ha^{-1} (Fig. 3). Positive exceptions are the systems where trees are not directly competing with rice (i.e., 'Biomass' and 'Pre-Rice'), whereas the systems where trees compete with rice (i.e., 'Hedgerow' and 'Intercrop') mostly have negative yield balances under fertilised conditions (Fig. 3). The implication is that if fertilizers are applied under high yielding environments, trees are likely to compete with crops rather than add resources that crops can benefit from and this implies an important risk for smallholders. If fertilizers are applied and yields are still low then there are possibly other constraints that trees can help overcome, which would greatly benefit smallholders. Trees in agroforestry contexts having more positive impact on yield and economic performance at lower fertilizer and monoculture yield levels have been observed and modelled for a range of tropical conditions (Sileshi et al., 2010).

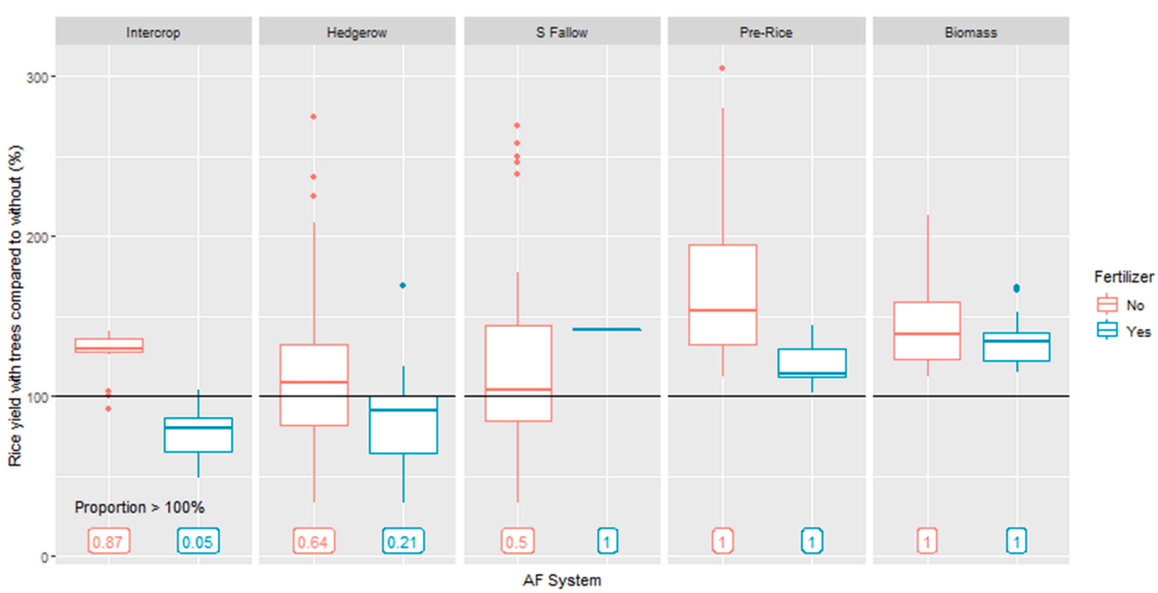

Fig. 4. Box-whisker plots of relative rice yield changes (in %) from incorporation of trees with or without additional fertilizers per agroforestry practice (in putative decreasing order of tree - crop interference): Intercrop (# studies= 6, n = 15/20 without and with fertilizers resp.), Hedgerow (# studies = 11, n = 36/28), S Fallow (# studies = 7, n = 27/1), Pre-Rice (# studies = 7, n = 32/5) and), Biomass (# studies= 3, n = 19/20). Horizontal black line indicates where yield with trees equals yield without trees. Values in boxes below the x-axis indicate the proportion (between 0 and 1) of individual data points above this break-even line.
Sources: (Intercrop: Khybri et al., 1992; Dhyani et al., 1996; Singh et al., 1997; Dagar et al., 2001; Bhatt and Misra, 2003; Dagar et al., 2016), (Hedgerow: Maclean et al., 1992; Danso and Morgan, 1993; Garrity and Mercado, 1994; Evensen et al., 1995; Schroth et al., 1995b; Schroth and Zech, 1995; Amara et al., 1996; Agus et al., 1998; Samsuzzaman et al., 1999; Hairiah et al., 2000; Hoang Fägerstrom et al., 2001), (S Fallow: Roder and Maniphone, 1998; Roder *et al.*, 1998; Hoang Fägerstrom *et al.*, 2001; Saito *et al.*, 2006; Saito *et al.*, 2008; Saito *et al.*, 2009; Saito *et al.*, 2010), (Pre-Rice: Buresh *et al.*, 1993b; Becker *et al.*, 1995; McDonagh *et al.*, 1995; Ndoye *et al.*, 1996; Herrera *et al.*, 1997; Bar *et al.*, 2000; Toomsan *et al.*, 2000), (Biomass: Whitbread *et al.*, 1999; Hoang Fägerstrom *et al.*, 2001; Tomar *et al.*, 2013).

A comparison of tree effects on rice yields for different practices, provides further insight (Fig. 4). When both the rice monoculture and the rice agroforestry practice do not receive additional fertilizers, the Hedgerow (64% of data points), Biomass (100% of data points), Pre-Rice (100%) and Intercrop (87%) practices generally result in higher yields than the no-tree control, although data variability, and hence uncertainty, are high. Also, yields of Hedgerow and Intercrop were not systematically corrected for land area occupied by the tree-component (see Section 2. Literature analysis). The S Fallow practice without fertilizer results in rice yield increases in 50% of the cases, but these figures are based on rice yields during both the pre- and the post-fallow stages. During the relay-intercropping stage prior to the fallow, only 33% of the cases showed higher rice yields than the monoculture (and 58% cases showed lower yields), but in the stage after the fallow 92% of the cases showed higher yields (and 8% similar yields) compared to the continuous monoculture. When both monoculture rice and tree-rice systems received additional mineral fertilizers, only the Biomass (100% of data points) and Pre-Rice (100%) practices result in higher yields.

These results indicate that the negative effects of trees (e.g., competition) are often cancelled out by the positive effects (e.g., soil fertility improvement) in cropping situations where fertilizers are not available. It also shows that the competition effect that trees exert on rice becomes more visible where trees compete directly with rice (i.e., under the 'Hedgerow' and 'Intercrop' practices), and soil fertility levels are less constraining to crop production.

Further disaggregation of data reveals tree effects for different agroforestry practice – tree species combinations (Fig. 5). This shows individual study results of (mean) yield differences obtained with trees only (no fertilizers) compared to non-fertilised monoculture rice, with

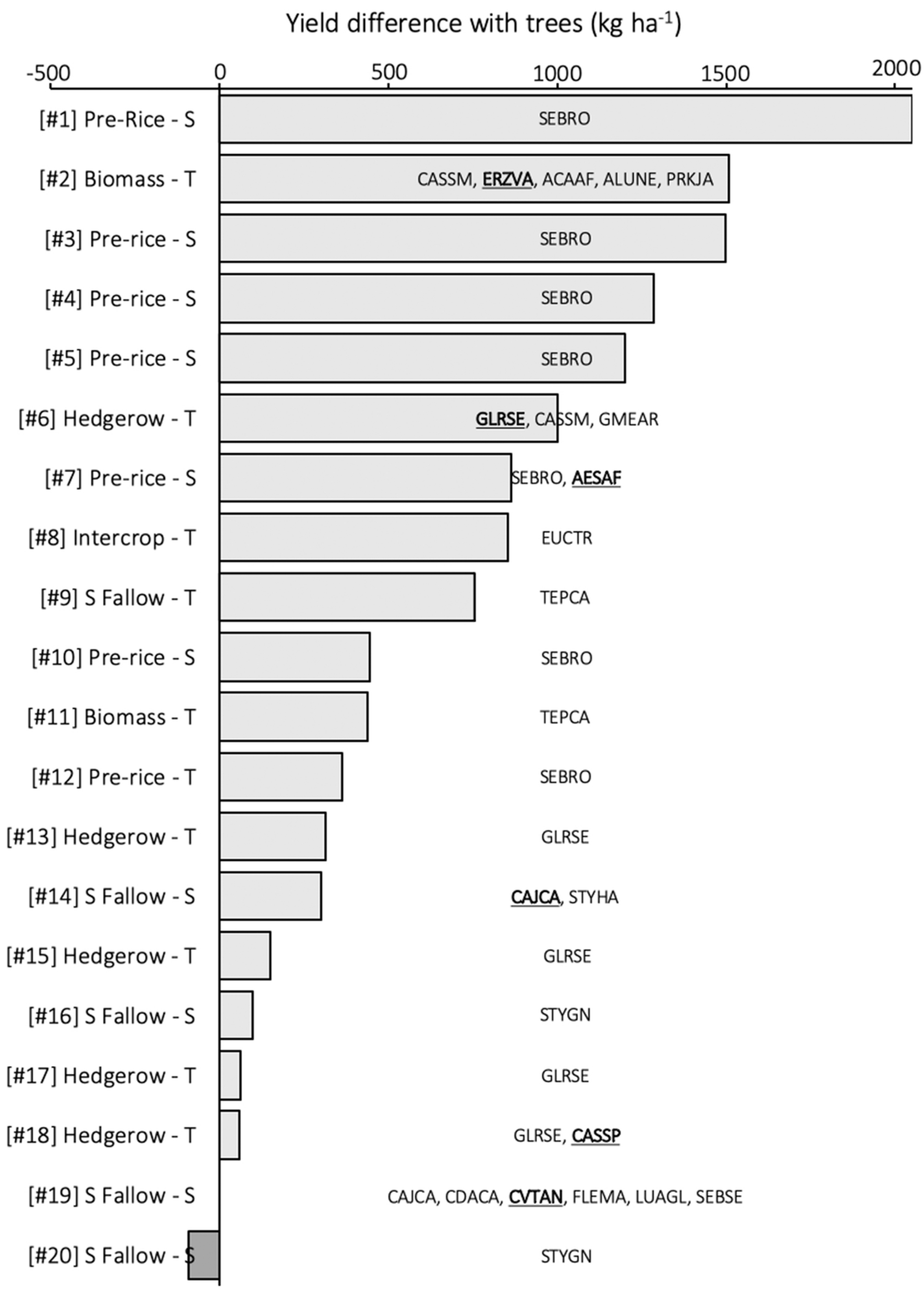

Fig. 5. Net tree effect on seasonal rice yields without additional fertilizers (in kg ha^{-1}), with rice yields on the horizontal axis and agroforestry practice on the vertical axis. Only studies reporting at least 1, 000 kg ha^{-1} of rice yield are included here. T = Tree species used, S= Shrub species used. EPPO codes (in italics) are used to indicate species (CASSM: *Senna siamiea*, ERZVA: *Erythrina indica*, ACAAF: *Acacia auriculiformis*, ALUNE: *Alnus nepalensis*, PRKJA: *Parkia roxburghii*, SEBRO: *Sesbania rostrata*, GLRSE: *Gliricidia sepium*, GMEAR: *Gmelia arborea*, AESAF: *Aeschynomene afraspera*, CAJCA: *Cajanus cajan*, STYHA: *Stylosanthes hamata*, STYGN: *Stylosanthes guianensis*, CASSP: *Cassia spectabilis*, CDACA: *Calliandra calothyrsus*, CVTAN: *Crotalaria anagyroides*, FLEMA: *Flemingia congesta*, LUAGL: *Leucaena leucocephala*, SEBSE: *Sesbania sesban*, TEPCA: *Tephrosia candida*, EUCTR: *Eucalyptus tereticornis*). In studies involving multiple tree/shrub species, the codes of species with highest rice yield benefits are underlined and bold.
Sources: ([#1] Ndoye et al., 1996), ([#2] Tomar et al., 2013), ([#3] Buresh et al., 1993b), ([#4] Herrera et al., 1997), ([#5] Becker et al., 1995), ([#6] Amara et al., 1996), ([#7] McDonagh et al., 1995), ([#8] Dagar et al., 2016), ([#9] Hoang Fägerstrom et al., 2001), ([#10] Toomsan et al., 2000), ([#11] Hoang Fägerstrom et al., 2001), ([#12] Bar et al., 2000), ([#13] Agus et al., 1998), ([#14] Roder et al., 1998), ([#15] Schroth et al., 1995b), ([#16] Saito et al., 2010), ([#17] Schroth and Zech, 1995), ([#18] Samsuzzaman et al., 1999), ([#19] Roder and Maniphone, 1998), ([#20] Saito et al., 2006).

only cases of yields (with trees) above 1000 kg ha^{-1} shown. The most successful agroforestry practices for rice, are those where the trees are separated from the rice crop, either in space (i.e., the Biomass practice) or in time (i.e., the Pre-Rice practice). One of the most successful practices was a Biomass practice with green leaves of tree species (*Erythrina indica*, *Acacia auriculiformis*, *Parkia roxburghii* or *Senna siamea*), applied at a rate of 10,000 kg ha^{-1} of fresh weight (Fig. 5). Compared to the unfertilized control, the mean yield increase obtained from this practice was 1500 kg ha^{-1}, and in the third season the mean rice yield following soil incorporation of green leaves of these four species was 300 kg ha^{-1} higher than that obtained with recommended fertilizer application (Tomar et al., 2013). *Erythrina indica* was the most yield increasing tree species. Another successful practice was Pre-Rice with *Sesbania rostrata* (Buresh et al., 1993b; Becker et al., 1995; McDonagh et al., 1995; Ndoye et al., 1996; Herrera et al., 1997; Bar et al., 2000; Toomsan et al., 2000; Whitmore et al., 2000). *Sesbania rostrata* was grown for only 40–60 days, after which it was ploughed into the soil prior to rice transplanting. In Senegal, without additional fertilisers, this practice increased yields in farmer-managed fields by an average of 2050 kg ha^{-1} compared to the unfertilised control crop without green manure (Ndoye et al., 1996). In the Philippines this resulted in a 1500 kg ha^{-1} rice yield increase over monoculture. Good results are also obtained with *Aeschynomene afraspera* (McDonagh et al., 1995). The Intercrop practice with *Eucalyptus tereticornis* also resulted in a yield benefit of nearly 1000 kg ha^{-1} (Dagar et al., 2016), but this was in the specific context of waterlogged saline soils, and evidence on performance of this practice across a wider range of contexts is lacking.

Without the use of fertilizers, Amara et al. (1996) obtained a mean yield advantage of 1000 kg ha^{-1} following Hedgerow practices, compared to rice production without trees (Fig. 5). Across studies on Hedgerow practices, *Gliricidia sepium* was the most successful tree species, but locally other tree species may be better fits or benefit rice yields more (e.g., *Paraserianthes falcataria* on weathered oxisols, see: Evensen et al., 1995) and it needs to be stressed that this species was also reported to require additional Ca fertilizers (e.g., gypsum) on soils with potential Al toxicity (Evensen et al., 1994). Promotion of any particular tree species should always be done with caution as many of them are known as competitive species and their biomass may not always be suitable as green manure, as reported before with *S. siamea* (Giller, 1998).

Cases where tree integration clearly implied a risk were also observed. For instance, yield reductions were found in the S Fallow practice during the pre-fallow stage, whereby *Stylosanthes* is (relay) intercropped with rice, mainly when the fallow species is sown at the same time as rice or shortly thereafter (Saito et al., 2006), or in an Intercrop practice with *Populus deltoides*, *Acacia nilotica* or *Eucalyptus tereticornis* (Singh et al., 1997), or in a Hedgerow practice with *Flemingia congesta* (Hairiah et al., 2000). Risks associated with agroforestry practices need to be evaluated across contexts to enable scaling-up (Coe et al., 2014).

3.2.3. Economic benefits of tree – rice integration

There were only ten studies presenting economic analyses of rice agroforestry practices in the literature that we identified, with mixed outcomes. These studies focussed on the Dispersed, Intercrop, Hedgerow and Pre-Rice practices only.

3.2.3.1. Dispersed. Dhyani et al. (1996) reported that sericulture with mulberry trees (*Morus alba*) planted on bunds of lowland rice fields was two times more profitable than rice alone and 1.25 times more profitable than mulberry alone. Returns were obtained from rice, fuel wood and silkworm cocoon production. Whereas rice grown alone led to negative net present values (NPV – an economic measure that discounts future costs and benefits). A traditional (Dispersed) agroforestry practice whereby rice was combined with *Calophyllum inophyllum* trees (in Indonesia known as 'Nyamplung') proved economically viable due to the oil-rich seeds of the tree, used as biofuel, and the associated honey production opportunities (Rahman et al., 2019). Viswanath et al. (2000) analysed the net returns from a Dispersed practice with *A. nilotica* (average density of 20 trees ha^{-1}) scattered in upland rice fields with decreasing densities over time (tree-tree intervals of around 5 m in year 1 and 10 m in year 10). Products, in addition to rice, were fuel and small timber wood, gum and seeds. Returns were recorded over a 10-year period. From the third year onwards the returns were variable but positive, with a mean (over the eight profitable years) of 15,537 Rs ha^{-1} (equivalent to about US $424) and a maximum of 42,040 Rs ha^{-1} (US $1148) in year 10.

3.2.3.2. Intercrop. Singh et al. (1997) studied three tree species —*Eucalyptus tereticornis*, *Acacia nilotica* and *Populus deltoides* — grown at 2 by 4 m spacing, intercropped with various crops in rotation (rice-wheat or rice-berseem). In the sixth year, economic returns from this system were estimated. The benefit-cost ratio from rice-based rotations, compared to monoculture rice, was higher with *P. deltoides* (by a factor 1.5–1.7) but lower with the other tree species. Cordeiro et al. (2018) compared rentability of a mixed farming system with eucalyptus (*E. camaldulensis* and *E. pellita*), intercropped with rice and soybean and integrated with cattle, to a monoculture eucalyptus plantation in Brazil, and concluded that the latter was more profitable. In Laos, a eucalyptus-rice intercrop generated higher returns (NPV: 20.1%) to farmers than eucalyptus trees (*E. camaldulensis* and *E tereticornis*) grown without an annual crop (NPV: 18.0%) (Phimmavong et al., 2019). In Laos, an agroforestry practice based on a 7-year rotation of *Persea kurzii* trees (locally known as 'yang bong') intercropped with rice in the first year and bananas thereafter was studied (van der Meer Simo et al., 2020). The trees contributed 10 times more to on-farm incomes than the associated agricultural crops.

3.2.3.3. Hedgerow. A Hedgerow practice with *Tephrosia candida*, for four years, had a return per unit labour (benefits minus costs, divided by total labour days) of 0.88 compared to 0.93 for a rice mono-crop, resulting in negative NPVs (Hoang Fägerstrom et al., 2001). When *Tephrosia candida* biomass from hedgerows outside the rice field was applied as mulch, the return per unit labour over four seasons was 1.16, resulting in positive NPVs.

3.2.3.4. Pre-Rice. Becker et al. (1995) applied partial budgeting methods to determine benefit:cost ratios for the Pre-Rice practice using *S. rostrata,* in irrigated rice when three rice crops per year can be grown. As *S. rostrata* was found to substitute 35–90 kg urea N, the most important benefit would come from savings in expenditures on fertilisers. They found that benefit:cost ratios of this practice were only above 1.0 during the dry season when *S. rostrata* was broadcast sown 2 weeks (benefit:cost ratio: 1.18) or 4 weeks (1.02) before harvest of the previous rice crop, as this was the most labour extensive method. Obviously with increasing fertiliser prices the benefit:cost ratio would improve.

3.3. Agroforestry research focussing on rice in Africa

Historically, AfricaRice (formerly WARDA) and partners, have focussed their rice research and development efforts mostly on breeding and good agronomic practices (Tollens et al., 2013). Apart from studies on improved short-term fallows (e.g., Becker and Johnson, 1998; Akanvou et al., 2000; Akanvou et al., 2002; Saito et al., 2010) no other research has been done on integration of trees in rice-based cropping systems. A review of annual reports of AfricaRice/WARDA (1970–2019) only revealed sporadic mention of trees and/or agroforestry as part of rice agronomy research and development work. In the 1980's the annal reports did make sparse mention of naturally occurring trees in and around rice fields but mainly as constraints. These included observations that after clearance, trees remaining in or around the field harbour rice pests, such as birds (annual report of 1983), while regrowing trees are indicated as persisting weeds (1986). The first appearance of the concept of trees as useful components in rice cropping systems is observed in the reports of the 1990′s: in 1991 agroforestry was mentioned in the context of alternative cropping systems that need to be developed; in 1995 planting trees was acknowledged as a measure to lower the groundwater table in waterlogged areas and the use of simulation models was suggested to investigate the effects of tree densities on groundwater fluctuations; in 1997 trees were described as part of traditional rice farming approaches and the declining fallow periods in shifting cultivation systems in the forest zone of Côte d′Ivoire were discussed; while in 1998 agroforestry was mentioned as an element of the characterisation of inland valleys. In the next two decades, the 2000s and 2010s, despite the increasing need to render rice production more sustainable, little tangible follow up is observed, in annual reports as well as the centre's strategic plans, other than the acknowledgement of trees as options for the often-mentioned diversification of rice-based systems (annual report of 2017).

The limited attention to agroforestry by the leading rice research organisation in Africa is also reflected in the published work we reviewed. Our systematic search for studies on explicit tree integration as to improve rice-based systems identified only 16 studies from Africa. With renewed attention for more sustainable production methods (driven by the current climate and biodiversity crises), and increasing evidence that agroforestry approaches contribute to climate-smart and biologically diverse agricultural systems (e.g., Tamburini et al., 2020; Bhattacharyya et al., 2021), it is time to more systematically integrate agroforestry practices in future rice agronomy research.

Most of the studies from Africa report on experimental work, indicating little extant practice of rice agroforestry in farmers' fields. This corresponds with our own observation that purposeful integration of trees in rice systems in Africa is uncommon. Exceptions are tree management in the context of shifting cultivation, slash-and-burn systems, that are common in humid forest zones, notably in Sierra Leone, Côte d′Ivoire and Guinea (Rouw, 1993; Sirois et al., 1998; Camara et al., 2009; Saravia-Matus and Paloma, 2015), the indigenous practice of tree planting by rice farmers in Ebonyi State, Nigeria for soil and water conservation purposes (Obinna, 2019), clove-based upland rice cultivation in Madagascar (Arimalala et al., 2019) and the practice of allowing, maintaining or managing trees in upland rice fields and in the higher fringes of inland valleys (Madge, 1995; Balasubramanian et al., 2007; Rodenburg et al., 2012), but we did not find documentation of their agronomic or economic performance.

4. Discussion

In line with the theme of the Special Issue on sustainable productivity enhancement of rice-based farming systems in Africa, the discussion below will concentrate on the opportunities and preconditions for integrating trees with rice production in Africa, with a focus on rice yield benefits and risks.

The Biomass practice and the Pre-Rice practice (e.g., with *Sesbania rostrata*) resulted in the most convincing and consistent yield improvements. Yield effects from these practices are smaller but less variable with fertiliser than without (Fig. 4). These solutions (Biomass, Pre-Rice) benefit rice yield through improvements in soil nitrogen and soil organic matter. Regarding the S Fallow practice in uplands, where a tree (or perennial shrub) is often (relay) intercropped with the rice and allowed to grow during the following off-season, the exact practice and timing matters in the assessment of effects on rice yield. During the stages before the fallow, when the fallow species is often relay sown into the rice, the rice yields are mostly reduced due to competition. However, rice yields obtained after the improved fallow period, are mostly higher than with the continuous monocrop practice. The S Fallow practice also improves soil fertility, in particular soil nitrogen content, and weed management including suppression of the parasitic weed *Striga* spp., which presence in rice systems seems restricted to Africa (Rodenburg et al., 2022). In Hedgerow practices, the evidence is less convincing and yield effects are potentially overestimated as most studies were not explicit as to whether yield estimates were including or excluding the land area occupied by the hedgerow itself. *Gliricidia sepium* and *Gmelina arborea* were the most suitable tree species for this practice. The limited number of Intercrop studies with reliable rice yield data do not allow us to draw strong conclusions on this practice and none of these Intercrop studies were done in Africa. Studies on the Dispersed practice did not present comparative rice yields but may be attractive for farmers because of the products and services derived from the trees. *Acacia nilotica* was an interesting species in this context, not only because of the benefits it provides but also because it is perceived as easy to manage (because it is self-generating), robust and widely adaptable, as it can withstand extremely dry environments and endure floods (Jones et al., 1998; Wolde-Meskel and Sinclair, 2000). These traits make the species suitable for integration in various rice production systems and growing environments.

Future rice agroforestry research should more systematically and accurately report how crop yields are assessed and expressed. For fair and comparative reporting the total area under crop and tree components need to be considered and this should be clearly communicated so that overall yields per unit area can be comparatively understood. It is also important to evaluate rice - tree cropping system performance over longer periods than the usual two to three seasons, to assess yield stability and other longer-term effects in relation to the real-world variation in field and farm context for which they may be relevant (Sinclair and Coe, 2019). In addition, fertilizer amounts, timings and compositions need to be reported alongside quantitative and qualitative information on nutrient and organic matter contributions derived from the trees.

System performance criteria other than rice yields are far less widely reported. This restricts the extent to which conclusions can be drawn with respect to the economic and environmental benefits and hence sustainability of rice agroforestry practices. Evidence of performance of practices under African conditions and with native tree species of the continent were sparse. Future research aiming at evidence-based promotion of tree integration in rice production systems, in particular in Africa, should address these main knowledge gaps. Key performance indicators (KPIs) this research should focus on need to be contextually defined in a participatory way with relevant stakeholders (Sinclair and Coe, 2019) but are likely to include those identified to assess agronomic gains (i.e., 1. productivity, incl. crop and labour productivity, 2. resource use efficiency and 3. soil health, incl. carbon sequestration, following Saito et al., 2021). Additional indicators include longer term socio-economic impacts (e.g., NPV), to take into account rotation lengths of tree components in agroforestry when assessing profitability (Do et al., 2020), food consumption score (FCS) to assess food and nutrition security (Leroy et al., 2015), gender-equity through gender disaggregated presentation of all relevant KPIs (Crossland et al., 2021) and biodiversity using species richness and native species richness at field and landscape scales and functional diversity at field scale (Lohbeck et al., 2020). A precondition for meaningful research on this topic may be for tree integration practices and benefits in African rice systems to be better characterised, in order to get a more comprehensive and systematic overview of the existence and importance of rice agroforestry in this region.

Specific focus of future agronomic research on rice agroforestry in Africa should identify and test (1) tree species and practices that minimise competition with the crop as well as (2) tree species and practices that combine multiple benefits with good adaptation to rice growing environments. For the selection of tree species and practices for rice systems in Africa the literature review and analyses presented here, can be seen as a useful starting point.

A synthesis of the environmental suitability of each agroforestry practice, their main benefits, preconditions for rice, and recommended tree species is presented in Table 1. The main identified agroforestry benefits for rice production systems are categorised as (RY) rice yield improvements, (TP) tree products, including (fuel or timber) wood, fruits, nuts, rubber, gum, resin, essential oil and spices (e.g. cloves), but also less marketable or profitable products such as biomass for fodder, mulch or soil incorporation, (EC) direct economic benefits, mostly based on these tree products (excluding biomass) or by-products (like silk, honey), (SF) soil fertility improvement, referring to positive tree-induced changes in chemical (and to a lesser extent biological) soil fertility and organic matter content, (SC) soil conservation, referring to the protection that trees can offer against soil erosion, and (WS) weed suppression, referring to the weed suppressive characteristics of trees through allelopathy or shading provided by vegetative soil coverage.

As mentioned before, the rice yield benefits are most obvious with the Biomass and Pre-Rice practices, where the trees do not compete with the crop at any stage. Tree products, on the other hand, are important benefits in practices where trees are grown together with the crop, most obviously the Hedgerow, Intercrop and Dispersed practices. The Pre-Rice practice only provides biomass for soil incorporation. The economic benefits are less widely reported than rice yields. They are mostly associated with the tree products that have clear economic value, and therefore mostly associated with Intercrop and Dispersed agroforestry practices, assuming that Hedgerow derived biomass for fodder, mulching or soil incorporation has a low monetary value. The soil fertility improvements are associated to all agroforestry practices, most obviously the Hedgerow, Biomass, Pre-Rice and S Fallow practices, that make use of leguminous tree species and are most explicitly focussed on returning and even incorporating tree biomass (in) to the soil. Soil conservation is also a general benefit across agroforestry practices, while most explicitly so in the Hedgerow practice that is often recommended for sloping land. Weed suppression is most obvious under the S Fallow practice (weeds and parasitic weeds) and, to a lesser extent, in the Biomass practice, depending on the choice of tree species (allelopathic or not) and the biomass management (soil incorporation or mulch). Apart from the yield benefits, weed suppression may have a range of associated benefits, such as labour savings from reduced weeding requirements, possible reductions in concomitant pests and diseases for which weeds act as vectors, and improved use efficiencies of resources (e.g., water and nutrients).

Seven main preconditions for rice-agroforestry are identified: Adapted species, Bunds or mounts as tree planting spaces, Pruning of tree canopy to reduce competition, Labour required for tree and associated soil management, Land availability, Tenure over land or trees and availability of Seed and planting materials of adapted tree species (Table 1). Adapted tree species, that tolerate anaerobic or flooded soil conditions, is an important precondition for the agroforestry practices Intercrop and Dispersed in rainfed and irrigated lowlands. Alternatively, tree species that are less tolerant to wet soils can be grown on bunds or mounts in the Intercrop or Dispersed practices. Selection of less competitive and non-invasive tree species and regular pruning would be necessary in all rice growing environments where the agroforestry practice dictates simultaneous presence of the trees and the rice crop. Such preconditions are much less relevant where trees and rice are separated in time, such as in Pre-Rice and Biomass practices. However, here the labour requirements may be high and there may be constraints regarding availability and costs of seed, other inputs (e.g, P fertilizers for leguminous green manure species) and water management. Other non-agronomic preconditions, that are also more generally applicable to agroforestry and not particular for rice, are related to the availability of land and (tree) planting material and land and tree tenure regulations. The precondition of the knowledge and availability of adapted planting material (precondition 'Seed' in Table 1) is less obvious for the Dispersed practice, where farmers often make use of spontaneous or regenerated trees of locally available and adapted species. Although species recommendations are very much context specific, some of the

Table 1
Synthesis of suitability of each agroforestry practice per rice growing environment (UL= upland, RL= rainfed lowland, IL= irrigated lowland), main attainable benefits per practice (RY= rice yield improvement; TP= tree products, including ones used in the farm system such as biomass for fodder, mulch or soil incorporation; SF = soil fertility improvement, referring to chemical and biological soil fertility; SC = soil conservation, referring to erosion protective functions; WS = weed suppression, by allelopathy or out shading, implying both labour savings, improved resource-use efficiencies and potential concomitant reductions in other pests and diseases; EC = non-crop related direct economic benefits), preconditions for implementation of each practice (Risks= accepting risks of rice yield losses combined with additional investments; Adapted species= the need to select tree species that are adapted to anaerobic of flooded soils; Bunds= requirement of bunds or mounts as tree planting spaces to enable tree growth; Pruning= the need to conduct regular tree pruning/trimming to reduce shade/avoid competition; Labour= the need for additional time required to manage the tree component of the agroforestry practice, including planting, fertilisation, pruning, thinning, mulching, slashing, soil incorporation; Land= availability and willingness to sacrifice land area for non-productive purposes; Tenure= conducive land and tree tenure rights allowing long-term investments; Seed= knowledge and availability of adapted tree planting material) and a selection of (max. 3) suggested tree/shrub species based on literature reports (environmental suitability, main benefits and preconditions for rice do not necessarily apply to all species).

Agroforestry practice	Environmental suitability[a]			Main benefits[b]						Preconditions for rice-agroforestry[c]							Tree species[d]
	UL	RL	IL	RY	TP	EC	SF	SC	WS	Adapted species	Bunds	Pruning	Labour	Land	Tenure	Seed	
Hedgerow	+ +	–	–	+ /-	+	–	+ +	+ +	+ /-	–	–	+ +	+ +	+	+ +	+	CASSM, GMEAR, GLRSE
Biomass	+ +	+ +	+ +	+ +	+ /-	–	+ +	+	+	–	–	–	+ +	+ /-	+ /-	+	ERZVA, TEPCA, ACAAF
S Fallow	+ +	+ /-	+ /-	+ /-	+ /-	–	+ +	+[(UL)]	+ +[(UL)]	–	–	+ /-	+	+ /-	+ /-	+	CAJCA, LUAGL, STYGN
Pre-Rice	+ /-	+	+ +	+ +	–	–	+ +	+ /-	+ /-	+[(RL/IL)]	–	–	+ +	–	–	+	SEBRO, AESAF
Intercrop	+ +	+ /-	+ /-	+ /-	+ +	+ +	+	+	+ /-	+ +[(RL/IL)]	+ +[(RL/IL)]	+ +	+	+ /-	+	+	GMEAR, PRKJA, SYZAR
Dispersed	+	+	+	–	+ +	+ +	+	+	–	+ +[(RL/IL)]	+ +[(RL/IL)]	+ +	+	+ /-	+ +	–	ACANL, MEIAD, TAMIN

[a] very suitable: + +; suitable: + ; provisionally suitable: + /-; unsuitable or not applicable: -;
[b] highly likely: + +; likely: + ; conditionally: + /-; unlikely or not applicable or known: -;
[c] highly important: + +; important: + ; context specific: + /-; not important or not applicable: -;
[d] EPPO codes of agriculturally important plant species (https://gd.eppo.int,), CASSM: *Senna siamea*, GMEAR: *Gmelia arborea*, GLRSE: *Gliricidia sepium,* ERZVA: *Erythrina indica*, TEPCA: *Tephrosia candida*, ACAAF: *Acacia auriculiformis*, CAJCA: *Cajanus cajan*, LUAGL: *Leucaena leucocephala*, STYGN: *Stylosanthes guianensis*, SEBRO: *Sesbania rostrata*, AESAF: *Aeschynomene afraspera*, PRKJA: *Parkia roxburghii*, SYZAR: *Syzygium aromaticum.* ACANL; *Acacia nilotica*, MEIAD: *Azadirachta indica*, TAMIN: *Tamarindus indica.*

tree species with good performance were *Gliricidia sepium* and to a lesser extent *Gmelia arborea* and *Senna siamea* for Hedgerow, *Erythrina indica*, *Tephrosia candida* and *Acacia auriculiformis* for Biomass, *Stylosanthes guianensis*, *Cajanus cajan* and *Leucaena leucocephala* for S Fallow, *Sesbania rostrata* and *Aeschynomene afraspera* for Pre-Rice, *Parkia roxburghii*, *Syzygium aromaticum* and again *Gmelia arborea* for Intercrop and *Acacia nilotica*, *Azadirachta indica* and *Tamarindus indica* for Dispersed (Table 1).

5. Conclusions

A wide range of woody perennial species numbering 204 in total, referred to here as trees, have been integrated with rice production around the world in six different types of improved agroforestry practices, involving different levels of interaction amongst trees and rice in time and space. Reports on extant rice agroforestry practices are predominantly from Asia. Deliberate integration of trees with rice production in Africa is less frequently observed and described in peer-reviewed sources.

Across the different types of agroforestry practices measured worldwide, where fertilizer was not used, on average trees increased rice yield over a monoculture control. When both the rice-agroforestry practice and the monoculture control receive fertilizers, rice yields are increased with trees in low-productivity environments only, or in practices where trees do not directly interfere with rice (i.e, Biomass and Pre-Rice). In higher yielding environments, in cases where trees are grown simultaneously with rice (i.e., Hedgerow and Intercrop practices), rice yields are reduced due to competition. The reported yield ranges in the literature imply that smallholder rice farmers adopting agroforestry practices are exposed to yield loss risks, which could be an important adoption disincentive in particular when the practices also require high labour inputs and other costs. The Biomass and Pre-Rice practices (most often applied in, but not restricted to, lowland rice systems), and to a lesser extent, the Hedgerow practice (in upland rice systems) are the most beneficial practices in terms of enhancing rice yield. These practices would be particularly beneficial under situations where fertilizers are not available or affordable.

Two widely suitable tree species for rice-based systems in Africa identified from those already tested are *Sesbania rostrata* and *Acacia auriculiformis*. These two species have proven yield-enhancing effects on rice, without additional fertilizer inputs (although applications of P fertilizer are recommended) and are already widely distributed on the continent and well adapted to African environments. Other potentially interesting species with broad applicability are *A. nilotica, Gliricidia sepium* and *Gmelia arborea*. There are many native and naturalised species in Africa well-adapted to local ecological and socio-economic contexts that might be incorporated in rice production, but these remain to be identified and tested. Future research and development investments should also explore and exploit wider economic and environmental benefits from rice agroforestry and address constraints to adoption of agroforestry practices by smallholder rice farmers in Africa.

Given the urgent need to develop sustainable agricultural systems that mitigate and adapt to climate change, and the established role that the incorporation of trees with crops can contribute to such outcomes, rice agroforestry in Africa merits greater attention than it has so far received.

CRediT authorship contribution statement

J.R. and F.S. initiated the study; J.R. reviewed papers and assembled data; R.C. and J.R. analyzed data and generated tables and figures; J.R., E.M., R.C. and F.S. collectively wrote the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Rice agroforestry studies: tree species, EPPO codes of species, agroforestry practices (Hedgerow, Biomass, S Fallow, Pre-Rice, Intercrop or Dispersed), rice growing environment (Env., UL= upland, RL= rain-fed lowland, IL= irrigated lowland, NA=information not available), system benefits (G. manure= green manure; S. conservation= soil conservation; S. fertility= soil fertility; S. organic matter= soil organic matter) and downsides –as explicitly specified in the studies under review—, countries and literature sources. Any open cells imply non-availability of information from the specific publication.

Species	EPPO[1]	AF Practices	Env.	Benefits	Downsides	Countries	Sources
Cassia spectabilis	CASSP	Hedgerow	UL	S. conservation, soil fertility, N and P contributions, fodder, mulch weed control, biomass	Crop competition, insect pests, rice blast, inorganic fertilizers required	Philippines	[3–6, 8]
Peltophorum dasyrrachis	PEFSS	Hedgerow	UL	Timber, charcoal, firewood, soil improvement	Relative low N and P content in biomass	Indonesia	[77,80]
Inga edulis	INGED	Hedgerow	UL	Weed control (mulch)	Rice yield reductions, decreasing soil P, shade	Peru	[13]
Erythrina indica	ERZVA	Hedgerow	UL	N supply, improved soil C, rice yield	Rice yield reductions, decreasing soil P, shade	India, Peru	[13,30]
Leucaena leucocephala	LUAGL	Hedgerow, S Fallow	UL	Weed control, biomass, soil N and P increase, food, charcoal	Rice yield reduction, decreasing soil P, shade	Bangladesh, Laos, Thailand Peru, Philippines	[7, 12–17, 19, 82]
Gliricidia sepium	GLRSE	Hedgerow, S Fallow	UL	Soil N, rice yield, s. conservation, fodder, weed control, biomass	Fertilizer required, poor tree establishment, crop competition, insect pests, rice blast	Philippines, Indonesia, Laos, S. Leone	[1–11, 77, 80]

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Species	EPPO[1]	AF Practices	Env.	Benefits	Downsides	Countries	Sources
Calliandra calothyrsus	CDACA	Hedgerow, S Fallow	UL	Rice yield	External fertilizer required	Indonesia, Laos, Philippines	[2, 14, 16]
Flemingia congesta, F. macrophylla	FLEMA	Hedgerow, S Fallow, Dispersed	UL	S. conservation, fodder, rice yield	External fertilizer required	Philippines, Laos, Indonesia	[2, 3, 7, 14, 77, 80]
Tephrosia candida	TEPCA	Hedgerow, S Fallow, Biomass	UL	G. manure, s. conservation, rice yield	Competition, bird attraction, labour requirement, costly seeds	Vietnam	[57]
Paraserianthes falcataria	PSZFA	Hedgerow, Dispersed	UL	Rice yield	External fertilizer required, shade	Indonesia, Bangladesh	[2, 12, 44]
Senna siamea	CASSM	Hedgerow, Dispersed, Biomass	UL, RL, IL	Improved soil N and C, rice yield	Highly competitive	S. Leone, Gambia, Bangladesh, India, Laos, Thailand	[11, 12, 29, 30, 19, 67, 82]
Gmelina arborea	GMEAR	Hedgerow, Intercrop	UL, IL	Soil microbial biomass, biomass N content	Poor survival	S. Leone, Bangladesh, India	[11, 12, 19, 64]
Phyllanthus taxodiifolius	PYLSS	Biomass	UL, RL	G. manure, firewood, rice yield		Laos, Thailand	[58,82]
Acacia auriculiformis	ACAAF	Biomass	UL, IL	Improved soil N and C, rice yields	Poor flood tolerance at seedling stage	Bangladesh, Philippines, India	[12, 16, 19, 30, 58]
Sesbania sesban	SEBSE	Biomass, S Fallow	UL		Poor survival hence not suitable for S Fallow,	Laos, Philippines, Thailand	[7, 14, 16]
Parkia roxburghii	PRKJA	Biomass, Intercrop	IL	Improved soil C and N, rice yield		India	[30,34]
Alnus nepalensis	ALUNE	Biomass, Intercrop, Dispersed	NA	Improved soil C and N, fuelwood, fodder		India	[30, 34, 35]
Cajanus cajan	CAJCA	S Fallow	UL	Rice yield, weed and nematode (M. graminicola) control, improved soil N and P	Variable/limited rice yield increase	India, Laos, Côte d'Ivoire	[7, 14, 15, 23, 58, 84–87]
Tephrosia villosa	TEPVL	S Fallow	UL	Rice yield, g. manure	Requires management	Côte d'Ivoire	[84–86]
Tephrosia purpurea	TEPPU	S Fallow	UL	Fodder		Côte d'Ivoire	[84]
Aeschynomene hystrix	AESHY	S Fallow	UL	Biomass, weed control, fodder		Côte d'Ivoire	[84,85]
Sesbania emerus	SEBSS	S Fallow	UL	G. manure	Low survival	Côte d'Ivoire	[84]
Sesbania speciosa	SEBSS	S Fallow	UL	G. manure	Low survival	Côte d'Ivoire	[84]
Sesbania cannabina	SEBCA	S Fallow	UL	G. manure	Low-medium survival	Côte d'Ivoire	[84]
Aeschynomene americana	AESAM	S Fallow	UL	Fodder		Côte d'Ivoire	[84]
Stylosanthes hamata	STYHA	S Fallow	UL		Slow growth	Laos, Côte d'Ivoire	[7,87]
Crotalaria juncea	CVTJU	S Fallow	UL	Biomass, weed control	Not broadly adapted	Côte d'Ivoire	[84–86]
Crotalaria retusa		S Fallow	UL	G. manure, biomass	Not broadly adapted	Côte d'Ivoire	[84]
Crotalaria anagyroides	CVTAN	S Fallow, Intercrop	UL	Weed control, rice yield	Poor survival of shrub into next crop season	Laos	[7, 84, 85]
Stylosanthes guianensis	STYGN	S Fallow, Intercrop	UL	Weed control (incl. *Striga*), S. conservation, s. fertility, biomass	Competition with rice crop	Laos, Benin, Philippines, Madagascar	[8, 39, 40, 50, 81, 84, 85]
Sesbania rostrata	SEBRO	Pre-Rice, S Fallow	RL, IL	Improved soil N, rice yield	Low survival, not suitable for S Fallow	S. Leone, Laos, Philippines, Thailand	[17, 31–33, 53,54, 56, 77–79, 84, 87]
Aeschynomene afraspera	AESAF	Pre-Rice, S Fallow	RL	G. manure	Low survival, not suitable for S Fallow	Thailand	[53,84]
Melaleuca leucadendra	MLALE	Intercrop	IL	C sequestration, essential oil, fuel wood	Slow growth	Indonesia	[42]
Eucalyptus tereticornis	EUCTR	Intercrop	UL, IL	Soil organic matter, high value timber	Rice yield reduction	India	[21, 23, 25–27, 55, 73]
Eucalyptus camaldulensis	EUCCM	Intercrop	RL, IL	Bioherbicide, timber, s. fertility, shade, pulp	Rice yield reduction due to shading, competition for water	Bangladesh, Pakistan, Thailand, Brazil	[19, 62, 67, 71, 73]
Morus alba	MORAL	Intercrop	UL	Silk, wood, fodder, fuel, bioherbicide	Rice yield reduction	India, Philippines, Pakistan	[3, 26, 37, 63]
Terminalia arjuna	TEMAJ	Intercrop	IL	Soil organic & microbial carbon		Bangladesh, India	[12, 19, 64]
Michelia oblonga	MAGOB	Intercrop	NA	Improves soil C and N content	Allelopathy	India	[34,43]
Bombax ceiba	BOMCE	Intercrop	NA	Soil improvement	Rice yield reduction	Bangladesh, India	[20,64]
Persea kurzii	PEBSS	Intercrop	UL	Firewood, aromatic bark		Laos	[51]
Lagerstroemia parviflora	LAESS	Intercrop	IL			India	[64]
Pinus kesiya	PIUKE	Intercrop	NA NA	Improved soil C and N		India	[33]
Salix tetrasperma	SAXTE	Intercrop	IL	Rice yield, soil improvement		India	[64]
Pongamia pinnata	PNGPI	Intercrop	IL			India	[64]
Bixa orellana	BIXOR	Intercrop	IL	Rice yield, soil improvement		India	[64]
Eucalyptus urograndis	EUCUG	Intercrop	UL	Soil organic carbon		Brazil	[70]
Eucalyptus pellita	EUCPJ	Intercrop	UL			Brazil	[71]
Calophyllum inophyllum	CMUIN	Intercrop	UL	Timber, biofuel, honey		Indonesia	[72]
Syzygium aromaticum	SYZAR	Intercrop	UL	Essence, cloves		Madagascar	[75]
Hevea brasiliensis	HVEBR	Intercrop	UL	Rubber (latex)		Philippines	[69]

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Species	EPPO[1]	AF Practices	Env.	Benefits	Downsides	Countries	Sources
Salvadora persica	SVDPE	Intercrop, Dispersed	IL	Fruits		India	[46]
Punica granatum	PUNGR	Intercrop, Dispersed	IL	Fruits		India	[46]
Elaeis guineensis	EAIGU	Intercrop, Dispersed	UL, RL	Palm oil		Guinea, Thailand	[61,67]
Grewia optiva	GRWOP	Intercrop, Dispersed	UL	Fodder, fuelwood, sericulture, basketry, timber	Rice yield reduction	India	[26,35]
Acacia nilotica	ACANL	Intercrop, Dispersed	UL, RL	Soil improvement, rice performance, fuel, fodder timber, medicine	Yield reduction (due to shading)	India, Bangladesh	[18–24]
Tectona grandis	TCTGR	Intercrop, Dispersed	UL, IL	High value timber production	Allelopathic to rice	India, Laos, Thailand	[27, 28, 43, 62, 67, 68]
Mangifera indica	MNGIN	Dispersed	UL, IL	Fruits (mango), bioherbicide, g. manure, timber	Rice yield reduction (due to shading)	Bangladesh, Laos, Thailand. Pakistan	[17, 20, 28, 49, 61, 63, 66–68, 82]
Azadirachta indica	MEIAD	Dispersed	RL, IL	Weed & insect pest control, food, timber, medicine	Inhibits rice germination	Bangladesh, Laos, Thailand	[12, 17, 19, 59, 60, 66–68, 82]
Dipterocarpus tuberculatus	DIXSS	Dispersed	RL, IL	Timber, resin, charcoal, fuel wood	Competes for soil nutrients	Laos, Thailand	[17, 66, 68, 69, 83]
Irvingia malayana	IRVSS	Dispersed	RL, IL	Timber, g. manure, charcoal, food, fodder, rice yield		Laos, Thailand	[17, 65, 67, 68, 82]
Tamarindus indica	TAMIN	Dispersed	RL, IL	G. manure, food		Bangladesh, Laos, Thailand	[12, 17, 65, 67,68, 82]
Samanea saman	PIFSA	Dispersed	IL	Soil organic matter, N, P, K, Ca, and Mg	Rice yield reduction (due to shading)	Thailand, Bangladesh	[12, 17, 19, 38, 58, 67, 68, 82]
Butea monosperma	BUAMO	Dispersed	RL, IL			India, Laos, Thailand	[41, 65, 67, 82]
Parinari anamensis	PNASS	Dispersed	RL, IL	Soil fertility, food, fuelwoord	Rice yield reduction (due to shading)	Laos, Thailand	[38,67, 68, 82]
Shorea obtusa	SHOSS	Dispersed	NA	Charcoal, fuelwood, timber, resin		Thailand	[17, 67, 75, 82]
Xylia xylocarpa	XYLXY	Dispersed	NA	Timber, fuelwood, food		Laos, Thailand	[17, 67, 68, 82]
Pterocarpus macrocarpus	PTKSS	Dispersed	RL	G. manure, timber. fuelwood, fodder		Laos, Thailand	[17, 67, 68, 82]
Terminalia alata	TEMAT	Dispersed	RL, IL	Timber, charcoal, fuelwood, medicine, g. manure		Laos, Thailand	[65, 68, 82]
Lagerstroemia macrocarpa	LAEMA	Dispersed	NA	Ornamental, firewood		Laos, Thailand	[67,82]
Shorea siamensis	SHOSS	Dispersed	NA	G. manure, timber, fuelwood resin		Laos, Thailand	[67,82]
Combretum quandrangulare	COGSS	Dispersed	RL	Shade, timber, firewood		Laos, Thailand	[67,82]
Sindora siamensis	SIQSI	Dispersed	RL	Timber, g. manure		Laos, Thailand	[67,82]
Careya arborea	CBRAR	Dispersed	RL	Food, medicine		Laos, Thailand	[67,82]
Michelia champaca	MIACH	Dispersed	NA	Timber	Allelopathic to rice	Thailand, India	[43,67]
Diospyros rhodocalyx	DOSSS	Dispersed	RL	Shade, s. fertility	Rice yield reduction (due to shading)	Thailand	[67]
Shorea roxburghii	SHORX	Dispersed		G. manure, timber. charcoal		Thailand	[67]
Afzelia xylocarpa	AFZCO	Dispersed	RL	Timber		Thailand	[67]
Dipterocarpus alatus	DIXAL	Dispersed	RL	S. fertility, timber, shade	Rice yield reduction (due to shading)	Thailand	[67]
Dipterocarpus intricatus	DIXSS	Dispersed	RL, IL	S. fertility, timber, fuelwood	Shade and resin reduced rice yields	Laos, Thailand	[38, 65, 67, 68, 82]
Dalbergia sissoo	DAGSI	Dispersed		Timber, fodder, fuelwood	Allelopathy	Bangladesh, India	[12, 19, 35, 36]
Cocos nucifera	CCNNU	Dispersed	UL, IL	Food, fuel, handicraft		Laos, Thailand, Indonesia	[28, 68, 82, 83]
Dipterocarpus obtusifolius	DIXSS	Dispersed	RL, IL	Soil fertility, timber, resin, charcoal, fuelwood	Shade and resin, reduced rice yields	Laos, Thailand	[38, 65, 68, 82]
Albizia lebbekoides	ALBLE	Dispersed	UL	Timber, fuelwood, fodder		India, Laos	[35, 41, 82]
Ceiba pentandra	CEIPE	Dispersed	RL, IL	Handicraft, food, fiber		Bangladesh, Laos, Thailand	[19, 68, 82]
Streblus asper	SBWAS	Dispersed	RL, IL	Firewood, fodder, food, medicine		Laos, Thailand	[67, 68, 82]
Acacia catechu	ACAPQ	Dispersed	IL	Fodder timber		Bangladesh	[20,49]
Artocarpus integrifolia, A. heterophyllus	ABFIN, ABFHE	Dispersed	IL	Fruits (jackfruit)	Rice yield reduction (due to shading)	Bangladesh	[20,49]
Populus deltoides	POPDE	Dispersed	NA	Improved soil organic matter, timber		India	[21,23]
Acacia albida	ACAAB	Dispersed	NA			Bangladesh	[12,19]
Acacia mangium	ACAMG	Dispersed	NA			Bangladesh	[12,19]
Anthocephalus cadamba	AQHCH	Dispersed	IL			Bangladesh	[12,19]
Borassus flabellifer	BASFL	Dispersed	IL			Bangladesh, Thailand	

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Species	EPPO[1]	AF Practices	Env.	Benefits	Downsides	Countries	Sources
				Sugar, fruits, wind break, timber, carbon sequestration			[49, 68, 76, 82]
Sesbania grandiflora	SEBGR	Dispersed	NA	N provision, food		Thailand	[17,68]
Syzygium cumini	SYZCU	Dispersed	RL	G. manure		Laos	[65,67]
Melia azedarach	MEIAZ	Dispersed	NA			Bangladesh	[12,19]
Terminalia bellirica	TEMBL	Dispersed	NA	Timber	Rice yield reduction	Bangladesh, Laos	[19,82]
Psidium guajava	PSIGU	Dispersed	UL, RL	Fruits, medicine		Guinea, Laos	[61,82]
Morinda tomentosa	MOJCI	Dispersed	RL	G. manure, medicine		Laos	[65,82]
Cassia fistula	CASFI	Dispersed	RL, IL	Timber		Laos, Thailand	[68,82]
Schleichera oleosa	SHHOL	Dispersed	RL, IL	Food, fuelwood		Laos, Thailand	[[68,82]
Spondias pinnata	SPXPI	Dispersed	RL, IL	Food		Laos, Thailand	[68,82]
Casaurina equisetifolia	CSUEQ	Dispersed	NA			Bangladesh	[12]
Boehmeria rugulosa	BOHSS	Dispersed	UL	Fodder, fuelwood		India	[35]
Celtis australis	CETAU	Dispersed	UL	Fodder, fuelwood		India	[35]
Ficus glomerata	FIUGM	Dispersed	UL	Fodder, fuelwood		India	[35]
Ficus religiosa	FIURE	Dispersed	RL			Laos	[65]
Lagerstroemia speciosa	LAESP	Dispersed	NA	Timber		Bangladesh	[12]
Parkinsonia aculeata	PAKAC	Dispersed	NA			Bangladesh	[12]
Phoenix sylvestris	PHXSY	Dispersed	IL			Bangladesh	[19]
Pyrus pashia	PYUPA	Dispersed	UL	Fuel wood, fodder		India	[35]
Albizia procera	ALBPR	Dispersed	NA			Bangladesh	[19]
Prunus cerasoides	PRNCS	Dispersed	UL	Fuelwood, fodder		India	[35]
Swietenia mahagoni	SWIMG	Dispersed	NA			Bangladesh	[19]
Nephelium lappaceum	NEELA	Dispersed	UL, RL	Fruits		Indonesia	[52]
Raphia ruffia	RAJFA	Dispersed	UL, RL	Palm wine, fibre		Guinea	[61]
Mitragyna diversifolia	MTGSS	Dispersed	RL	Charcoal, fuelwood		Thailand	[67]
Dolichandrone spathacea	DQLSP	Dispersed	RL	Food, timber		Thailand	[67]
Bambusa arundinecea	BAMBM	Dispersed	RL, IL	Food, materials		Thailand	[68]
Ziziphus jujuba	SIPJS	Dispersed	RL, IL	Food, shade		Thailand	[68]
Populus nigra	POPNI	Dispersed	IL	Wind break		Kyrgystan	[74]
Oroxylum indicum	OOXIN	Dispersed	RL, IL	Food		Laos	[82]
Annona squamosa	ANUSQ	Dispersed	RL, IL	Food		Laos	[82]
Millingtonia hortensis	MZLHO	Dispersed	RL, IL	Medicine		Laos	[82]
Jatropha curcas	IATCU	Dispersed	RL, IL			Laos	[82]
Ziziphus mauritania	ZIPMA	Dispersed	RL, IL	Food		Laos	[82]
Ziziphus oenopolia	ZIPOE	Dispersed	RL, IL			Laos	[82]
Ziziphus cambodiana	ZIPSS	Dispersed	RL, IL			Laos	[82]
Bambusa blumeana	BAMSS	Dispersed	RL, IL	Food, timber, handicraft		Laos	[82]
Bambusa bambos	BAMBM	Dispersed	RL, IL	Food, handicraft		Laos	[82]
Carica papaya	CIAPA	Dispersed	RL, IL	Food		Laos	[82]
Plumeria obtusa	PLIOB	Dispersed	RL, IL			Laos	[82]
Delonix regia	DEXRE	Dispersed	RL, IL	Food		Laos	[82]
Crescentia cujete	KTQCU	Dispersed	RL, IL	Handicraft		Laos	[82]
Calotropis gigantea	CTRGI	Dispersed	RL, IL			Laos	[82]
Phyllanthus acidus	PYLAC	Dispersed	RL, IL	Food		Laos	[82]
Phyllanthus emblica	PYLEM	Dispersed	RL, IL	Food		Laos	[82]
Cassia alata	CASAL	Dispersed	RL, IL	Medicine		Laos	[82]
Aporosa villosa	ZPSSS	Dispersed	RL, IL	Medicine		Laos	[82]
Mitragyna rotundifolia	MTGSS	Dispersed		Timber		Laos	[82]

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Species	EPPO[1]	AF Practices	Env.	Benefits	Downsides	Countries	Sources
			RL, IL				
Terminalia mucronata	TEMSS	Dispersed	RL, IL	Charcoal		Laos	[82]
Terminalia chebula	TEMCH	Dispersed	RL, IL			Laos	[82]
Terminalia glaucifolia	TEMSS	Dispersed	RL, IL	Firewood, timber		Laos	[82]
Dillenia ovata	DLNOV	Dispersed	RL, IL	Food		Laos	[82]
Gluta usitata	MLRUS	Dispersed	RL, IL			Laos	[82]
Strychnos nux-blanda	SYHNV	Dispersed	RL, IL	Medicine		Laos	[82]
Lophopetalum wallichii	LHPSS	Dispersed	RL, IL	Food		Laos	[82]
Syzygium gratum	SYZAN	Dispersed	RL, IL	Food		Laos	[82]
Calycopteris floribunda	COGSE	Dispersed	RL, IL	Firewood		Laos	[82]
Diospyros mollis	DOSSS	Dispersed	RL, IL	Firewood, food		Laos	[82]
Diospyros montana	DOSMN	Dispersed	RL, IL			Laos	[82]
Olax scandens	OLXSS	Dispersed	RL, IL	Food		Laos	[82]
Maytenus marcanii	MYUSS	Dispersed	RL, IL	Food		Laos	[82]
Salacia chinensis	SLXCH	Dispersed	RL, IL	Firewood, medicine		Laos	[82]
Naringa crenulata	NGICR	Dispersed	RL, IL	Food		Laos	[82]
Acacia harmandiana	ACASS	Dispersed	RL, IL	Firewood, medicine		Laos	[82]
Crateva adansonii	CVAAD	Dispersed	RL, IL	Firewood		Laos	[82]
Haldina cordifolia	AFNCO	Dispersed	RL, IL	Firewood		Laos	[82]
Cananga latifolia	CANSS	Dispersed	RL, IL	Timber, firewood		Laos	[82]
Capparis flavicans	CPPSS	Dispersed	RL, IL			Laos	[82]
Bombax anceps	BOMAN	Dispersed	RL, IL			Laos	[82]
Oxyceros horridus	OXWSS	Dispersed	RL, IL	Medicine		Laos	[82]
Casearia grewiaefolia	CWSSS	Dispersed	RL, IL	Medicine		Laos	[82]
Lepisanthes rubiginosa	LQZRU	Dispersed	RL, IL	Food		Laos	[82]
Breynia glauca	BYISS	Dispersed	RL, IL			Laos	[82]
Holarrhena curtisii	HRHSS	Dispersed	RL, IL			Laos	[82]
Catunaregam tomentosa	KTUSS	Dispersed	RL, IL			Laos	[82]
Croton roxburghii	CVNSS	Dispersed	RL, IL			Laos	[82]
Morus macroura	MORMA	Dispersed	RL, IL	Food		Laos	[82]
Artocarpus lakoocha	ABFLA	Dispersed	RL, IL	Food		Laos	[82]
Trachelospermum asiaticum	TCHAS	Dispersed	RL, IL			Laos	[82]
Suregada multiflora	SGASS	Dispersed	RL, IL			Laos	[82]
Hura crepitans	HURCR	Dispersed	RL, IL	Firewood		Laos	[82]
Sterculia pexa	SRLSS	Dispersed	RL, IL	Timber, medicine		Laos	[82]
Wrightia arborea	WRIAR	Dispersed	RL, IL	Firewood		Laos	[82]
Dialium cochinchinense	DJACO	Dispersed	RL, IL	Timber, food		Laos	[82]
Urena lobata	URNLO	Dispersed	RL, IL			Laos	[82]

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Species	EPPO[1]	AF Practices	Env.	Benefits	Downsides	Countries	Sources
Helicteres hirsuta	HCTSS	Dispersed	RL, IL			Laos	[82]
Helicteres lantana	HCTSS	Dispersed	RL, IL			Laos	[82]
Durio zibethinus	DURZI	Dispersed	UL	Food		Indonesia	[83]
Cinnamomum burmanii	CINBU	Dispersed	UL	Food		Indonesia	[83]
Pithecellobium lobatum	PIFLO	Dispersed	UL			Indonesia	[83]
Parkia speciosa	PRKSP	Dispersed	UL			Indonesia	[83]

[1]For EPPO codes ending at 'SS' the species-specific EPPO code is not available.

Literature sources: **1.** (Agus et al., 1998), **2.** (Evensen et al., 1994), **3.** (Fujisaka et al., 1994), **4.** (Garrity and Mercado, 1994), **5.** (Maclean et al., 1992), **6.** (MacLean et al., 2003), **7.** (Roder et al., 1998), **8.** (Samsuzzaman et al., 1999), **9.** (Schroth et al., 1995a), **10.** (Schroth et al., 1995b), **11.** (Amara et al., 1996), **12.** (Hocking and Islam, 1995), **13.** (Salazar et al., 1993), **14.** (Roder and Maniphone, 1998), **15.** (Saito et al., 2008), **16.** (Stewart, 1992), **17.** (Vityakon and Dangthaisong, 2005), **18.** (Bargali et al., 2009), **19.** (Hocking and Islam, 1998), **20.** (Hocking et al., 1997), **21.** (Kaur et al., 2000), **22.** (Pandey and Sharma, 2003), **23.** (Singh et al., 1997), **24.** (Viswanath et al., 2000), **25.** (Stille et al., 2011), **26.** (Khybri et al., 1992), **27.** (Mutanal et al., 2001), **28.** (Roder et al., 1995), **29.** (Danso and Morgan, 1993), **30.** (Tomar et al., 2013), **31.** (Bar et al., 2000), **32.** (Buresh et al., 1993b), **33.** (Buresh et al., 1993a), **34.** (Ramesh et al., 2014), **35.** (Semwal et al., 2002), **36.** (Akhtar et al., 2010), **37.** (Dhyani et al., 1996), **38.** (Sae-lee et al., 1992), **39.** (Saito et al., 2010), **40.** (Saito et al., 2006), **41.** (Singh et al., 2008), **42.** (Budiadi and Ishii, 2010), **43.** (Bhatt et al., 2009), **44.** (Evensen et al., 1995), **45.** (Saito et al., 2009), **46.** (Dagar et al., 2001), **47.** (Schroth and Zech, 1995), **48.** (Bhatt and Misra, 2003), **49.** (Hocking and Islam, 1994), **50.** (Randrianjafizanaka et al., 2018), **51.** (van der Meer Simo et al., 2020), **52.** (Godoy and Feaw, 1991), **53.** (McDonagh et al., 1995), **54.** (Herrera et al., 1997), **55.** (Dagar et al., 2016), **56.** (Toomsan et al., 2000), **57.** (Hoang Fägerstrom et al., 2001), **58.** (Whitbread et al., 1999), **59.** (Xuan et al., 2004), **60.** (Nathan et al., 2005), **61.** (Camara et al., 2009), **62.** (Bhatt and Singh, 2009), **63.** (Khaliq et al., 2012), **64.** (Panwar et al., 2013), **65.** (Miyagawa et al., 2013), **66.** (Miyagawa et al., 2017), **67.** (Pham et al., 2015), **68.** (Watanabe et al., 2017), **69.** (Hondrade et al., 2017), **70.** (Oliveira et al., 2018), **71.** (Cordeiro et al., 2018), **72.** (Rahman et al., 2019),**73.** (Phimmavong et al., 2019), **74.** (Thevs et al., 2019), **75.** (Arimalala et al., 2019), **76.** (Dumrongrojwatthana et al., 2020), **77.** (Whitmore et al., 2000), **78.** (Becker et al., 1995), **79.** (Ndoye et al., 1996), **80.** (Hairiah et al., 2000), **81.** (Rodenburg et al., 2020), **82.** (Kosaka et al., 2006), **83.** (Murniati et al., 2001), **84.** (Becker and Johnson, 1998), **85.** (Becker and Johnson, 1999), **86.** (Akanvou et al., 2000), **87.** (Akanvou et al., 2002).

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