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Recent advances in maize production in integrated systems: A review

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Abstract. Maize is an important crop around the world supporting food security, especially in developing countries. The increasing demand for food and renewable energy resources has been supported studies of competitiveness and complementarity interactions between trees, crops, and animals. Thus, the integrated systems should promote a synergic relationship between the components, resulting in greater production of crops, animals, and forestry. Our objective was to describe recent advances on maize production in integrated systems and how recent research can contribute to intensify and/or diversify the production system. The current literature supports the following appointments. The increase in the soil organic carbon in integrated systems improves the physical (density and aggregate stability), chemical (nutrient retention), and biological (greater diversity and microbial mass) properties. Great grain yield and input reduction are possible with the microbial inoculants' use. The inoculants' action is maximized when associated with fertilizers and/or biochar. The biochar acts as a soil conditioner, increasing the water and nutrients retention in the soil, favoring the maize growth. Maize can be grown in the understory (moderate shade), but productivity will be reduced. Thus, we identified the need for research on shading-tolerant genotypes, intercropped management to minimizes competition, quantification of the stratified light profile by a system component (tree, maize, and grass), and more complex and accurate mathematical models to support decisions in the integrated systems arrangements. Understanding these practices would encourage producers to enhance the use of integrated systems.
Keywords. agroforestry, grain yield, forage mass, shade, soil quality

Introduction

Sustainable systems have been discussing in international forums, as well as rational land use, environmental issues, and, mainly, deforestation of the Brazilian Amazon rainforest. Many of these discussions are more driven by economical protectionism rather than the search for socioenvironmental solutions, which should support sustainable production systems. Nevertheless, Brazil and other developing countries have strongly contributed to world food security, especially maize production, due to the increasing demand for food (Herforth et al., 2020).

The need to intensify production associated with breaking paradigms has transformed the world agricultural sector, which has invested efforts in diversifying and increasing productivity with less environmental impacts (Röös et al., 2017). Maize is one of the crops at the intensification vanguard due to advances in breeding research and the development of cultivars adapted to a broad edaphoclimatic condition, followed by the development of nutritional management, pest, and weed control (Manchanda et al., 2018). Thus, maize became the most produced crop in the world with 1.12 billion tons, and the largest producers are the United States, China, and Brazil (FAS-USDA, 2019).

In addition to the high use of maize for human and animal feed, there is an increased demand for renewable energy such as biodiesel and ethanol. This demand boosted the number of companies installing great industries in Brazil, enhancing the maize demand to produce ethanol and distilling co-products. As a result, there is a need to increase maize production to support the enhanced demand (Subramaniam et al., 2020). Assuming that the opening of new land is not an option due to environmental reasons, we should work to: increase production in degraded pasture areas and the intensification of current cropping systems.

In both conditions, integrated systems appear as a promising strategy for the recovery of degraded areas, introducing row crops to intensifying forage-livestock systems (Carvalho et al., 2019; Domiciano et al., 2020; Silva, Da et al., 2020). Although the practice of integrated systems dates back to the early days of agriculture (Anghinoni et al., 2013), in Brazil the current format is recent and has been incentivized by the Low Carbon Agriculture Plan (Brazil acronym, Plano ABC) of the Minister of Agriculture, Livestock and Food Supply (Brazil acronym, MAPA) (Carvalho et al., 2014).

The integrated systems should be arranged to address the particularities of each region to promote a synergistic relationship between the components, enhancing crops, animals, and/or trees production, and consequently improving the social, economic, and environmental aspects of the system (Costa et al., 2018).

Thus, our objective was to describe the recent advances in integrated systems with maize production and the gaps that research needs to advance. We searched several databases throughout the world to identify manuscripts through keywords including integrated systems, integrated systems, and maize production, not limited by geographic region or climate. We do not intend to include all literature, but a representative subset that provides a recent advance and, in some cases, represents the diversity of opinion.

The maize

Maize belongs to the *Poales* order, *Poaceae* family, *Panicoideae* subfamily, *Maydeae* tribe, *Zea* genus, *Zea mays* species (Brieger & Blumenschein, 1966). The most accepted origin of maize is the American tropical region, probably Mexico. This culture was initially cultivated by the Mayan and Aztec peoples, who not only fed on it but also had a religiously meaning (Iltis, 2009).

Maize has great worldwide importance, not only for the greatest producing countries such as the United States, Brazil, China, and the European Union as an export product, and broadly used for animal feed, but also in developing countries, mainly Africa and Asia, as a human food source (Sans & Combris, 2015).

Maize, the first native American crop of global proportion, has a multipurpose use and has been mainly used for food (human and animal) and ethanol production (ERS-USDA, 2019). Regarding human food, the main consumption forms are flour (maizemeal), starch, and oil. Maize products, especially starch, can be an ingredient to other foods, medicines, cosmetics, adhesives, resins, cleaning products, plastics, tires, paints, papers, and fireworks (Lotha et al., 2019).

In recent decades, great advances have been made in maize genetic improvement (genome) and the broad agronomic knowledge of the plant (Manchanda et al., 2018) supported important advances in production techniques.

The optimum growing temperature is from 25 to 30 °C, wherein the germination period requires a minimum temperature of 10 °C. High temperatures (above 24 °C at night) contribute to reducing the net photosynthetic rate increasing respiration and directly affecting production. Besides, the maize plant requires a rainfall between 350 and 500 mm (Cruz et al., 2010).

Maize productivity, for grain or silage, is a function of the cultivar or hybrid choice. The average Brazilian production was 5.71 Mg/ha of grains yield in the 2018/2019 crop season, with the greatest productivity in the south region, averaging 6.85 Mg/ha (MAPA, 2019), while the United States was 11.07 Mg/ha (FAS-USDA, 2019). Maize silage forage mass range from 10 to 26 Mg DM/ha (Jaremtchuk et al., 2005; Pariz et al., 2016; Fischer et al., 2020).

Maize in integrated systems

In integrated systems, the association of species and the use of conservation practices, such as no-tillage system, emerges as an option for system intensification and diversification, as well as the recovery of degraded pastures (Pedreira et al., 2017b). Crops and/or pastures (animal production) can be integrated with tree species, simultaneously or sequentially, which increases land-use efficiency, resulting in greater income diversification (Pedreira et al., 2018).

Accurate and systematic planning during the establishment of the integrated systems can define success or failure. During the planning, producers should take into account soil, climatic, agricultural, forage, and forestry conditions (Pedreira et al., 2017b). Besides, analyze marketing, logistics, and availability of trained labor before deciding to move towards integrated systems and define the arrangement (Balbino et al., 2012) to warrant economic and environmental returns.

Soil quality in integrated systems and soil conditioner

The integrated systems are complex systems in which interactions between system components must be deeply assessed. The soil plays a key role in influencing all other components. Thus, sustainable soil management in these systems requires a complex understanding of soil properties and functions.

In western France, a region characterized by great stocking rates and integration between annual crops (cereals and grass) and permanent pastures, the physical, chemical, and biological properties of the soil were evaluated in 164 sites distributed over several properties. Soil properties were incremented in 22, 5, 6, and 3% for aggregate stability, total nitrogen, organic carbon, and microbial mass, respectively, from monoculture to pasture-integrated systems (Viaud et al., 2018). The authors integrated these results into a soil quality index (SQI) and observed that crop rotations did not affect SQI in pasture-associated production systems. Thus, pasture-crop rotation with temporary pastures presented higher SQI than the annual crops under conventional monoculture.

The SQI integrates a complex system aspects and it can be effective in assessing the impact on qualitative and quantitative soil aspects, contributing to clarify the relationships among soil properties in cropping and livestock systems, and facilitating comparisons (Viaud et al., 2018; Rahman et al., 2019). In this perspective, the SQI in integrated production systems with maize/sheep and goats in West Africa increased by 51% when the animals (70-140 animals ha^{-1}) were introduced in the area (Rahman et al., 2019).

The SQI is strongly influenced by soil microbial biomass. Thus, the importance of microbial quantification in the soil quality evaluation, as well as determining the organic substrate availability (e.g., organic matter and/or organic carbon) for soil microbial growth is essential (Paz-Ferreiro & Fu, 2016).

There are some ways to increase soil organic matter (SOM) content, however, in tropical soils where mineralization rates are more intense, higher SOM-efficiencies increase are achieved in no-till cropping systems with cover crops associated with crop-rotation or succession, especially when livestock is included as a component (Paramesh et al., 2019; Rahman et al., 2019; Sarto et al., 2020).

The increase in SOM is essential to improve SQI and microbial activity, as well as mitigating greenhouse gases by sequestration of organic carbon, making it a challenge for tropical agriculture. However, this challenge can be overcome with the use of biochar. In a review, Sarfraz et al. (2019) demonstrate that the combined application of plant growth-promoting (PGP) microorganisms and biochar improved soil quality, carbon sequestration, and plant growth.

Biochar is a derived compost from plant biomass, as woody materials or straw residues obtained by the pyrolysis process. The heterogeneous nature makes biochar an excellent soil conditioner, capable to buffering the soil (lower pH variation), with great adsorption potential and water retention (great porosity), large specific surface area (lower particle size), and cation exchange capacity (a large number of functional groups) (Sarfraz et al., 2017; Sarfraz et al., 2019). In addition, it is highly stable in the soil, taking millions of years to be degraded and, consequently, release organic carbon in the atmosphere (Lehmann et al., 2006).

The biochar as a soil conditioner on maize crops has increased water-use efficiency (WUE), with the reduction of evapotranspiration and increase of the water retention capacity in the soil through the total porosity increase (biochar + soil), minimizing the negative impacts of water stress (Faloye et al., 2019). Residual biochar associated with phosphorus fertilizer and microbial inoculants (arbuscular mycorrhizal fungi) increased the nutrients extraction by hyphae due to the effective root colonization. However, regardless of microbial inoculants, biochar addition increased P, K, and Ca uptake to maize plants (Rafique et al., 2020). This maximizes the residual use of nutrients applied in the ancestor crop with productivity gain. Considering that the maintenance of soil microbial fauna also plays an important role in plant production, in biochar-conditioned soil has the potential for nematode reduction, particularly bacterivorous groups can be up to eight times greater than in non-conditioned soils (Kamau et al., 2019).

The biochar-conditioned soil (associated or not with mineral fertilizer and/or microorganisms) increases cation exchange capacity due to the increase in the total soil organic carbon, and reduction in soil pH. Also, increases photosynthetic rate, stomatal conductance, and WUE (Sarfraz et al., 2017), resulting in greater grain yield (Faloye et al., 2019; Kamau et al., 2019; Kätterer et al., 2019; Rafique et al., 2020). The addition of biochar (1% w/w; ~25 kg DM biochar $^{-1}$) increases the nitrogen-use efficiency in maize crops, reducing nitrogen fertilization by up to 50% of the recommended dose, due to improved soil organic matter and cation exchange capacity (Sarfraz et al., 2017), minimizing production costs and greenhouse gases emissions.

Soil and plant microbiology

To understand the soil microbial relationships in integrated systems, the community, and microbial activity of a tropical soil [Arenic Hapludult (Soil Survey Staff, 2014)], an integrated system with palisadegrass [*Urochloa brizantha* (Hochst. Ex A. Rich.) R. Webster 'Marandu'] and eucalyptus (*Eucalyptus* sp.) tree was analyzed by Sarto et al., (2019). Authors reported that the composition of the microbial community enzymatic activities (β-glucosidase and N-acetyl glucosidase) from soil was reduced in areas at 0 and 6 m from the trees in the soil profile (5–20 cm), while increasing at 2 and 4 m of the trees. Microbial biomass (actinomycete, gram-positive bacteria, mycorrhizal fungi arbuscular and fungal abundance) was greater in the Cerrado (Savannah) than in the pasture, either in monoculture and integrated system. The eucalyptus addition in the pasture resulted in soil carbon and nitrogen stocks similar to the Cerrado (native vegetation).

Although the importance of microbial activity on soil quality, especially in grazing integrated systems, the utilization of bacteria with special characteristics (e.g. diazotrophic/endophytic), such as PGP or nutrient solubilizers and atmospheric nitrogen-fixers (BNF) is essential when cropping maize (Marag & Suman, 2018; Salvo, Di et al., 2018; Youseif, 2018; López-Carmona et al., 2019).

Evaluating the potential of bacteria isolated from maize plants with PGP activity and/or BNF indicated an effective reduction of ~25% of mineral nitrogen fertilizer input (Marag & Suman, 2018). It can contribute to mitigating the risks of environmental contamination (nitrate leaching to watershed), as well as reducing total system production costs.

In this sense, Youseif (2018) isolated 49 rhizospheric/endophytic bacterial *in vitro* by restriction analysis of amplified ribosomal DNA using four restriction enzymes and evaluated for PGP characteristics and the beneficial effects on early maize growth. Thus, from 49 isolates, seven produced high levels (32.1–82.8 μg mL^{-1}) of indole-3-acetic acid; 11 had phosphate solubilization skills (101–163 μg mL^{-1}) and 12 had potential acetylene reduction activities (100–1800 nmol C_2H_4 mg^{-1} protein h^{-1}). Under greenhouse conditions, the inoculated plants showed greater biomass compared to non-inoculated plants due to the great BNF efficiency of the isolates resulting in indol-3-acetic acid production (Youseif, 2018) and the potential for biocontrol activity of fungal pathogens in maize such as Turcicum leaf rust (*Exserohilum turcicum*) and root rot (*Rhizoctonia solani*) (Marag & Suman, 2018). Discussions of structural and functional diversity of plant microbiota, as well as proteomic and host-specific site analysis in maize, are available in the literature (Lade et al., 2018; Hartmann et al., 2019; Vidotti et al., 2019)

In Brazil, the main genus of endophytic bacteria used in grasses, especially maize (Schaefer et al., 2018; Galindo et al., 2019; Zeffa et al., 2019) and pasture (Pedreira et al., 2017a; Bourscheidt et al., 2019; Leite et al., 2019), is *Azospirillum* spp. This genus, as well as *Azobacter* spp., is an associative bacteria that release part of the nitrogen fixed to the associated plant and, unlike symbiotic bacteria, they do not nodule (Hungria, 2011). Thus, the mineral fertilizer nitrogen input can be reduced, but still needed to fill the plant´s requirements (Bourscheidt et al., 2019).

Studies were carried out to elucidate the effect of maize seed inoculation with *Azospirillum brasilense* under different nitrogen levels and/or efficiency of nitrogen utilization intercropped or not with pasture. Schaefer et al. (2018) analyzed the maize inoculated or not with *A. brasilense* on a winter pasture (*Avena strigosa* + *Lolium multiflorum* Lam.) in an integrated system with a residual 10, 20, and 30 cm height post-grazing (continuous stocking) and fertilized with 0, 75, 150, 225 or 300 kg N ha^{-1}. Authors reported an increment on biomass and grain yield, where, in the absence of bacteria, the responses were linear with maximum dose presenting the highest grain yield (10.2 Mg DM ha^{-1}) regardless of post-grazing height, while most of inoculated treatments responses presented quadratic effect for fertilization, with the curve vertex ~210 kg N ha^{-1}.

Similarly, when maize was inoculated with *A. brasilense* and evaluated different doses and sources of nitrogen fertilization, Galindo et al. (2019) observed that there was no difference between nitrogen sources (urea or urea with thiophosphoric N-(n-butyl) triamide urease inhibitor), but inoculation improved nitrogen use efficiency of the 3.5-fold, with an increase of 14% on grain yield. Moreover, although increasing the nitrogen input up to 200 kg N ha^{-1} with inoculation increased grain yield, regardless of source, the economic viability was obtained with 100 kg N ha^{-1} with urea and *A. brasilense* inoculation. It supports that *A. brasilense* can be an alternative to reduce mineral fertilization input without reducing grain yield.

Maize-grass intercropping

Intercropping grasses and maize is a common practice in the tropical region, especially in those with great rainfall. The grass can be used as a cover crop or by grazing animals (Pedreira et al., 2018). However, intercropping should not affect the maize growing and yield, for that reason, competition for light, water, and nutrients should be minimized (Moreira et al., 2018). To avoid water and nutrients restrictions in the soil, the intercropped maize can be planted with row spacing from 0.45 to 0.90 m without compromising forage or grain yield (Borghi et al., 2012). When intercropped maize is used for silage production, it should preferably be harvested above 0.45 m of height, warranting a great nutrient concentration in maize leaves, resulting in maize forage mass with great nutritive value, as well as greater soil coverage and N, P and K cycling (Pariz et al., 2016).

In Brazil, grasses of the genus *Brachiaria* (syn. *Urochloa*) spp. has been predominantly used for maize intercropping in integrated systems (Borghi et al., 2012; Pariz et al., 2016; Almeida et al., 2017; Pariz et al., 2017), with or without trees due to lag initial growth of the grass and great adaptation under limited irradiance (Gomes et al., 2019; Nascimento et al., 2019). The cultivars of the species *B. brizantha* (Hochst. Ex A. Rich.) have been greatly used due to the rapid growth after maize harvesting, increasing forage and animal production, and nutrient cycling. This cultivar has more response when rainfall conditions are favorable (rainy season), while *B. ruziziensis* and *B. decumbens* are most used in the offseason (less favorable water conditions) (Oliveira et al., 2019; Pezzopane et al., 2020). Moreover, common practice in grass-maize intercropping is the herbicide application (atrazine and nicosulfuron) in sub-doses for weed control and delay forage growth minimizing the competition with maize and reducing yield losses (Santos et al., 2015).

The productivity of the maize-grass intercropping is depending on the maize variety, plant density (maize and grass), and management practices. Borghi et al. (2012) compared the maize-palisadegrass intercropping and reported that grain yield in monoculture (10.3 Mg DM ha^{-1}) did not differ from the intercropped (9.7 Mg DM ha^{-1}). Similarly, Almeida et al. (2017) evaluated the nitrogen fertilization rates on the grain yield and total forage mass in a maize-palisadegrass intercropping and reported that the grain yield was affected by intercropping when the N doses were lesser than 100 kg ha^{-1}, but above that rate, grain yield in the intercropping and monoculture did not differ reaching 10 Mg DM ha^{-1} of grain yield and 19.0 Mg DM ha^{-1} in total forage mass.

Maize-forestry intercropping

In integrated systems with forestry (also called agroforestry system), crop, livestock, and forestry activities need to be established, considering the distinct management characteristics of each component and the need for temporal and spatial management adjustments allowing the long-term sustainability of the system (Macedo et al., 2019).

There are several aspects to be considered in the planning of agroforestry systems (Pedreira et al., 2018). Among the essential planning parameters for the success of agroforestry systems, there is the choice of the species that will compose the system (forestry and crop/pasture), the arrangement, and the temporal sequences of implantation and management of the system (Macedo et al., 2019).

The tree species choice, as well as their spatial arrangement, requires attention because the trees will be the most influencer over the other system components, which may cause deleterious effects rather than synergic (Pedreira et al., 2019). Excessive shading, tree litter deposition, and the allelopathic effect can negatively affect the system (Melotto et al., 2019), specially C_4 plants (Gomes et al., 2019; Gomes et al., 2020b; Gomes et al., 2020a). In addition, it is essential to consider the site-specificities characteristics (climate, soil, relief, trade, and logistics) for wood and/or non-wood products such as fruits, seeds, tannins, oils, and others that may be used as raw material (Leakey & Page, 2006).

The spatial arrangement of trees in the agroforestry system mainly influences the understory microclimate conditions (Magalhães et al., 2020), reducing the temperature (Domiciano et al., 2018), wind speed (Karvatte Jr et al., 2016), and mainly photosynthetically active radiation (PAR) (Gomes et al., 2019; Nascimento et al., 2019). Thus, in agroforestry systems, especially in situations where there is an increase in shade levels near to the trees, a reduction in forage production has been reported (Gomes et al., 2019; Nascimento et al., 2019; Pezzopane et al., 2019; Pezzopane et al., 2020) and crop yield (Moreira et al., 2018; Pardon et al., 2018; Nardini et al., 2019). These factors are magnified when associated with water competition (Jose et al., 2004). However, moderate shading also may be positive for forage quality characteristics, increasing mainly the crude protein concentration (Orefice et al., 2019; Pang et al., 2019; Pezzopane et al., 2019; Pezzopane et al., 2020).

Maize intercropping with trees and other grasses, shading, and competition for soil resources may directly affect maize growth and development (Pardon et al., 2018; Pontes et al., 2018). Maize is a C_4 plant, which concentrates CO_2 at the Rubisco activity site and reduces O_2 concentration, greatly reducing photorespiration, and warranting a better photosynthetic efficiency (Taiz et al., 2017). Although plants with C_4 metabolism can greatly respond to moderate shade (Mugunga et al., 2017; Nascimento et al., 2019; Pezzopane et al., 2019; Silva, Da et al., 2020) when grown under reduced PAR over long periods, a decrease in crop growth rates is expected (Mathur et al., 2018), because adaptation mechanisms are not able to increase the processes efficiency to follow the PAR reduction.

Shading adaptation mechanisms are regulated by phytohormones and signaling molecules, mainly red and far-red light signals, such as phytochromes, photosensitive phosphoproteins that have crucial roles in plant development responses to light throughout the life cycle (Franklin & Quail, 2010). Phytochromes, especially B, D, and E (Franklin, 2008), driven the plant plasticity in response to changes in the light environment, regardless of species (Gururani et al., 2015).

Plants can respond to moderate shading (red: far-red ratio [R:FR] reduction) or intense shading (R:FR reduction plus PAR reduction) at greater planting densities (Wu et al., 2019) or in agroforestry systems, with several adaptive responses including increased stem elongation, reduced branching or tillering, reorientation of leaf growth direction and early flowering (increased apical dominance) (Franklin & Quail, 2010). This reaction is known as 'shade avoidance syndrome' (Franklin, 2008). In addition to these responses, C_4 metabolism plants under light-limited (moderate shade) may have greater photosynthetic efficiency (Nascimento et al., 2019) due to the increase in the antenna complex, especially chlorophyll *b* and carotenoids (Baig et al., 2005). These responses increase the chances of plant individual success under limited irradiance, which may be insufficient to support grain yield compared to full sun (Wu et al., 2019).

The productivity of maize-forestry intercropping responds greatly to the species, arrangement, density, and orientation of the trees, also to the maize management grown in the understory. In this sense, Moreira et al. (2018) evaluated the grain yield and total forage mass of maize-forestry (*Eucalyptus* sp.) intercropping and monoculture system and observed that averaging of three years, the intercropped and monoculture systems presented grain yield of 5.4 and 7.5 Mg DM ha^{-1} and total forage mass of 12.1 and 16.1 Mg DM ha^{-1}, respectively. Similarly, Pardon et al. (2018) evaluated the influence of trees distance and age (varying tree species) on maize grain yield and forage mass in Western Europe and reported that in the average of the distances in systems with young, middle-aged, and long-standing trees presented forage mass of 11.8, 13.5, and 9.1 Mg DM ha^{-1}, respectively, while the monoculture produced 19.9 Mg DM ha^{-1}, and grain yield presented 9.1, 5.8, and 6.5 Mg DM ha^{-1}, respectively, and 10.2 Mg DM ha^{-1}

in the monoculture. The lesser yields were reported in the distance near the trees (2.5 m) than farther (30 m), where the forage mass was 6.1 and 17.9 Mg DM ha^{-1}, while the grain yield was 4.8 and 9.2 Mg DM ha^{-1}, respectively.

Maize silage quality in integrated systems

Following the same tendency to reduce maize productivity with trees proximity (Mugunga et al., 2017; Pardon et al., 2018; Nardini et al., 2019), there is a tendency to a nutritional value increasing, mainly on crude protein (CP), and dry matter (DM) decreases in the pasture (Lima et al., 2019; Pezzopane et al., 2019) and in maize forage mass for silage (Pardon et al., 2018; Pontes et al., 2018). Overall, the increased CP concentration in shaded plants is attributed to an increase in the N concentration due to the absorption of mineralized N from the soil organic matter under the trees (Dollinger & Jose, 2018) and physiological changes (Reynolds et al., 2007).

Pontes et al. (2018) evaluated the nutritive value of maize silage in a maize-forestry intercropping and monoculture system under 90 and 180 kg N ha^{-1} and reported a 13% reduction in DM and a 35% increase in CP of the intercropping system to monoculture with 90 kg N ha^{-1} fertilized. When 180 kg N ha^{-1} were applied, the CP was similar among systems (78 g DM kg^{-1}), as well as between doses in the intercropping (80 g DM kg^{-1}). It allows the inferring that the maize-forestry intercropping system is more N-use efficient, making it possible to reduce the N-fertilization and obtain similar nutritive value silage.

Considerations and future perspectives

In recent years, great effort in scientific research has been done to support maize production in integrated systems as an economically viable and environmentally sustainable land use practice, which may be applicable for either small and/or large producers.

The maize production in a more complex system like integrated systems requires a comprehensive understanding of tree-crop interactions to warrant long-term system sustainability. Although science has made progress in understanding complex interactions, studies generating basic and applied information is needed to establish guidelines defining tree-crop arrangements in integrated systems.

The evidence presented here contributes to understanding the state of the art in maize production in integrated systems. However, we also indicated some research gaps, which are critical for addressing deeper knowledge and to support crop-forestry systems adoption. This suggests future research in various areas, including:

1. Genetic breeding with a genomic understanding of tree, maize, and grass components to increase productivity. For example, selection and/or morphogenic modifications for vertical growth of tree roots and maize leaves, or genetic manipulation of phytochrome expression to support greater shade tolerance;
2. Research in management practices to minimize competition and maximize yields, for example, deepening of planting furrows and soil conditioners use to deepen trees rooting, also the fertilization and/or differential harvesting maize (silage or grain) at a function of radiation availability (e.g., tree-row distances), etc.;
3. Use of tree species (native and exotic) arranged at low density (e.g., greater tree-row distances) with maize in integrated systems to favor maize production;
4. Quantification of light extinction coefficients considering quantity (photosynthetic photon flux density) and quality (spectral wavelength) aspects in the integrated system (tree, crop, and grass) to identify the most appropriate management strategies (e.g., thinning and pruning);
5. Parametrization and validation of mathematical models that allow the integration of different interaction vectors (positive and negative) in the integrated systems. It could improve the chances to design a successful system predicting yields based on available resources.

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