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Jay Ram Lamichhane

INRAE, Université Fédérale de Toulouse, UMR AGIR, F-31326 Castanet-Tolosan, France

*Corresponding author: jay-ram.lamichhane@inrae.fr

Tel: +33 (0)5 61 28 52 50; Fax: +33 (0)5 61 28 55 37

1. A three-fold challenge of the 21st century agriculture

In this century, stakeholders involved in the food chain are concerned by a three-fold challenge of raising agricultural productivity, reducing the negative environmental impact of agriculture, and adapting agriculture to ongoing climate change. These challenges are of concern worldwide, although to a different extent, depending on countries and regions. Consequently, also the possibility and initiatives to address these challenges may differ across regions. For example, the first two challenges – increasing agricultural productivity while promoting environmental sustainability at the same time – have become a priority for developed countries. This is because the intensive agricultural model is unsustainable not only from environmental but also from economic point of view, as yields of several staple crops have been stagnating across different regions of the world (Ray et al., 2012; Schauberger et al., 2018), despite the use of high input levels. This clearly highlights the need for alternative agricultural models to the productivist one that can be sustainable from environmental and socio-economic point of view. Developed countries have a better possibility to reduce environmental impact due to agricultural practices at the expense of agricultural productivity while this approach may be less readily applicable yet for developing countries, especially for those facing the food security issues. In contrast to the first two challenges, both developed and developing countries are concerned to the same extent to cope with the third challenge of the 21st century agriculture, i.e. adapting agriculture to the changing climate, to ensure the viability of agriculture.

Many agricultural systems may have potential to address the above-mentioned three-fold challenge, although to a different extent. These systems include, and not limited to, organic agriculture, integrated agriculture, conservation agriculture, double cropping, relay cropping, agroforestry etc. More specifically to the agroforestry system (AFS), this is generally referred to systems where perennial plants managed by growers are associated with annual or perennial crops. Behind this single definition, a wide range of complexity lies within these systems, spanning from relatively simple agroforestry systems, characterized by only two associated species, to very complex ones, close to natural systems, with several species and vegetation strata. Therefore, also the management of AFSs is complex as many factors interact in these systems and the benefits generated by AFSs may markedly differ based on the factors involved and their interactions.

2. Agroforestry systems to address the three-fold challenge of the 21st century agriculture?

AFSs are a telling example of integrated systems that bridge the gap separating agriculture and forestry thereby addressing both environmental and socio-economic objectives. Overall, AFSs have the capacity to enhance delivery of all four ecosystem services (MEA, 2005): provisioning (food, fresh water tec.), regulating (climate regulation, pollination, pest, weed and disease regulation etc), cultural (recreation, biodiversity etc.) and supporting (nutrient cycling, soil formation and retention etc.)

services. For example, AFSs maintain food supplies and at the same time increase climate resilience, raise carbon stocks in agricultural systems, maintain or even improve soil fertility and control soil erosion, regulate soil moisture content, enhance pollination, provide fuelwood, fodder, medicines and promote food supply and many other products (Cerda et al., 2014; Kuyah et al., 2019; Mbow et al., 2014). More specifically to regulating services, AFSs may affect pests' (*sensu lato*, that include pathogens, animal pests and weeds) incidence and abundance both through increased top-down regulation by natural enemies or via bottom-up factors such as moderation of microclimate, soil nutrients and water content, that may affect both the pests and the host plants. Nevertheless, there is no consensus in the literature and evidence is still inconclusive concerning the overall potential of AFSs on crop health. Although the term crop health is not a well-defined yet (Döring et al., 2012), here, it is used to indicate the capacity of a given crop to provide ecosystem services in general and regulating services in particular. This is because the effect of AFSs on pests maybe context-specific and can depend on the environmental conditions, tree and crop species concerned and management practices. Therefore, there is an increasing research need in order to understand how several key factors and their interactions affect the delivery of regulating services and how this finally affect provisioning services. A better research focus in this regard not only provides insights for their own improvement but also contributes with general theoretical and practical lessons on how to take advantage of vegetation. In particular, more research is needed to better elucidate the role of crop management practices, and in particular shade management, which represents a key agronomic lever affecting crop health in AFSs (Andres et al., 2018; Babin et al., 2010; Loguercio et al., 2009).

3. Introduction to the special issue: crop health in agroforestry systems

Pests can threaten crop health in AFSs, either by affecting the crop *per se* or perturbing associated tree species, thereby altering the delivery of ecosystem services. However, crop health in AFSs is a result of very complex interactions, as reported by works presented in this special issue. The articles published in this issue are selected from works presented at the 4th World Congress of Agroforestry, which was held in France from 20th to 22nd May 2019 (https://agroforestry2019.cirad.fr/). Of 12 original articles, most papers in this special issue deal with pests affecting coffee- and cocoa-based AFSs although other AFSs such as mixed crop tree-vegetable systems are also studied. Based on the key findings, the papers in this issue are classified into five sections with those highlighting: i) shade level and distribution as a key driver affecting crop health in AFSs, ii) mechanisms and interactions unraveling the role of shade in crop health in AFSs, iii) role of tree species composing the landscape in natural pest regulation, iv) management practices and decision support systems promoting crop health in AFSs, and v) socio-economic factors as a driver affecting crop health in AFSs. The following are representative short summaries of the articles that appear in this issue.

3.1. Shade level and distribution as a key driver affecting crop health in AFSs

In complex coffee-based AFSs, quantifying the impact of associated trees on pest regulation and coffee yield is of paramount importance to improve the existing systems and to design more sustainable ones. Durand-Bessart et al. (2020) by taking into account a wide range of pedo-climatic conditions and management practices, analyze the interaction between tree species being part of AFSs as well as the complex of coffee airborne-diseases. In particular, they characterize soil, coffee trees status, coffee growth and coffee yield, using structural equation modeling. The authors report that associated tree species, and in particular the percentage of shade, was positively correlated with air-borne diseases and soil quality with consequent negative impact on coffee growth and yield. The authors conclude that shade management at an optimal level may be an important solution to reduce the airborne diseases and to improve the coffee yield.

Under natural conditions, crop health is affected by a complex interaction between abiotic and biotic factors as well as cropping practices. This is also the case for citrus grown in cocoa-based AFSs, which suffer by a phenomenon called citrus tree decline, caused by several fungal diseases (Pseudocercospora leaf and fruit spot disease, citrus scab disease, Phytophthora foot rot disease) and insect pests (mites, whiteflies and aphids). Mvondo et al. (2019) demonstrate that the health of citrus trees located under dense shade and with regular distribution in the cocoa-based AFSs are much improved compared with citrus trees in full sun or with irregular shade distribution pattern.

3.2. Mechanisms and interactions unraveling the role of shade in crop health in AFSs

Shade either enhances or reduces the coffee leaf rust development in AFSs although little is known to date about the underlying mechanism. Avelino et al. (2019) attempt to unravel this mechanism by studying three stages of the disease cycle separately: viz. sporulation, uredospore wash-off by rain, and uredospore deposition on leaves. The authors highlight that, compared with coffee plants in full sun, the number of uredospore was higher for coffee trees under shade, the uredospore wash-off by rain was less efficient under shade, and the deposition of uredospores on healthy leaves was higher under shade. All this leads to an increased coffee leaf rust severity under shade compared with that in full sun.

Shade levels plays a key role in coffee health in a number of ways, including enhancement or reduction of the coffee rust disease, caused by the obligate fungal pathogen *Hemileia vastatrix*, through microclimate modifications of the canopy. Wind is one of the key weather variable affecting the dispersal of *H. vastatrix* uredospores during the dry season, which is affected by the presence and level of shade tree, especially at the edge of AFSs. Despite this potential role of wind, little is known to date on how shade tree leaf functional and canopy-level architectural traits impact wind dynamics and subsequent air-borne uredospore dispersal and deposition in this transition zone. Gagliardi et al. (2020) determine the contribution of shade tree leaf functional and canopy traits to changes in throughflow wind speeds and *H. vastatrix* uredospore dispersal under three shade levels (sparse, medium, and dense) of the shade tree *Erythrina poeppigiana* at the edge of farms. The authors show that the dense level of shade trees reduces throughflow wind speeds into the farm more frequently than do other shade levels and that leaf functional traits of shade trees significantly predicted these speeds. This explains the importance of shade tree canopy and leaf functional traits in reducing wind speeds and subsequent uredospore deposition.

3.3. Role of tree species composing the landscape in natural pest regulation

Plant species abundance and diversity in a landscape play an important role in providing suitable habitats for living organisms, including pests and their natural enemies. A better understanding of landscape factors promoting natural pest regulation may provide important insights into designing sustainable cropping systems. Sow et al. (2020) assess the association among landscape vegetation types in traditional AFSs and their impact on richness as well as on abundance of bird and bats and their contribution to natural regulation of millet head miner. The authors show that grain losses due to millet head borer are reduced when panicles were accessible to these predators. They however conclude that the contribution of trees for natural pest regulation is species-dependent as some tree species provide habitats for crop pests while other provide refuges for their predators. This highlights the importance of a better landscape management based on the appropriate choice of tree species.

3.4. Management practices and decision support systems to promote crop health in AFSs

Cacao-based AFSs, compared with sole crops, can provide pest regulating services but they can also enhance crop damage due to pests, depending on the production system (conventional or organic) and management practices applied. For example, several studies in the literature report that organic farming is much more sustainable than conventional farming although these studies did not take into account heterogeneity of crop management practices or crop diversity applied to these systems. Armengot et al. (2019) investigate the effect of different cacao production systems (organic vs. conventional) under sole and mixed cropping and the consequent impact on pest incidence and cacao yield, without any external inputs. The authors show that, when best cropping practices are applied (e.g. regular tree pruning and fortnightly removal of infested pods as preventive phytosanitary measures), cacao productivity increases with no significant differences in terms of pest incidence between sole and mixed cropping, both in organic and conventional systems. The authors however highlight the need for extra labor related to the adoption of good management practices, and thus higher production costs, which should be compensated by incentives for farmers.

Several studies investigated the impact of different environmental factors and farm management systems on coffee pests and predators separately. However, only few studies have been conducted to understand the complex regulating network that result from interactions between cropping practices, farming systems and their interactions both on coffee pests and their predators. Beilhe et al. (2019) assess the potential effects of environmental conditions (e.g. percentage of shade cover, tree area surface, coffee density) and farm management (i.e. conventional, integrated, and, organic) on the abundance and related damage from coffee berry borer *Hypothenemus hampei*, as well as the ant predatory groups, and their interactions. The authors show how crop management practices (e.g. shade management, plant diversity, preventive phytosanitary measures) can reduce the coffee berry borer population without considerable side effects on the ant predatory group.

Coffee-based AFSs can differ in their complexity, ranging from simple systems including a few tree species to very complex systems comprising many tree species across a range of pedo-climatic and cropping practice gradients. Consequently, the ecosystem services provided by these systems in general and pest regulating services in particular may widely vary from one system to another. Identification of the most promising coffee agroecosystems, by comparing all these different levels of complexity that foster ecosystem services represents a key point to obtain information that can be used for designing sustainable AFSs. Cerda et al. (2020), by taking into account a wide range of shade and management conditions, quantify indicators of ecosystem services and disservices provided by these AFSs. In such a way, the authors identify six most promising coffee-based AFSs that allow to reduce crop losses while providing other ecosystem services.

Many research works have been conducted to understand the role of AFSs combining perennial crops on pest populations and their natural enemies. In contrast, little is known to date as to whether AFSs including annual and perennial crops may play a positive, negative or neutral role on insect pests. Imbert et al. (2020) estimate population dynamic parameters of three major vegetable pests (the green peach aphid *Myzus persicae*, the gray cabbage aphid *Brevicoryne brassicae*, and other pests of the "caterpillars" group) in mixed fruit tree-vegetable plots, combining apple and cabbage, compared with sole crops. The authors report that mixed fruit tree-vegetable systems, compared with sole crop: can enhance reproduction or survival of some pests; pest predation level in this mixed cropping system may be similar or even lower than in sole crops; and trees do not necessarily constitute a barrier to pest immigration. This demonstrate that mixed cropping systems are not always favorable for crop health, especially if crop species are not carefully chosen.

The use of decision support systems play an important role to reduce crop losses due to pests. Although a large number of decision support tools, including weather forecasting models, have been developed to predict risks related to pests, these tools are not always used by growers. The reasons behind a low uptake of these tools are several including cost, reliability in terms of their prediction and user-friendliness. More specifically to coffee rust disease, to date, almost two dozen predictive models have been developed to predict different indicators of the disease development and management. One of the drawback of these models is that they determine *a priori* standardized periods of influence of the meterological predictors. However, symptom appearance can be affected by complex combinations of meterological variables acting at different times and duration. Merle et al. (2019) by using a statistical approach, identify the complex interactions of weather variables responsible for changes in lesion status. Based on this, the authors develops three models predicting lesion emergence probability, lesion sporulation probability and growth of its infectious area, which take into account temperatures and rainfall values for specific stages of the disease cycle. These models are useful to predict risks of infection, sporulation and infectious area growth, which are helpful to optimizing phytosanitary treatment recommendations.

Coffee orchard floor management, based on tree species as cover crops, can offer the potential for greater labor and herbicide efficiency as well as positive contributions to coffee productivity and a better weed management. However, the choice of tree species as cover crops needs a particular attention to improve coffee productivity and reduce risks related to weed development. Staver et al. (2020) perform a long-term trial including two dry season cover crop species combination of deciduous and non-deciduous leguminuous and non-leguminuous species (*Inga laurina* and *Tabebuia rosea*) with two intensities of organic and conventional coffee management. The authors show that, despite several potential for a better weed management and increased coffee productivity through a better coffee orchard floor management, numerous challenges remain for the selection of tree species. These challenges include water use efficiency, nutrient cycling and soil biology, tree growth habit and canopy form as well as ease of management.

3.5. Socio-economic factors as drivers affecting crop health in AFSs

There have been several cases of disease epidemics in the modern history of agriculture leading to devastating crop losses with consequent impact on food security. These disease epidemics have been most often associated to crop pests or, at best, pests x weather interactions without taking into account other drivers, which may have triggered disease epidemics. This has been also the case for coffee rust epidemics, caused by the obligate fungal pathogen *H. vastatrix*, that hit Central America since 2012. While several studies have been conducted on the biology and epidemiology of the causal agent, little is known to date about socio-economic drivers affecting the disease epidemic. Villarreyna et al. (2020) identify how socio-economic factors, in particular economic constraints, affected the decision making process of farmers, in terms of access to best cropping practices and how all this has triggered the development of coffee rust epidemic in Nicaragua.

4. Conclusions and future perspectives

This special issue sheds light on how pests affect different kind of host plants of AFSs -- by focusing on the multiple interacting mechanisms that take place at different scales (plot, farm, and landscape) as a result of the vegetation biodiversity such as microclimate modifications, soil quality improvement, host plant physiology changes, permanent shelter for invertebrates (both beneficials and pests), alternate sources of disease inocula etc. These mechanisms either can lead to natural regulation of pests or conversely increase their populations, depending on their specific requirements or specific phases of the host/pest interaction. Structuring and managing biodiversity in AFSs are thus essential to improve pest regulation, by promoting desirable mechanisms while discouraging undesirable ones. However, papers presented in this issue also show that pest regulation services can also compete with other ecosystem services, which suggests the need of several trade-offs to improve the functioning of the whole system.

Results of some works in this special issue are complementary to others as they corroborate on key factors affecting crop health in AFSs. For example, Armengot et al. (2019) show that, when external input is excluded and when best cropping practices are adopted, no difference in pest incidence occur between cacao grown in monocropping and classical AFSs managed under organic and conventional farming. This confirms what Villarreyna et al. (2020) demonstrate, meaning that socio-economic constraints that do not allow farmers to bear labor costs related to best cropping practices, trigger crop health problems as was the case for coffee rust epidemics in Nicaragua. AFSs, with the integration of trees into cropland, can be beneficial for smallholder family survival only when properly managed, as tree species compete with crops for light, nutrients, and water. Labor demand in AFSs are higher compared with the monocropping system due to its complexity in terms of crop management needs. Policy initiatives are, therefore, needed to provide economic incentives to those farmers who cannot afford labor costs required for a better crop management. This will ensure farmers' access to best management practices and thus finally improve the sustainability and durability of AFSs. Finally, future studies focusing on crop health in AFSs should aim at better elucidating some key points not necessarily addressed by papers presented in this issue **(Box 1)**.

Box 1. Future research priorities to fill current knowledge gaps in AFSs

- Shade seems to be an important driver affecting pest incidence and severity in AFSs. Which species and which leaf functional traits and canopy architecture for crops grown in AFSs to maximize ecosystem services? How breeding programs for shade trees can contribute to this objective?
- Maximization of an ecosystem service may have negative impacts on other ecosystem services. How can we find a trade-off between non-commercial vs. commercial ecosystem services across contrasting pedo-climatic and socio-economic gradients?
- Which socio-economic and environmental indicators for model AFSs capable of improving farmers' livelihoods, collective well-being, socio-economic development, and equity across contrasting pedo-climatic and socio-economic gradients?
- A higher priority toward non-commercial ecosystem services may be needed to increase resilience of AFSs in the long term. However, this may affect the short-term productivity of AFSs. What possibility of public policy support to help farmers during this transition phase?
- AFSs, by definition, are integrated systems and thus should address both environmental and socio-economic objectives. What feasibility of interdisciplinary collaboration, combining socio-economic and bio-technical research to better understand crop health in AFSs?

Acknowledgements

I thank Stephen N. Wegulo and the reviewers of this special issue, who very efficiently collaborated with me to ensure timely publication of this issue. I am grateful to Jacques Avelino for his kind availability for interactions from the beginning until the completion of this special issue as well as his useful comments on an earlier version of this editorial. I am also thankful to Jean-Pierre Sarthou for his initial contribution to the special issue.

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Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: