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REVIEW

# CHALLENGES PROVIDING MULTIPLE ECOSYSTEM BENEFITS FOR SUSTAINABLE MANAGED SYSTEMS

Hans LAMBERS (✉)[1,2], Wen-Feng CONG (✉)[2]

1 School of Biological Sciences and Institute of Agriculture, University of Western Australia, 35 Stirling Highway, Perth, WA 6009, Australia.

2 College of Resources and Environmental Sciences, Key Laboratory of Plant-Soil Interactions, Ministry of Education, National Observation and Research Station of Agriculture Green Development (Quzhou, Hebei), China Agricultural University, Beijing 100193, China.

**KEYWORDS**

crop diversification, ecosystem services, food security, sustainable cropping systems

**HIGHLIGHTS**

- For 8000 years, agricultural practices have affected atmospheric $CO_2$ concentrations.
- Paddy rice cultivation has impacted atmospheric $CH_4$ concentration since 5000 years ago.
- Modern agricultural practices must include carbon storage and reduced emissions.
- Sustainable management in agriculture must be combined with decarbonizing the economy and reducing population growth.

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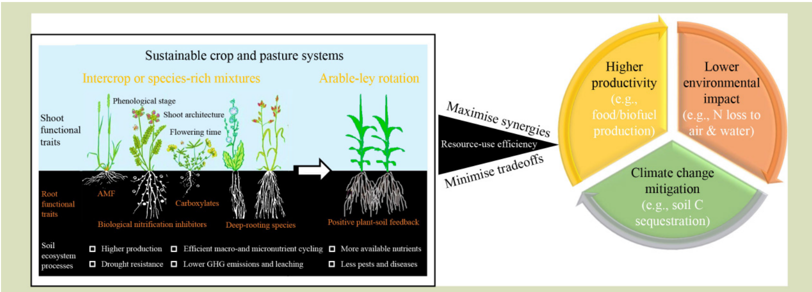
Correspondences: hans.lambers@uwa.edu.au, wenfeng.cong@cau.edu.cn

**GRAPHICAL ABSTRACT**




**ABSTRACT**

Since humans started practicing agriculture at the expense of natural forests, 8000 years ago, they have affected atmospheric $CO_2$ concentrations. Their impact on atmospheric $CH_4$ started about 5000 years ago, as result of the cultivation of paddy rice. A challenge of modern agricultural practices is to reverse the impact cropping has had on greenhouse gas emissions and the global climate. There is an increasing demand for agriculture to provide food security as well as a range of other ecosystem services. Depending on ecosystem management, different practices may involve trade-offs and synergies, and these must be considered to work toward desirable management systems. Solution toward food security should not only focus on agricultural management practices, but also on strategies to reduce food waste, more socially-just distribution of resources, changes in lifestyle including decarbonization of the economy, as well as reducing human population growth.



## 1 FOOD SECURITY AND BEYOND

If we accept the urgent need to increase food production and food security, rather than aiming to curtail the unbridled growth of the human population, enhanced food production must be achieved while concurrently providing multiple other ecosystem services. Services such as, enhanced food security must be achieved while reducing greenhouse gas emissions, nutrient leaching, and the use of pesticides and fertilizers, enhancing carbon (C) sequestration, improving soil health, and increasing biodiversity[1]. Is that even possible, given the many trade-offs among these ecosystem services? In this Special Issue, several authors explore to what extent it may be possible and how. Yet, ways to limit the increase of the human population without natural catastrophes also deserve further attention. Without curtailing human population growth, solutions to other aspects of ecological and social concern are far more difficult[2–4].

## 2 TRADE-OFFS OR SYNERGIES BETWEEN MULTIPLE ECOSYSTEM SERVICES

One key feature of sustainable crop and pasture systems is crop diversification. Crop species or cultivars differ in plant functional traits (both shoot and root), mediating key ecosystem processes. Combining these species/cultivars with complementary or facilitative functional traits will lead to higher resource-use efficiency, which will to a certain extent help achieve the synergy between food or biofuel production, lower environmental pollution and climate-change mitigation (Fig. 1). Storkey and Macdonald[5] analyzed the long-term experiments on grasslands at Rothamsted Experimental Station[6] to explore trade-offs as well as synergies among ecosystem services. The authors conclude that there are inevitable trade-offs and that there is no single management strategy that maximizes the three ecosystem services they considered in their study: aboveground productivity, species richness and soil organic C. Competitive exclusion explains the trade-off between aboveground biomass and plant species richness; the addition of mineral fertilizers makes nutrients non-limiting and selects for inherently fast-growing competitive plant species[7,8]. However, of particular interest are grassland plots at Rothamsted Experimental Station that support greater proportions of forbs and legumes and plant communities characterized by a longer flowering duration and lower leaf dry matter content that partly mitigate the trade-off between productivity and diversity. The positive correlation of species richness with the proportion of forbs indicates that communities on these plots have greater resource-use complementarity[5,9]. The amount of soil organic C in the topsoil increased synergistically with aboveground plant production. To minimize trade-offs and maximize synergies, plant functional traits have to match[10,11]. Neighboring plants either reduce or enhance disease transmission, neighbor-induced shifts in the direction of disease transmission in communities make or break disease transmission chains[12]. Understanding how diversity affects disease transmission requires integrating interactions between neighbor species and their pathogens.

George et al.[13] explore how to achieve the triple challenge of food security, reversing biodiversity decline, and mitigating climate change, based on ecological principles. Using diversifies cropping systems, it may be possible to reduce nutrient inputs and mitigate effects of climate change by using less fuel and storing more C in soils. Soil C is important,

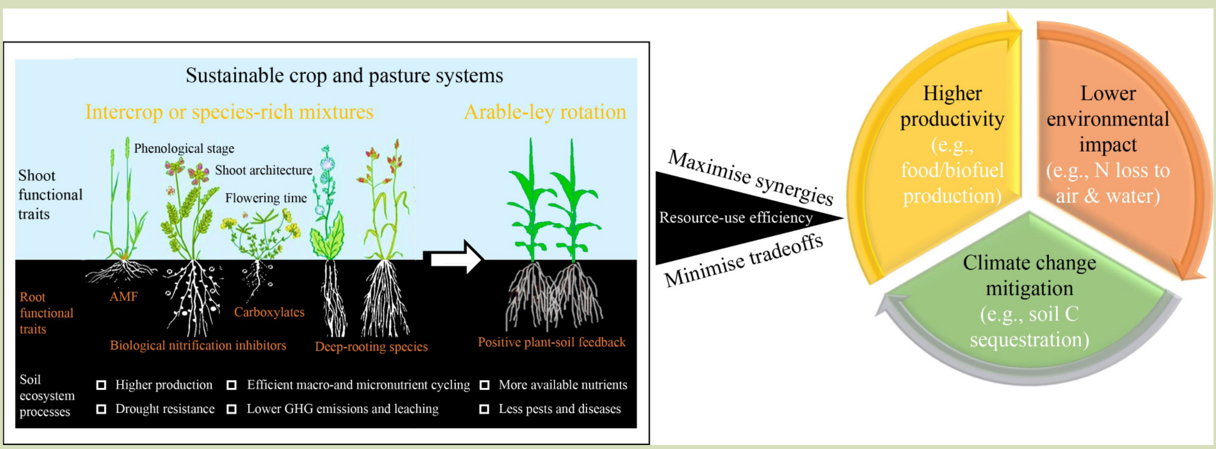



**Fig. 1** A conceptual illustration of how sustainable crop and pasture systems contribute to the synergy and tradeoffs between multiple ecosystem services. Left panel illustrates plant functional traits harnessed to design diversified cropping systems. Right panel shows that resource-use efficiency is the key to maximizing synergies and minimizing trade-offs among higher productivity, lower environmental impact and climate change mitigation.

because soils contain approximately 2344 Gt of organic C globally; it is the largest terrestrial pool of organic C[14]. Diversification of the system can also enhance resilience to abiotic and biotic stress. Soil and plant management, such as reduced tillage and fertilizer inputs, may also enhance soil quality and utilization of legacy nutrients accumulated in soils[13].

Accessing legacy phosphorus (P) may reduce losses due to runoff and leaching[15]. George et al.[13] show improved soil functions through greater reliance on soil biological processes and trophic interactions than on chemical inputs and physical soil interventions. If accessing legacy nutrients involves the mineralization of organic nitrogen (N) and P, this becomes a double-edged sword, as some organic C may be lost as well[13,16]. Comparing soils under N-fixing trees (*Falcataria falcata* (formerly *Albizia falcataria*), *Leucaena leucocephala* and *Casuarina equisetifolia*) with those beneath two *Eucalyptus* spp. (*E. robusta* and *E. saligna*; non-fixing), showed that the N-fixing species allowed 0.11 $kg \cdot m^{-2} \cdot yr^{-1}$ of total soil organic C to be sequestered, whereas there was no change under the *Eucalyptus* trees[17]. George et al.[13] also highlight the importance of intercropping with legumes to deliver sustainability through ecological principles and use legumes as an example of the innovation needed to allow the effective deployment of such principles into agriculture. Resh et al.[17] found that more than half of the greater C sequestration under the N-fixing trees was the result of greater retention of older recalcitrant C which was correlated with accretion of soil N; less resulted from greater accumulation of new C. Laboratory soil incubation experiments showed that greater soil organic C concentrations were the result of greater C inputs, rather than slower decomposition of fresh litter from N-fixing plants. This may be associated with the release of P-mobilizing exudates, which has been shown for some Fabaceae[18,19] as well as for *Casuarina* spp., which produce cluster roots[20,21]. The finding that gum exudates of some *Falcataria* (formerly *Albizia*) spp. exhibit high manganese concentrations[22] suggests that these may release carboxylates[23,24], but no data are available for *F. falcata*.

Synergies between efficient nutrient use and soil C sequestration may be achieved through harnessing the right plant nutrient-efficient traits. Ding et al.[25] suggest that harnessing plant genotypes that are efficient at P acquisition may influence soil organic C in opposite directions, depending on plant traits related to P acquisition. For example, plants with strong exudation of carboxylates and/or flavonoids could destabilize organic-mineral associations and aggregates, making C accessible to soil microorganisms and thus stimulate the decomposition of soil organic matter. In contrast, plants with greater root length density and colonization of arbuscular mycorrhizal fungi could foster the stabilization of C in soil organic-mineral associations and aggregates, thus sequestering C in soil, involving arbuscular mycorrhizas and glomalin-related protein[26,27]. In addition to organic C in soils, plant P-acquisition strategies may also influence soil inorganic C sequestration in calcareous dryland soils through carboxylate-induced release of calcium, which can precipitate with $CO_2$ to form pedogenic carbonates[28]. Weathering by lichens over tens to thousands of years does not lend support for a major role in C sequestration[29] and more work needs to be done on the quantitative effect of both primitive biota and vascular plants on the rate of weathering[30]. Exploration of the net effect of plant P-acquisition strategies on soil C sequestration should consider both organic and inorganic C in soils[31].

As acknowledged above, an important ecosystem service of managed systems is storage of organic C. Raven[32] uses a range of sources to make the point that the gradual decrease in atmospheric $CO_2$ and $CH_4$ concentrations in the pre-agricultural Holocene was reversed about 8000 years ago for $CO_2$, which was associated with the emergence of agriculture and associated deforestation. For $CH_4$, the reversal occurred about 5000 years ago, when rice was domesticated, and irrigated production was increased with its introduction. The decrease in organic C in soil and aboveground biomass over the last 8000 years is a staggering 38 Pmol C (1 Pmol equals $10^{15}$ mol). Raven[32] argues that agriculture has resulted in a global decline of 9.7–11.3 Pmol of organic C in the topsoil (up to 2 m). In contrast to managed systems, terrestrial vegetation and soils in uplands and wetlands are a sink for both atmospheric $CO_2$ and $CH_4$[33]. The challenge will be to reverse the gigantic losses of soil organic C resulting from long-term (8000 years) agricultural practices using the knowledge compiled in this Special Issue[5,13]. This reversal will be important but is no substitute for globally decarbonizing the economy[34,35].

In addition to $CO_2$ and $CH_4$, $N_2O$ is an important greenhouse gas related to dysfunctional N cycles in cropping systems. Arbuscular mycorrhizas reduce N loss via runoff, leaching and emission of $N_2O$ from microcosms of paddy fields[36]. Incomplete denitrification of nitrate releases $N_2O$, as opposed to $N_2$ which is released during complete denitrification, but both comprise losses of N applied as fertilizer[37]. If ammonium was not nitrified to nitrate, there would be no substrate for denitrifiers. Nitrification inhibitors produced by plants have been known for a long time[38–41]. This was the reason to explore the release of biological nitrification inhibitors from roots of *Brachiaria humidicola*, a tropical grass[42–44]. It is now known that a range of plant species produce root exudates that inhibit ammonia-oxidizing microorganisms. This biological nitrification inhibition (BNI) may decrease N losses and increase N uptake from the rhizosphere. O'Sullivan et al.[45] investigated for the existence and magnitude of BNI capacity in *Brassica napus* (canola) and discovered genetic variation for this trait. The capacity of BNI was similar to that of the high-BNI *B. humidicola*[42–44]. By reducing nitrification rates, it might be possible to grow canola crops with lower N losses and greater agronomic N-use efficiency, with both environmental and economic benefits.

## 3 TOWARD SUSTAINABLE CROPPING SYSTEMS AT THE REGIONAL LEVEL

Since the Green Revolution, cropping systems have relied on a limited number of genotypes[46] and have been intensified with increasing inputs of fertilizers, pesticides and water[47]. Although this has resulted in enhanced crop productivity, it has also led to off-site effects such as eutrophication, increased pollution and water depletion[48,49]. Groot and Yang[50] explore opportunities for increasing crop productivity while reducing environmental impact, taking into account trade-offs between the two[5]. They analyzed how 30 crop rotations practiced on the North China Plain might be combined at the regional level to overcome trade-offs. Their aim was to model a compromise, to maximize revenues (livestock products, dietary and vitamin C yield), and minimize off-site impacts (decline of the groundwater table). Compared with the most common irrigated winter wheat-summer maize cropping system, the compromise scenario would double economic revenues while reducing groundwater decline and additionally providing considerable quantities of vitamin C and livestock products. Implementation of several strategies have provided opportunities to mitigate trade-offs between objectives.

Cooledge et al.[51] explore the benefits of reintroducing herbs, including legumes, as multispecies leys (temporary grasslands in crop rotations). These arable ley rotations have the potential to alleviate soil degradation and reduce greenhouse gas emissions. To achieve maximum benefits, we need to understand specific traits of the plant species involved and the services that are required. For example, deep-rooted plants may promote the water relations and survival of shallow-rooted neighbors during drought[52,53]. In other systems, deep-rooted plants may prevent nitrate leaching and groundwater pollution, enhancing agronomic N-use efficiency[54]. Other deep-rooted systems offer scope to increase soil C sequestration through increased root mass inputs and rooting depth[55]. Other benefits include mobilization of P that is poorly available for most species for neighbors of the following crop[56,57]. Likewise, beneficial elements such as silicon may be mobilized by carboxylate-releasing species, to make these available for neighbors or subsequent crops to boost their defense[58,59]. Research to explore the various plant traits of species available for multispecies leys is needed to enable farmers to make informed decisions on what species combinations are desirable for the ecosystem services they seek to provide and under which conditions. This will then allow evidence-based recommendations[51].

Mostly, crops have been used for the production of food, feed and fiber, but increasingly they are also used for biofuel production, to reduce reliance on fossil fuels[60]. Kervroëdan et al.[61] explore cropping systems that are needed to develop new agricultural sectors (i.e. biofuel production combined with food and feed production). They advocate mixed cropping systems, integrating feed and biogas production, because these have greater potential in terms of environmental and agronomic performance, but acknowledge that their greenhouse gas emissions are greater. What needs to be explored further is the longer-term environmental footprint the C emissions and the prospects for C sequestration in deep soil[55,62], given the high biomass production of biofuel crops[63,64].

## 4 PERSPECTIVES

Having contributed to the gigantic increase of $CO_2$ and $CH_4$ in the Earth's atmosphere for thousands of years, it is pivotal that global food production becomes C neutral, and preferably continues with a negative environmental footprint. Even if we achieve C neutrality by 2050, that still involves a global temperature increase of 1.5 °C, with catastrophic climate impacts such as massive wildfires, floods, landslides and droughts. Completely decarbonizing the economy will be vital to sustain human civilization[65,66].

Several papers in this Special Issue explore ways crop and pasture systems can be adjusted to enhance food security, and to reduce the C emissions and other off-site impacts of agriculture. Implicitly, all these contributions accept the growing human population as axiomatic whereas the unbridled growth of the human population is a leading cause of greenhouse gas emissions, global climate change and loss of biodiversity[67,68]. Solution toward food security should include strategies to reduce food waste, more socially-just distribution of resources, changes in lifestyle including decarbonization of the economy, and curtailing human population growth[3,34,69].

Our aims toward food security must acknowledge the need to balance reproductive rights with reproductive responsibilities to promote the wellbeing of future generations. It is naive to focus exclusively on food security and ignore the unbridled growth of the human population as the major cause of our problems to balance the various ecosystems services associated with food production.

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**Compliance with ethics guidelines**

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