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Deciphering the biodiversity-production mutualism in the global food security debate

Ralf Seppelt, Channing Arndt, Michael Beckmann, Emily A. Martin, and Tom Hertel

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About the project

Southern Africa –Towards Inclusive Economic Development (SA-TIED)

SA-TIED is a unique collaboration between local and international research institutes and the government of South Africa. Its primary goal is to improve the interface between research and policy by producing cutting-edge research for inclusive growth and economic transformation in the southern African region. It is hoped that the SA-TIED programme will lead to greater institutional and individual capacities, improve database management and data analysis, and provide research outputs that assist in the formulation of evidence-based economic policy.

The collaboration is between the United Nations University World Institute for Development Economics Research (UNU-WIDER), the National Treasury of South Africa, the International Food Policy Research Institute (IFPRI), the Department of Monitoring, Planning, and Evaluation, the Department of Trade and Industry, South African Revenue Services, Trade and Industrial Policy Strategies, and other universities and institutes. It is funded by the National Treasury of South Africa, the Department of Trade and Industry of South Africa, the Delegation of the European Union to South Africa, IFPRI, and UNU-WIDER through the Institute's contributions from Finland, Sweden, and the United Kingdom to its research programme.

Towards Inclusive Economic
Development in Southern Africa

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ABSTRACT

Without large changes in consumption as well as sharp reductions of food waste and post-harvest losses, agricultural production must grow to meet future food demands. The variety of concepts and policies relating to yield increases fail to integrate an important constituent of production and human nutrition – namely biodiversity. We here develop an analytical framework to unpack this biodiversity-production mutualism, which bridges the research fields of ecology and agro-economics. The analytical framework makes explicit the trade-off between food security and protection of biodiversity. In so doing, a route is sought to avoiding possible lock-ins of the global food system through over-intensification and to limiting further biodiversity loss through more comprehensive agro-ecosystem management. The framework suggests that, in low-input areas such as sub-Saharan Africa (SSA), the scope for increasing production is high, as is the scope for either damaging or preserving biodiversity. Landscape perspectives can help to realize this scope for production, especially in high potential regions such as Southern Africa, while preserving biodiversity.

1 INTRODUCTION

The quest for greater crop output for food and non-food products [1–3] leads to both an increase in agricultural land use and an increase in yields, typically achieved through an intensification of cultivation methods [4,5]. This, in turn, leads to a loss of biodiversity in agricultural landscapes [6], and increases pressure on natural diversity [7], which continues declining despite ongoing efforts for protection [8]. The avoidance of food waste and dietary changes offer two demand-side options to reduce the pressure on food production [9], but these have thus far not succeeded in doing so at the macro level [10].

Biodiversity is a crucial component of ecosystem functions that are essential for agricultural production, such as soil fertility, pollination and biocontrol [11–14]. This interdependence of biodiversity and agricultural production has led to a variety of concepts that aim to optimize the management of agricultural landscapes, balancing yields, biodiversity and sustainability [15], see Glossary at the end of the paper. These concepts make use of agroecological principles [16], suggest ecological [17] or sustainable intensification [18] and take the perspective of managing a coupled socio-ecological system (SES). While there is much published research on the SES concept, quantitative, empirically based and model-based implementations are largely lacking, or their improvement through process-based validation is pending [19]. As a result, it is currently not possible to capture and quantify the biodiversity-production mutualism in its entirety. However, recent research provides the necessary basis for such a comprehensive, quantitative, process-based understanding of the biodiversity-production mutualism (BPM) concept [14,19,20]. Therefore, this paper develops the concept to quantify the effects of crop and landscape management on agricultural production and biodiversity. The concept provides avenues for future research that combines agricultural, economic, biodiversity and nature conservation sciences. Based on the BPM concept, we develop a quantitative analytical framework, derive research questions, and illustrate applications as well as implications for the global biodiversity-food provisioning debate.

2 A MULTIDISCIPLINARY PERSPECTIVE ON THE RELATIONSHIP BETWEEN AGRICULTURE AND BIODIVERSITY

2.1 How is biodiversity affected by cropland management?

Management of agricultural landscapes serves the provisioning of agricultural goods and has had mostly negative impacts on biodiversity [6,7]. This occurs through both the expansion and intensification of cultivated areas, which in turn warps the composition of landscapes and their structure. Conventional intensification to increase yields is typically done by homogenizing the landscape (fewer, larger fields), increasing inputs (labor, fertilizer, irrigation, chemicals) and/or higher harvest intensities [21–24]. Conventional intensification typically leads to a loss of species present and a change in the composition of communities, e.g. in the form of a general decrease in abundance [6,7,25]. There is evidence of a long-term decline in insect species due to habitat loss and agricultural intensification [26,27]. This can also be associated with a proportionally greater abundance of pest species due to a reduction of biological pest control [28]. Ecological intensification directly or indirectly addresses that trade-off [17,29], however, a process-based understanding of these relationships is context-dependent and therefore highly fragmented [30,31]. Homogenization of environmental conditions typically leaves a few abundant generalists, while specialists tend to be lost [19,32]. Pests and their predators react differently to the composition of the surrounding landscapes [14]. Consequently, predicting the effects of intensification requires careful consideration of multiple factors, including landscape configuration and species characteristics [20,33,34]. This requires a broader perspective that includes management of landscapes.

2.2 Comprehensively measuring agricultural sustainability: Green total factor productivity

The positive effect of intensifying land management on yields is well studied. The relevant range of classical reductionist production functions is regarded as positively sloped in input intensification, as no rational agent would purchase inputs to reduce production, Fig. 1(A). However, groups of farmers operating in interlinked agricultural landscapes may find that their individual choices collectively reduce productivity because each operator ignores the mutualism of biodiversity and production [35 Fig. 4.1]. Hence, the yield function in intensification may become flat or even turn negatively sloped when BPM is considered, Fig. 1(B). This suggests a revision to agro-economic models. In standard models, each input is usually weighted according to its economic contribution, and an index of all outputs can be obtained by weighting each crop according to its share in the total economic value. If the output index increases faster than the input index, Total Factor Productivity (TFP) increases [36]. TFP was proposed to provide a metric for agricultural sustainability [37,38], but since the output and input measures typically cover only those aspects for which markets exist, non-market implications are ignored [39].

TFP growth can be neutral or beneficial to biodiversity. For example, pest- or disease-resistant varieties can achieve the same yields with reduced use of potentially harmful chemicals. Here, the technology can have positive external effects (i.e. improved health, reduced chemical run-off) [40]. However, new technologies are not always environmentally friendly. For example, the use of the dicamba weed killer in conjunction with Monsanto's new soybean varieties has led to numerous lawsuits from people who suffered collateral damage from drifting dicamba [41]. These negative results due to the new technology would be ignored in traditional TFP approaches, but would be captured by a Green TFP approach – also termed Total Resource Productivity (TRP) [39]. Green TFP or TRP include negative outputs (such as pollution or biodiversity loss) and inputs based on natural resources (such as groundwater or biodiversity) valued for their societal contribution rather than at their (often lower or zero) market value. Green TFP has been suggested as a more appropriate performance measure. However, such attempts have frequently failed [35], partly due to missing indicators but also due to a lack of available modeling concepts. Applying the BPM concept can inform estimates of Green TFP [42].

A landscape-related perspective that incorporates BPM has rarely been brought to bear in production agriculture, for at least two reasons. First, the missing indicators problem—valuation of non-market inputs and outputs—is challenging, because the details of the BPM relationship are complex and location-specific. Second, relatively few individual farms operate at the scale where taking a landscape-related perspective results in private gains to the owner/operator of the farm. As shown in Figure 1, recognizing the BPM concept opens the possibility that, for intensively operated land, biodiversity gain may coincide with minor yield losses; or, for extensively operated land, substantial yield gain can occur with limited intensification if biodiversity, and hence the BPM relationship, is maintained. Indeed, gains along both dimensions may be possible [43].

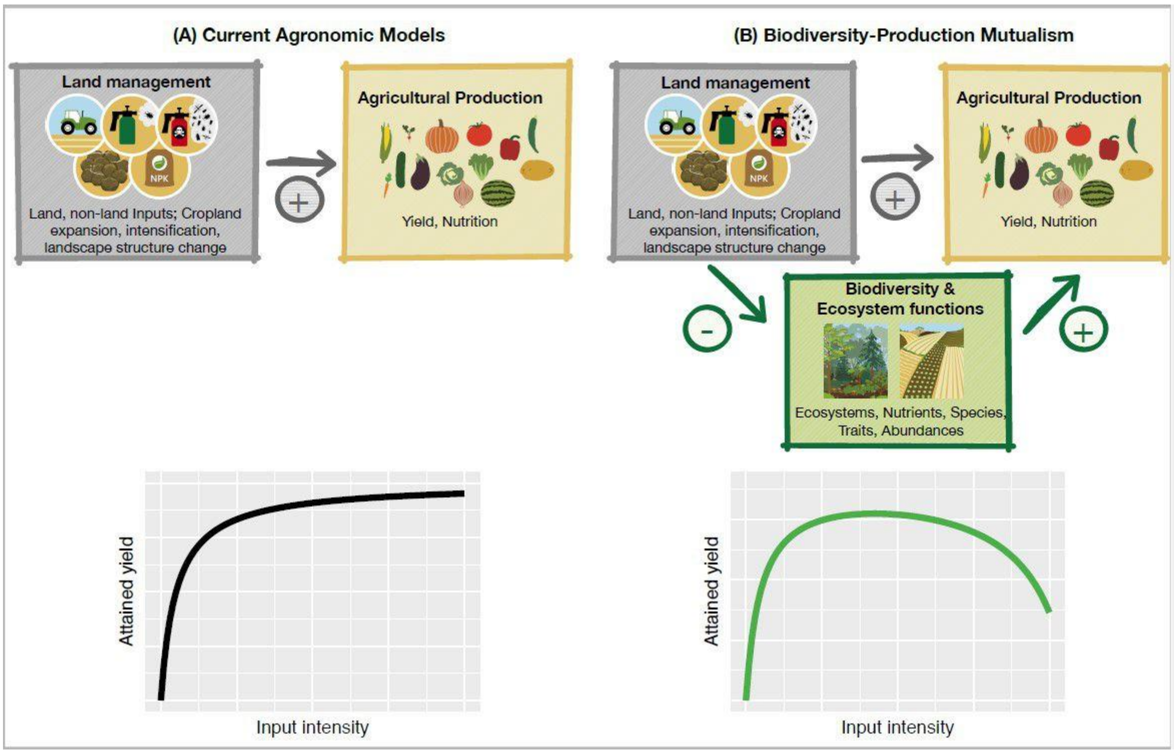


Figure 1: *Conceptual juxtaposition of current agronomic models (A) and the biodiversity–production mutualism concept (BPM) (B). In both cases (panels A, B) landscape management for agriculture with all its aspects (gray box) impacts production positively (gray arrow). The relation between input intensity levels and yields can be assumed as a saturation function (A, lower part). The BPM (panel B) concept additionally considers positive effects of biodiversity and ecosystem function on yields, but also negative effects of land management on biodiversity-based ecosystem functions. In the BPM concept, however, a humpback-shaped curve can be expected, due to declining yields at very high levels of input intensity.*

3 RETHINKING THE BIODIVERSITY-PRODUCTION MUTUALISM IN AGRO-ECONOMIC MODELS

3.1 Modeling the biodiversity-production mutualism

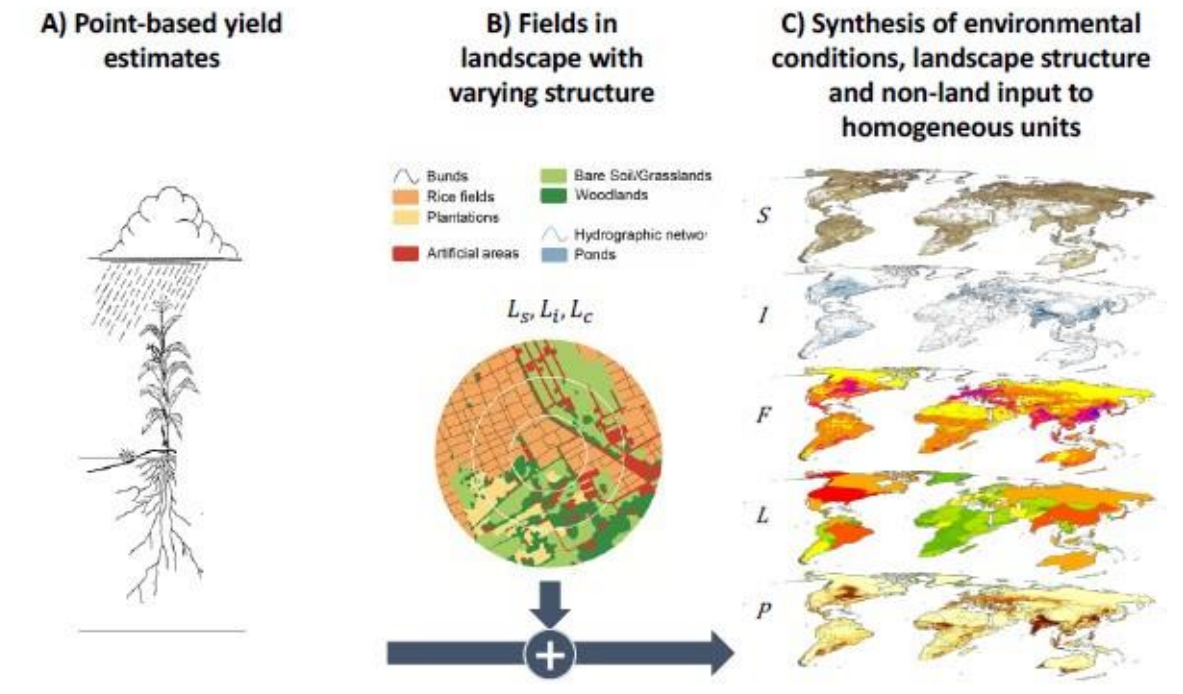
To implement and test the BPM concept an analytical framework is needed (see Box 1). It illustrates how the mutual feedbacks between biodiversity and production can be integrated into regional or global agro-economic models. The starting point is the simulation of plant production for a given location depending on the environmental conditions and the inputs for agriculture. In order to make these simulations dependent on ecological functions and incorporate multitrophic interactions, suitable scaling parameters are required that consider landscape structure and composition. Homogeneous spatial units providing the input parameters for yield simulations are usually derived from spatially referenced intersection data on environmental conditions. For the analytical framework to implement BPM, these scaling parameters must additionally consider landscape structure and composition, as well as negative externalities due to input intensity, which ensures the interdependence between biodiversity and yields in the yield estimates. This allows a nuanced quantitative assessment of the effects of changes in landscape parameters or input intensity on crop yields and biodiversity. Established model systems like LPJml [44], InVEST (http://naturalcapitalproject.stanford.edu/software/invest), or SWAT (http://swat.tamu.edu) could serve as testbeds for implementing our analytical framework.

Box 1: Analytic framework deciphering the biodiversity-production mutualism.

An agro-ecological and -economic framework that comprehensively accounts for the most relevant land and non-land inputs, including biodiversity, starts with underlying crop growth processes. Panel A of Fig. I illustrates how growth of individual crops depends on environmental parameters E, such as available water, nutrients and soil fertility, but also anthropogenic, i.e. non-land, inputs such as labor, irrigation and fertilizer. This is illustrated by a differential equation estimating crop growth Y dynamically. Crop growth could be implemented in more complex ways, i.e. by distinguishing different plant organs, or in more aggregated ways, i.e. through using regression models that do not account for intra-annual dynamics. To upscale such models to larger regions or even to the global level, such models are often repeatedly run with changing model parameters depending on the location x and by using spatial maps that supply data on cropland extent, environmental conditions E, and non-land input A (see Panel C).

Incorporating multitrophic interactions of crop growth with above-ground biodiversity in such an approach is challenging, as biodiversity changes are driven beyond the point scale. A crop growth model that fully accounts for the biodiversity-production mutualism requires incorporating landscape-scale properties which are the relevant drivers of biodiversity, such as composition and configuration of the landscape, as well as input intensity [45]. While information on input intensity L_I is often available on a grid scale (such as fertilizer F, irrigation I or labor L), the quantification of landscape composition and structure can be assessed by landscape metrics, e.g. [46]. A specific multitrophic interaction (e.g. pollination, biocontrol) defines the radius around a field in which landscape configuration, composition as well as input intensity matters for the relevant biodiversity metrics (BD) such as presence, absence or abundance of important species traits that provide pollination or biocontrol services. For example, insect-based pollination landscape metrics can be calculated for a radius of 250 m, 750 m or 1 km around fields, distances of up to 3 km can be relevant for both pollination and biocontrol-providing organisms [47–49].

Biodiversity data on species' presence or abundance in turn alters the crop growth process, either by promoting or reducing growth. Besides the well-established functions, which modify a maximum growth rate r_{max} given available water or nutrients, this maximum growth rate r_{max} can be adapted based on multitrophic interactions (Panel C).



A) Point-based yield estimates

$$\frac{dY}{dt} = r_{max} r_E r_A Y \left(1 - \frac{Y}{C_E C_A}\right)$$

$$C_E, r_E = f(S, W, P, 1 - H, \ldots)$$

$$C_A, r_A = f(I, F, L, \ldots)$$

Yield Y: *max* growth rate r_{max} capacity C

Environ. conditions and biotic interactions E: Soil fertility (S), avail. water (W), pollination (P), herbivory (H) modify r_E, C_E

Anthropogenic/non-land inputs A: Fertilizer (F), Irrigation (I), technology, labour (L)

B) Fields in landscape with varying structure

$$BD = g(L_s, L_i, L_c)$$

$$P = g_P(BD) = g_P(L_s, L_i, L_c)$$

$$H = g_H(BD) = g_H(L_s, L_i, L_c)$$

$$L_i = h(I, F, L, \ldots)$$

Biodiversity facets BD: Landscape structure L_s, composition L_c and intensity L_i,

Ecosystem functions from BD: pollination (P), herbivory (H)

L_i depending on non-land inputs, e.g. Fertilizer (F), Irrigation (I), technology, labour, (L)

L_c, land use for cropland, equals land input

C) Synthesis of environmental conditions, landscape structure and non-land input to homogeneous units

$$\frac{dY(x)}{dt} = r_{max} r_E r_A Y \left(1 - \frac{Y}{C_E C_A}\right)$$

$$BD(x) = g(L_s, L_i, L_c)$$

$$C_E, r_E = f(S, W, g_P(L_s, L_i, L_c), \ldots)$$

$$C_A, r_A = f(I, F, L, \ldots)$$

Yield Y and **biodiversity** BD for **location** x: environ. conditions (S, W, ...), non-land inputs (F, I, L, ...) location dependent.

Biotic interactions P, H as function of location-specific landscape features L_s, L_i, L_c

***Figure I**: Recipe for embedding landscape-scale biodiversity-driven ecological functions (multitrophic interactions) in global agro-economic models.*

3.2 Worked example and knowledge gaps

It is estimated that in 23% of cultivated terrestrial landscapes yields are declining, most likely due to land degradation, lack of ecosystem functionality and declining biodiversity [8]. The association of yield losses with lack of farmland biodiversity-based ecosystem functions is challenging because (i) the use of chemicals or technical processes may compensate for the loss of ecosystem functions; (ii) the remaining biodiversity may provide the same ecosystem functions; and/or (iii) the negative effects of intensified cultivation methods on biodiversity and yields via BPM may occur with a long time-lag [50]. A comprehensive quantitative understanding of the mutualism between biodiversity and production is urgently needed for both global and regional assessments. With few exceptions, such as pollination [51], most ecosystem functions are still poorly understood. Box 2 uses the example of pollination to illustrate how the BPM concept could be implemented for other ecosystem functions.

Data that could contribute to a better process-based understanding of ecosystem functions and quantify the BPM concept and support implementing the analytical framework are currently being developed. Data syntheses that consider landscapes, biodiversity and agricultural management are garnering attention [14,46,52]; nevertheless, agronomic indicators (management, yields) are often ignored in ecological studies, and biodiversity indicators are underrepresented in agronomic studies [6,20,52,53]. The most crucial knowledge gap, however, arises because ecosystem services such as biocontrol, i.e. the control of plant pests by their natural enemies, are complex and hence difficult to implement in larger models. Biocontrol is a crucial service relevant to all agricultural commodities, including staples that do not depend on animal pollinators [54], and it applies to both weeds and arthropod pests. In order to overcome these shortcomings, studies that demonstrate trait-matching between pests and their natural enemies, that identify how pest densities and damage relate to landscape structure, and that investigate the relative importance of different types of pests for overall yields at global scales (including plant viruses and funguses), are urgently needed.

Properly implemented, models deploying the analytical framework shown in Box 1 will enable researchers to determine the circumstances where biocontrol provides a more reliable, robust, cost-effective and ecologically sustainable form of plant protection [55]. While robust models that relate landscape structure to biocontrol are still lacking, there is evidence that a more structured landscape can provide habitat for biocontrol species [14,52,56]. These have the potential to at least partially replace commercial inputs [57], and show a positive relationship between species-richness of pollinators and biological control species, while controlling for yield performance [52].

Box 2: Application of yield models that consider the biodiversity-production mutualism for a pollination example.

Natural pollination supports production of 75% of all crops [11] and its contribution is estimated at EUR 153 billion worldwide [58]. Pollination is critical for the production of macro- and micro-nutrients: 90% of the crops that provide vitamin C, the majority of vitamin A, calcium, fluoride, and a large portion of folic acid are pollinated by animals [59].

Even though a complete global loss of pollination service is unlikely, assuming it as a thought experiment can help to provide insights into how current agro-economic models deal with such assumptions [60]. If pollination disappears and all other inputs remain unchanged, then output in the economic model decreases by the percentage loss caused by the loss of pollination [11]. However, the resulting increase in food prices provides an incentive for intensification to mitigate the loss of production [60]. In addition, rising prices on the world market encourage production increases in other parts of the world, particularly where dependence on pollinators is less pronounced.

Given comprehensive information on how crop yields depend on the abundance of pollinating species [11,61,62], we can – in the simplest case – assume a linear relationship between the abundance of pollinating species and the achievable yield (Fig. I). If an increase in yield is pursued via intensification, this can lead to a reduction of insect species richness and their abundance, which in turn reduces the pollination function [13]. It can be hypothesized that increasing agricultural intensity in landscapes with a high production of pollinator-dependent products will lead to the following pattern (Fig. II): (i) yields increase with increasing intensification; (ii) after reaching a threshold (e.g. due to a decrease in pollinator abundance) yields start to decrease; (iii) the maximum level of possible yields is unknown and could also depend on spillover effects (high land-use intensity in the surrounding areas). Negative repercussions of declining biodiversity-based ecosystem function on productivity are not yet implemented in global agro-economic models.

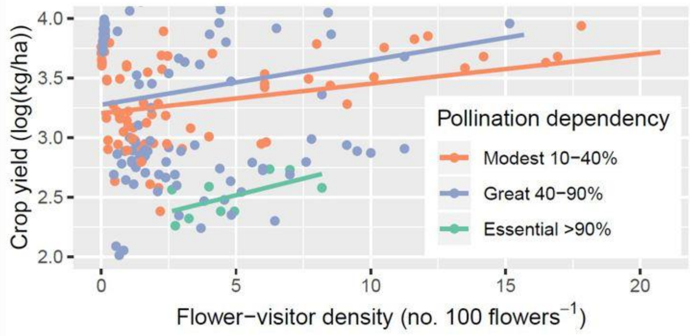


***Figure I**: Yield increases differ by crop type of pollinator dependency [11], given different visitation rates of pollinating species [61].*

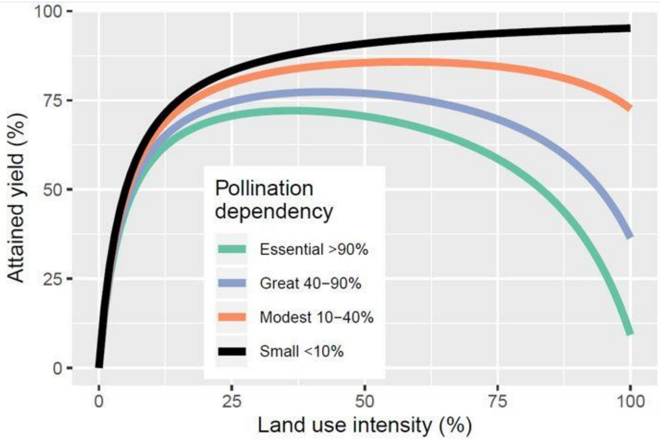


***Figure II**: Combining a saturating increase of yields under land use intensification (black line) with pollination functions, which decline under intensification through increased species loss, provides an application of the conceptual plot in Fig. 1. Here it suggests – as a testable hypothesis – a hump-shaped relationship of pollination-dependent yields under intensification.*

3.3 Implications for global food security

A nuanced picture of the biodiversity-production mutualism in global food production can be derived by characterizing all countries along a food and intensification gradient [22,23]. In regions with high income and high input intensity (e.g., Europe and North America), food demand is unlikely to increase, because of negligible population growth and advanced or completed dietary transitions. In low-income countries where input intensity is low (e.g., most of sub-Saharan Africa), growth in population and food demand per capita is expected to be rapid. The intermediate cases (e.g. India, Indonesia) exhibit high variations in input intensity, continued population growth at a moderate and slowing rate, and ongoing but incomplete dietary transitions. The vast majority of growth in global food demand over the next 30 years is expected to come from these low-income and middle-income countries.

Our framework suggest that, in low-input areas such as sub-Saharan Africa (SSA), the scope for increasing production is high, as is the scope for either damaging or preserving biodiversity [9]. In these regions, large parts of the population, especially poor people, depend on agriculture for their livelihoods, allowing a dynamic agricultural sector to become an effective means of poverty reduction. The BPM concept also highlights, that to ensure healthy diets, which eliminate “hidden hunger”, i.e. the lack of micronutrients in food consumption, functioning ecosystems are needed to provide pollination-based commodities (Box 2). Growth in demand for food is expected to be high, with a likely concomitant growth in food production in these regions. And, consistent with our framework, grain production growth has been rapid in SSA since about 2000, especially when South Africa (high-input-intensity agriculture) and Nigeria (oil exports have slowed agricultural growth) are excluded (Fig. 2).

With appropriate understanding, i.e. fully considering the BPM concept, a functioning ecosystem can be a partner in the drive to improve livelihoods, reduce malnutrition, and preserve the global environment. Landscape perspectives can help to realize this partnership. Without this understanding, area expansion and intensification in SSA present clear threats to biodiversity. The framework suggests that accounting for BPM while seeking production increases may lead to a more favorable outcome from all perspectives. High potential regions with relatively low input use, such as Southern Africa outside of South Africa, are promising areas for research into modes and potential gains.

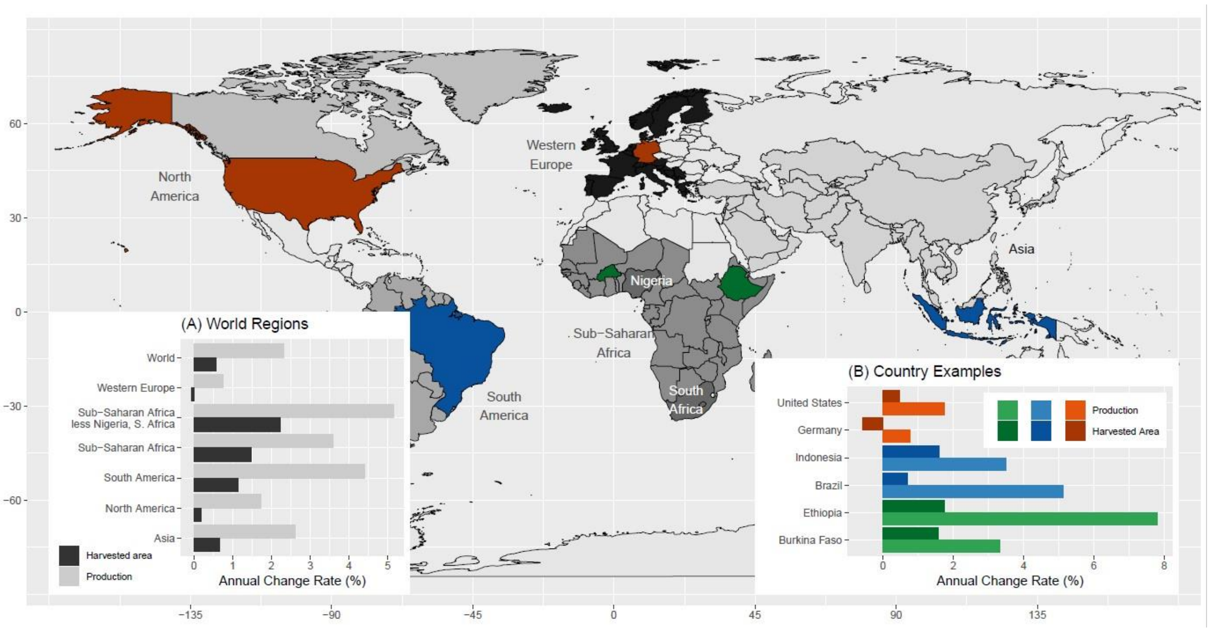


Figure 2: *Growth rates of cereals production. Panel A shows annualized growth rates of harvested area (dark) and production (light gray) based on data from 2002-2005 and 2012-2015 for different world regions of panel A, shaded in grey and labeled on the map. Panel B displays the same annualized growth rates for selected country examples along the intensification gradient: high-input intensity (red), intermediate cases (blue), and low-input intensity (green). While high-intensity countries were even able to reduce harvested area, all other regions and examples countries increase production through intensification both in terms of land use and yield per hectare. Source: FAOSTAT (www.fao.org/faostat/ accessed August 2018).*

Our framework also suggests the need for a paradigm shift in high-input agricultural systems. In high-input regions, less rapid growth in demand for food creates scope for reducing commercial and natural resource inputs and increasing production of positive externalities and reduction of negative ones. Once again, there is evidence that this is happening. In Western Europe and East Asia, the growth of TFP was accompanied by little or no growth in agricultural output and a reduction in the overall amount of conventional inputs, including land, used for agriculture over the last two decades [63]. In the United States, TFP growth has remained strong, while overall input use has remained flat and yield growth has slowed compared with SSA, Asia or South America [64].

It is important to highlight that a failure to realize adequate food production growth in low-input regions will translate into production pressure in high-input regions via trade linkages. This observation reinforces the need for mechanisms that channel these broadly positive trends in such a way that the production of positive externalities is increased and the production of negative externalities is minimized. In high-input environments, the concept of Green TFP can provide a basis for reorienting policies, such as the subsidy system of the European Union Common Agricultural Policy, towards environmental protection and results-based incentives [65]. In low-input environments, Green TFP could help research and extension programs clarify the full costs and benefits of alternative agricultural development pathways so that local actors can make informed choices.

4 CONCLUDING REMARKS

The biodiversity-production mutualism concept provides a conceptual basis and a common language for different disciplines such as agronomy, agroecology, economics and conservation ecology to solve a question of utmost importance: How do we manage the resources of our planet in such a way that we produce enough healthy food without destroying our life support system? To respond to this question, it is argued here that a new metric of productivity is required – one that accounts not only for all commercial inputs, but also for interactions with the environment. The concept of Green TFP, or Total Resource Productivity, is one such measure. Indeed, in 2016 the G-20 commissioned a white paper on the subject of 'Metrics of Sustainable Agricultural Productivity' [35]. This features many of the themes raised in the paper – including the importance of extending the traditional TFP measure as well as the need to link farm and landscape impacts in order to capture what is here called biodiversity-production mutualism.

A comprehensive understanding of economic and ecological interactions across scales, from point to landscape to regional and global models will provide decision-makers with relevant knowledge for policy implementation [29]. These same analytical efforts could also support redirection of existing agricultural subsidies towards more economically beneficial and ecologically effective greening measures.

GLOSSARY

Ecological intensification entails the replacement of anthropogenic inputs or enhancement of crop productivity, through fostering biodiversity-based ecological functions in agricultural practices [17]: Recent research tends to focus on specific processes (e.g., pollination) rather than outcomes (e.g., profits) and results are presented at spatio-temporal scales that are less relevant to farmers [29].

Agroecological principles are supposed to contribute to transform the food systems by applying ecological principles (→ ecological intensification) to ensure a regenerative use of natural resources while addressing the need for socially equitable food systems. While the focus initially was on understanding field-level farming practices, now landscape-scale processes (such as BPM) as well as the development of equitable and sustainable food systems are considered [16].

Closing yield gaps aims at assessing differences between observed yields and those attainable under comparable bioclimatic conditions. Differences are identified by either statistical or model-based comparisons to similar regions [4,5,66]. Critiques: (i) Such comparisons cannot account for socio-economic constraints (prices for inputs and outputs; access to markets, credit and technology) and ignore impacts on ecosystems and biodiversity; (ii) Nutritional values are considered implicit, "**hidden hunger**", i.e. lack of micro-nutrients, unaddressed.

Land sparing advocates an increase of set aside land for biodiversity protection while increasing production (mostly through intensification) on the remaining managed land. **Land sharing** denotes less intense, wildlife friendly farming at the cost of further agricultural expansion [67]. Critiques*:* (i) Studies adopt a regional, rather than a global perspective [68]; (ii) Its scale dependency hampers a clear association of landscapes to sharing or sparing type [69]; (iii) The sparing concept suggests to preserve biodiversity at distant sites while compromising biodiversity in farmlands, which maintains ecosystem functions such as biocontrol or pollination (→ BPM concept).

Organic farming characterizes farm management that focuses on wildlife friendly farming by avoiding the use of synthetic pesticides, usually with expected lower yields or profits [25], i.e. a specific farm level application of →agroecological principles, ecological intensification. Critiques: (i) There is no explicit use of biodiversity, which would require landscape-scale management beyond farm level [70]; (ii) Certification schemes vary across regions and countries.

Sustainable Intensification (SI) is closely related to → agroecological principles but suggests a multifaceted approach and oversees the entire food system by considering nutrition, food sovereignty, adapting to localities defined by socio-economic as well as environmental conditions. SI encompasses four aspects: (i) attain higher yields, while (ii) achieving a major reduction of environmental impacts, (iii) achieve a drastic reduction of resource intensive foods (change diet gap) and (iv) acknowledge a diversity of regions specific approaches [18].

Total factor productivity (TFP) has been considered as a metric for agricultural sustainability [37,38]. Growth in TFP denotes growth in an index of all outputs subtracted by the growth of an index of all inputs, influenced by changes in knowledge and management [36]. To account for inputs and outputs such as climate, soils and biodiversity for which no markets **Green TFP** also termed **Total Resource Productivity (TRP)** was suggested [42].

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