Tailored policies for perennial woody crops are crucial to advance Sustainable Development

Authors: Carlos Martinez-Nuñez[1*], Elena Velado-Alonso[1,2], Jacques Avelino[3,4], Pedro J. Rey[5], G. Martijn ten Hoopen[3], Guy Pe'er[6,7], Yi Zou[8], Yunhui Liu[9], Philip Antwi-Agyei[10], Adrien Rusch[11], Charles Staver[12], Tharaka S. Priyadarshana[13], Denis J. Sonwa[14,15], Damayanti Buchori[16], Lucas A. Garibaldi[17,18], Elena D. Concepción[19], Owen T. Lewis[20], Ivette Perfecto[21], Ignasi Bartomeus[1].

Affiliation:

1. Department of Ecology and Evolution, Estación Biológica de Doñana EBD (CSIC), C. Américo Vespucio, 26, 41092, Seville, Spain.

2. Functional Agrobiodiversity, George August University of Göttingen, Göttingen, Germany.

3. French Agricultural Research Centre for International Development (CIRAD), UMR PHIM, Montpellier, France.

4. PHIM, Université de Montpellier, CIRAD, INRAE, Institut Agro, IRD, Montpellier, France.

5. Departamento de Biología Animal, Biología Vegetal y Ecología. Universidad de Jaén, Jaén, Spain.

6. Department of Biodiversity and People. Helmholtz Centre for Environmental Research Leipzig (UFZ), Germany.

7. Department of Biodiversity and People, German Centre for integrative Biodiversity Research (idiv) Jena-Halle-Leipzig, Germany.

8. Department of Health and Environmental Sciences, Xi'an Jiaotong-Liverpool University, Suzhou, China.

9. College of Resources and Environment, China Agricultural University, Beijing, China.

10. Department of Environmental Science, Kwame Nkrumah University of Science and Technology, Ghana.

11. INRAE, Bordeaux Sciences Agro, ISVV, SAVE, Villenave d'Ornon, France.

12. Universidad Veracruzana, Xalapa, Mexico.

13. Asian School of the Environment, Nanyang Technological University, Singapore City, Singapore.

14. CIFOR, Center for International Forestry Research, Yaoundé, Cameroon.

15. World Resources Institute (WRI), Kinshasa, Democratic Republic of Congo (DRC)

16. Center for Transdiciplinary and Sustainability Sciences (CCTS), IPB University (Bogor Agricultural University), Bogor, Indonesia.

17. Universidad Nacional de Río Negro, Instituto de Investigaciones en Recursos Naturales, Agroecología y Desarrollo Rural. Río Negro, Argentina.

18. Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Instituto de Investigaciones en Recursos Naturales, Agroecología y Desarrollo Rural. Río Negro, Argentina.

19. Museo Nacional de Ciencias Naturales (CSIC), Madrid, Spain.

20. Department of Biology, University of Oxford, 11a Mansfield Road, Oxford, UK.

21. School for Environment and Sustainability, University of Michigan, Michigan, EEUU.

***Corresponding author:** Carlos Martínez Núñez. cmnunez@ujaen.es**.** Department of Ecology and Evolution, Estación Biológica de Doñana EBD (CSIC), C. Américo Vespucio, s/n, 41092, Sevilla, Spain.

Preface

Perennial woody crops, crucial to our diets and global economies, have the potential to play a major role in achieving multiple Sustainable Development Goals pertaining to biodiversity conservation, socioeconomic development, and climate change mitigation. However, this potential is hindered by insufficient scientific and policy attention specific to perennial woody crops, and by intensification of perennial crop cultivation in the form of monocropping with high external inputs. In this Perspective we highlight the potential of properly managed and incentivized perennial woody crops to support holistic sustainable development and urge scientists and policymakers to develop an effective agenda to better harness their benefits.

Keywords: agricultural policy, agroecosystems, biodiversity conservation, common agricultural policy, deforestation, sustainable agriculture, sustainable development goals, tree crops.

Most current agricultural models prioritize immediate economic profitability and increased productivity at the expense of long-term sustainability [1]. This has led to severe environmental challenges such as habitat loss and fragmentation, water and air pollution, and soil degradation. These issues are primary drivers of the ongoing biodiversity crisis[2] and have major impacts on human health[3]. Biodiversity decline caused by unsustainable agriculture hampers nature's contribution to people [4], increases farmers' dependence on agrochemicals, and threatens food security worldwide[5]. Therefore, finding solutions to minimize the adverse ecological impacts derived from agriculture is key to reducing biodiversity loss[6,7], mitigating climate change and adapting to its adverse effects[8], ensuring food sovereignty[9], and safeguarding the long-term viability of agriculture[5]. Among the environmental targets set at the recent United Nations Biodiversity Conference (COP 15) of the Convention of Biodiversity (CBD) in Kunming-Montreal 2022, eight are closely related to the management of agricultural landscapes, including target 10 for sustainable use of agricultural lands and target 18 for identifying and removing harmful agricultural subsidies (https://www.cbd.int/gbf/). Addressing these issues is a multifaceted, high-priority challenge at the interface of ecology and economics, and interfacing with social issues such as human rights, equity (including access to land), and the fair distribution of wealth.

Cropping system design and management will play a key role in reaching post-2020 global biodiversity targets[10,11]. Perennial woody crops (hereafter also referred to as 'perennial crops' for brevity) have great potential in the progress towards achieving Sustainable Development Goals (SDGs) by reconciling agricultural production and biodiversity conservation. Although agriculture has been a key driver of recent and ongoing land-use change, and perennial woody crops have contributed to these changes (e.g., tropical deforestation [12–14]), some perennial crops, if managed under sustainable principles, can be amenable to biodiversity conservation. Furthermore, perennial cropping systems tend to be less mechanized and often require significant human labor, offering the opportunity to reduce unemployment and support rural livelihoods[15,16], especially in developing countries where many of these crops are grown. Unfortunately, these potential benefits are often undermined by low wages, seasonal labor, worker exploitation, and immigration[16], problems that are exacerbated as perennial crop production is intensified. This intensification partly reflects a lack of recognition of the ecological and social significance of perennial crops, and a lack of incentives to promote sustainable practices. Most agricultural policies aimed at improving environmental and economic sustainability emphasize annual crop management (arable land), with very few specifically targeting perennial crops [17]. A focus on annual crops is clearly important for improving agricultural sustainability, and associated actions, such as Agri-environmental Schemes[18,19] are proving successful overall (albeit with scope for improvement [20]). However, we argue that leveraging the potential of perennial crops to contribute to SDGs for environmental and economic sustainability requires more research, legislative support, and the implementation of tailored policies[21,22].

In this Perspective we aim to highlight the unexploited potential of properly managed and incentivized perennial woody crops to contribute to SDGs. In doing so, we do not aim to diminish the importance of annual crops or to compare the two cropping systems. Rather, we emphasize that annual and perennial crop systems each have particular risks and advantages that require different management approaches (Supplementary Table 1). Although intensification affects both systems and typically diminishes their contribution to SDGs, annual crops have on average a lower ecological value even when properly managed due to their simpler structural complexity and short-term dynamics[23–25]. Perennial crops require a longer-term commitment from growers, which make them less flexible and hence more vulnerable to climate change and novel pests and diseases. Yet, perennial crops managed under agroecological principles with higher reliance on ecological processes ('ecological intensification'[26]) have substantial potential to contribute to key SDGs. This results especially from their greater structural complexity, temporal stability, and strategic presence in biodiversity-rich and socio-economically developing regions[10]. We argue that new, complementary agricultural policies should aim to maximize the contribution of perennial woody crops to SDGs, and counter the current trend toward unsustainable farming in these systems.

Relevance of perennial crops for the SDGs

Perennial woody crops typically include plantations of fruit trees (e.g. citrus), nut trees (cashews, walnuts, or almonds), berry plantations (blueberries), stimulants (coffee, cocoa, tea), vine crops, and palm and olive tree plantations, among others. Although not woody, we include bananas and plantains in this discussion as they are ecologically and socio-economically important tree-like perennial crops. Perennial crops cover ca. 183 M ha worldwide, many of which overlap with key biodiversity hotspots[27]. For instance, coffee is extensively grown in tropical areas of Mesoamerica, olive trees in the Mediterranean Basin hotspot, cocoa in the Guinean Forests of West Africa, and oil palm in Sundaland (Fig. 1 and Supplementary Table 2).

As with any other cropping system, perennial woody crops inherently conflict with the conservation of the natural habitats they replace. However, some of their characteristics can make them compatible with biodiversity conservation. Their heterogeneous and often forest-like structure, encompassing many vegetation layers, offers a wide range of micro- and macrohabitats that can support high diversity, including native plant species in the herbaceous cover (e.g., vineyards, olive or apple groves), overhead shade trees (e.g., cocoa, or coffee), and mixed species associations [29–32]. Consequently, a high number of vertebrate and invertebrate taxa can coexist in these agroecosystems [33–36]. In addition to the inherent structural heterogeneity, perennial crops occupy the land over multiple years without replanting, offering relatively stable habitats within and across years. As a result, habitat and species diversity can be more easily maintained in perennial crop systems compared to arable crops.

Many perennial woody crops have extensive root structures, provide abundant litter, and thus can reduce soil erosion, increase soil fertility and soil health, minimize nutrient leaching, and provide permanent habitats for many species[37–39], while being highly productive (i.e., ca. 1 billion metric tons a year worldwide, FAOstats, 2021). Furthermore, woody tree-like perennial crops can help reduce greenhouse gases through above and belowground carbon sequestration [39–41]. Perennial crop systems can also act as a permeable matrix through which wildlife can travel between forest patches, enhancing connectivity and contributing to the maintenance of fragmented forest populations as metapopulations [42]. As such, they can buffer protected areas and other natural and semi-natural habitats within intensively managed agricultural landscapes [43].

Perennial crops can thus, when correctly managed, support a wide range of plant and animal species alongside the crop, playing a key role in reconciling biodiversity conservation with the needs of people – and in some cases maximizing nature's contribution to people (Fig. 2 and Supplementary Figure 1). Nevertheless, leveraging these opportunities requires greater representation in the scientific literature (Fig. 3), and in agricultural policies.

Most potential gains discussed here pertain to diversified woody or tree-like perennial crops because of their high biomass and complex structure. However, it is worth noting that herbaceous perennial crops, such as alfalfa, also cover extensive areas and are also highly relevant for biodiversity and soil health [44]. Given the substantial advantages of perennial herbaceous crops over their annual counterparts [23,45,46], significant effort is underway to develop and cultivate perennial varieties of key herbaceous species (e.g., grains)[25,47]. Developing new and improved crop varieties, while preserving the genetic diversity of crops, could be crucial, particularly in marginal landscapes, resource-constrained settings, and in regions facing increased drought from climate change [45,46].

Legislation gaps harm conservation efforts

With a few exceptions (see ASEAN 2022 Regional Guidelines for sustainable palm oil production), perennial cropping systems have received limited attention within the global agricultural policy framework. For example, there is no explicit mention of perennial crops in the latest agricultural policy monitoring and evaluation report conducted by the Organization for Economic Co-operation and Development (OECD), which encompasses agricultural legislation from 54 countries worldwide[17]. This is surprising given the overarching theme of this report, i.e., "Reforming Agricultural Policies for Climate Change Mitigation". Another example is the European Union (EU), known for its wide-ranging agricultural policies and a substantial budget to implement them (e.g., €387 billion for the period 2023-2027). In the EU, perennial crops have historically been considered 'green' by definition, and it is only in the most recent reform of the Common Agricultural Policy (CAP 2023-2027) that guidelines specific to them have been introduced, such as the conservation of living or inert ground cover. Although these guidelines represent a step forward, they fall short of fully realizing the potential of perennial crops for conserving agrobiodiversity and promoting sustainability. Furthermore, long-term unsustainable incentives persist, such as the promotion of inefficient irrigation systems that deplete groundwater in semiarid rainfed Mediterranean crops, or the exemption of perennial crops from some environmental requirements. For instance, according to EU-CAP, establishing seminatural areas of non-production for nature (formerly known as 'set-aside', now a component of 'Good agricultural and environmental conditions' or GAEC) is a requirement that only applies to arable crops, with perennial crops and grasslands essentially exempt. Moreover, payments for specific sectors – such as fruit trees, olives, and wine – are not attached to environmental standards, meaning that the opportunity is missed to secure their environmental value. More worryingly, it is precisely in perennial crops that, in Europe, contamination by the so-called 'Candidates for substitution' (that is, pesticides listed as hazardous to humans) has seen a steep rise in recent years, reaching extremely high levels in fruits such as cherries, apples, pears, peaches and kiwi (PAN 2022, https://www.pan-europe.info/).

Specific environmental legislation regarding the long-term sustainability of perennial crop landscapes is virtually absent globally[17]. This limited focus and presence of proactive measures have been a contributor to the ongoing rapid trend towards deforestation[12–14], and extreme intensification of many perennial crops worldwide, especially in tropical areas. For instance, Jha et al. (2014) found that the area of traditional shaded coffee decreased from 43% to 24% in 19 countries between 1996 and 2010, resulting in high biodiversity loss[48]. This general trend, also generalizable to other perennial crops and areas, poses an important threat to biodiversity and sustainability across millions of hectares worldwide[49] (Fig. 4).

Some of the most frequent and environmentally damaging practices within perennial crops currently include: (i) loss of forest- or savannah-like structure as traditional low-density orchards are replaced by hyper-dense planting lines (i.e., hedge-like plantations) [50,51]; (ii) loss of soil and decline in soil quality through frequent tillage and, especially, the use of pre- and post-emergence herbicides that leave bare soils by persistently removing herbaceous cover [52]; (iii) loss of crop diversity and genetic/varieties diversity [53,54]; and iv) loss of landscape complexity through the removal of field margins and patches of semi-natural vegetation and reduction of native flora in agroecosystems[6]. These negative practices can often co-occur, as in super-intensive olive, apple, or even coffee/cacao farming systems, turning traditional (often smallholder) forest-like agroecosystems into high-input, hyperdense monocultures (Fig. 5, and Supplementary Table 3).

Besides the conservation threats arising from unsustainable practices, there are also crucial socio-economic consequences to consider. Current models for perennial crop cultivation, which rely heavily on rapid and extensive automation and mechanization, contribute to rural unemployment, a major political challenge worldwide[55]. Moreover, the prevalence of corporate farming — large-scale monocultures owned by major companies — fosters a decline in community engagement and leads to income reduction for millions of people worldwide [7]. Since ensuring a decent job for all is one of the Sustainable Development Goals (SDG-8), avoiding extreme levels of mechanization and promoting fair and stable labor for people appears to offer a viable approach to balancing employment and profit, especially when striving to ensure an equitable redistribution of profits among stakeholders.

In light of the prevailing tendency towards less sustainable agricultural practices, it is timely to stress the need for national and international agricultural policies that strategically allocate targeted and tailored incentives aimed at fostering socially responsible and sustainable perennial crop cultivation. Measures in this direction (e.g., the minimum social and labor standards to receive subsidies implemented in the last CAP within the European Union) have the potential to safeguard the long-term sustainability and ecological value of these agricultural systems, while ensuring equitable incomes for farm households and laborers, and thus supporting the progress of other SDGs, such as providing decent jobs and economic development.

Policies for perennial crop sustainability

Solutions offering a favorable balance between production and sustainability exist, but agricultural policies are still inadequate in encouraging farmers to adopt them.

The viability of sustainable agricultural practices largely depends on economic benefits for farmers and wider society[56,57]. Payment of incentives for ecosystem service provision has been highly effective at promoting sustainable practices in some contexts[7,58]. Nevertheless, the complex nature of agroecosystems, influenced by diverse socio-political circumstances, means that there is no one-size-fits-all solution applicable to all ecological and socio-economic contexts. Therefore, we share our vision about the status and threats to key perennial crops worldwide (Fig. 5 and Supplementary Table 3), and propose the incentivization of specific practices to promote more sustainable agriculture in key agroecosystems (Fig. 6 and Supplementary Table 4), such as oil palm, cocoa, coffee, olive, grapevine, banana, citrus and apple (extended in Supplementary Notes 1 to 8), to increase their sustainability and support the progress towards SDGs[59].

We identify three priorities. Firstly, most perennial woody crops will benefit from within-field and landscape-level management practices that foster biodiversity (i.e., 'ecological intensification')[26], and those good practices often require both regulation and economic incentives[56]. Secondly, for some perennial crops grown in tropical biodiversity hotspots (e.g. cocoa, coffee, or oil palm), there is a need for stricter regional land use planning together with international trade regulation efforts to adjust offer and demand [60]. Such regulations should target the whole food chain and are necessary to ensure deforestation is halted and reversed. Finally, transitioning towards agricultural sustainability demands a holistic and multidimensional approach. This involves integrating a variety of tools across the entire food chain into policy design, creating targeted campaigns for technology adoption, and providing comprehensive support to farmers through training, extension programs, financial aid, fair prices (i.e., living income reference price), and incentives. Addressing market access, certification standards, consumer awareness, and fostering participatory approaches are equally crucial. A combination of incentives, such as subsidies for biodiversity-friendly farming practices, payments for ecosystem services, or results-based payments, can significantly enhance conservation outcomes. Additionally, measures such as tax reductions, insurance support for farmers willing to sacrifice some yield in favor of more sustainable practices, assistance with certification processes, promotion of sustainable products, support for implementing adaptive measures against climate change risks, and land stewardship programs can further reinforce these efforts.

Intertwined complexities and a way forward

Legislating agriculture is a complex challenge since there are multiple trade-offs and interconnections between ecological, economic, and social components. In this context, solutions are not absolute and universal but need to be implemented progressively and revised to avoid undesired outcomes. In particular, much work remains to be done to understand the interplay between various socio-economic and ecological dimensions in different key agroecosystems, particularly perennial crops, and how to maximize benefits in some components (e.g., farmer profitability or rural development) without compromising others (e.g., biodiversity conservation) [56].

The first key aspect is that a large fraction of biodiversity-friendly measures relates to promoting smallholders. However, it is crucial to recognize that smallholders often lack the capacity to implement efficient and sustainable practices due to limited resources, while some larger producers could transition more easily towards sustainable farming. Therefore, it is important to consider that the type and extent of exploitation are affected by various economic, social, and environmental factors affecting farmer's decisions. Accordingly, support should be tailored to farmers' capacities and needs, to ensure that larger producers are incentivized to pursue agroecological efforts, while vulnerable farmers receive sufficient help to adopt sustainable practices without compromising their livelihoods[61]. Similarly, regulations can prove ineffective if we do not tackle problems such as the unfair distribution of the income generated by perennial crops across the food chain; decentralizing food chains could help in this context[56]. Regulating crop production cannot be done without integrating the social, economic, and ecological dimensions, and their interconnections and ramifications. Pressing global issues such as food waste, climate change, food security challenges, and biodiversity loss depend heavily on the actions we suggest here.

Second, we need to understand how potential solutions at small scales can work when implemented at larger scales, as we still have poor knowledge about the feedback effects (positive or negative) of large-scale expansion of sustainable practices [62]. For example, imposing a fast transition towards organic agriculture in a generalized manner, without properly facilitating the transition, can have positive results for biodiversity, but bring problematic consequences for food production and food security if yields decrease significantly (e.g. due to elevated pest damage) and products become unavailable or unaffordable for part of the population[63]. In some cases, certifications or labels (e.g., organic or fair-trade for coffee or cocoa) have been implemented successfully to distinguish specific products in the market, encouraging more sustainable management in these systems. This assumes that a segment of the public is willing to pay more for certified products. However, predicting market behavior becomes challenging as the proportion of production achieving certification increases, and certification might only work if certified products are relatively scarce. Hence, while we support the promotion of certified products through economic incentives, international customs duties, and national tax differentials to alleviate the certification costs incurred by farmers, this recommendation should be revisited in the midterm once higher market quotas for certified products are reached.

Third, some of the key problems in agriculture are inherent to the current market system and predominant consumption model. Therefore, a deep transformation in the way people purchase and consume agricultural goods and products could be needed to change these dynamics. For instance, many tree crops yield non-essential products from a nutritional standpoint that are consumed far from the production areas, which is often regarded as less sustainable compared to using local products. Hence, as a society, we should reflect on the biodiversity impacts of consumption of non-local and non-essential products, and on which crops we would like to prioritize to promote healthy and nutritious diets; for example, crops with high protein content.

Reflecting on these complexities, we argue that the following three key are crucial to achieving SDGs. Firstly, international trade needs international agreements focusing on the entire supply chain. Countries and companies that import products from producing areas (often located in developing countries in Latin America, Africa and Asia) should also take responsibility for the socio-economic and ecological impacts of these transactions (e.g., waive customs duties or avoid externalization of environmental damage)[60]. Working on international agreements could have a positive impact on the way we produce food and on people's livelihoods worldwide. Special care must be taken not to shift the burden of environmental protection onto smallholder farmers, who typically have lower incomes and are more vulnerable to both environmental stresses and the economic and social impacts of agricultural policies. Instead, they should be supported and incentivized to adopt sustainable practices while also ensuring they receive a fair income. For example, rising temperatures and erratic rainfall patterns driven by climate change are increasingly affecting the production and profitability of some perennial crops such as cocoa, coffee, and citrus. This is particularly critical for smallholder farmers whose livelihoods are closely linked to these crops[64]. Addressing the challenges posed by climate change for these perennial crops requires ingenuity from smallholder farmers and support to implement adaptive measures including shade-planting, establishment of cover vegetation to protect the soil (including marketable crops), or rainwater harvesting and provision of irrigation[65,66]. Smallholder farmers, especially those in dryland farming systems, are also confronted with non-climatic stressors (e.g., limited access to markets and inadequate agricultural equipment) that are often exacerbated by existing inequalities in relation to access to land and other productive capital resources[67]. These challenges drive smallholders' vulnerability to climatic and non-climatic threats including food insecurity. Therefore, there is an urgent need for holistic policy interventions that could empower smallholders to adopt new, efficient, and sustainable practices where possible. Additionally, larger commercial growers can learn from smallholders (e.g., about the use of different parts of the plants). The exchange of knowledge and practices should be mutual, ensuring that different types of farmers benefit both environmentally and economically. Secondly, each agricultural system has its particular problems and needs, and one policy will not fit them all. While some regions should focus on the protection and conservation of natural areas (e.g., palm oil production) using regulatory policies and land-use planning, others should concentrate on restoring already degraded lands, semi-natural habitats in exploitation, and the surrounding landscape through incentives (e.g., olive farms, vineyards, or apple orchards). Thirdly, the multiple socio-political feedbacks and interactions in place imply that policies cannot work in isolation from society and local communities. Rather, a socio-cultural and economic context that facilitates the evolution and development of green and equitable policies should be fostered. There is a need to work bottom-up with local communities to incentivize and encourage local sustainable crops and ensure the uptake of such policies by local communities, instead of enforcing market needs upon them.

In conclusion, perennial crops can play a crucial role in harmonizing agriculture and the achievement of the SDGs if correctly managed. However, their significance warrants increased attention in scientific research and agricultural policies. Neglecting the value of perennial crops can lead to increased unsustainability, accelerating a myriad of environmental and social issues, that are compounded by climate change. To secure the future of agriculture and biodiversity, and progress towards the achievement of the SDGs, governments should consider legislative support and tailored policies for perennial woody crops. A variety of actions proposed here could promote sustainable practices in perennial crop cultivation globally, reducing biodiversity loss, supporting livelihoods and rural development, addressing climate change concerns and building resilience of farmers especially smallholders, and enhancing food security in the years ahead. The ultimate goal of this article is to bring attention to this issue, stimulate debate involving as many actors as possible, and motivate policymakers and scientists to place this important matter on their agenda.

Additional information

Correspondence should be addressed to Carlos Martínez-Núñez.

Acknowledgments

The authors acknowledge funding from the project SHOWCASE (SHOWCASing synergies between agriculture, biodiversity and Ecosystem services to help farmers capitalizing on native biodiversity) within the EU's Horizon 2020 Research and Innovation Programme (grant agreement 862480). C.M.-N. was supported by the 'Juan de la Cierva' program (ref. FJC2021-046829-I). T.S.P. was supported by a research scholarship awarded by the Nanyang Technological University, Singapore (Application No: R2004096). P.J.R acknowledges the projects RECOVECOS (PID2019-108332GB-I00, funded by MICIN/AEI/10.13039/501100011033) and OLIVARES VIVOS + (LIFE20 AT/ES/001487, European Commission). The contribution of D.J.S. was made possible by the financial support of NORAD (Grant number: QZA-21/0124) for the CIFOR GCS-REDD+ (Global Comparative Study on REDD+) project. A.R. acknowledges the support of the French National Research Agency (ANR) under the grant 20-PCPA-0010 and the support of the National Program PEPR 'Solutions fondées sur la Nature' (SOLU-BIOD), through the Living Lab 'Bacchus'. G.P. acknowledges funding from the strategic project iCAP-BES by the German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig (DFG FZT 118), as well as from the EU Horizon Europe project Agroecology-TRANSECT (grant agreement No. 101060816). This publication reflects only the authors' opinions.

Author contributions

C.M.-N. conceptualized the study, coordinated the team, and wrote the first draft of the manuscript. E.V.-A. created the map figure and a table, and helped to structure the study. J.A., P.J.R., G.M.t.H., G.P., Y.Z., Y.L., P.A.-A., A.R., C.S., T.S.P., D.J.S., D.B., L.A.G., E.D.C., O.T.L., and I.P. contributed to writing and improving different sections of the manuscript. I.B. contributed to structuring and writing the article. All authors contributed significantly to the final version of the manuscript.

Competing interests

The authors declare no competing interests

References

1. Clough, Y. *et al.* Land-use choices follow profitability at the expense of ecological functions in Indonesian smallholder landscapes. *Nat. Commun. 2016 71* **7**, 1–12 (2016).
2. Newbold, T. *et al.* Global effects of land use on local terrestrial biodiversity. *Nat. 2015 5207545* **520**, 45–50 (2015).
3. Rohr, J. R. *et al.* Emerging human infectious diseases and the links to global food production. *Nat. Sustain. 2019 26* **2**, 445–456 (2019).
4. Díaz, S. *et al.* Assessing nature's contributions to people. *Science (80-.).* **359**, 270–272 (2018).
5. FAO. *Tool for Agroecology Performance Evaluation (TAPE) - Test version: Process of development and guidelines for application.* https://www.fao.org/documents/card/en/c/ca7407en/ (2019).
6. Tscharntke, T., Grass, I., Wanger, T. C., Westphal, C. & Batáry, P. Beyond organic

farming – harnessing biodiversity-friendly landscapes. *Trends Ecol. Evol.* **36**, 919–930 (2021).

7. Garibaldi, L. A. *et al.* Policies for Ecological Intensification of Crop Production. *Trends Ecol. Evol.* **34**, 282–286 (2019).

8. Lal, R. *et al.* Management to mitigate and adapt to climate change. *J. Soil Water Conserv.* **66**, 276–285 (2011).

9. Perfecto, I., Vandermeer, J. & Wright, A. *Nature's Matrix Linking Agriculture, Biodiversity Conservation and Food Sovereignty*. (Taylor and Francis group, 2019). doi:https://doi.org/10.4324/9780429028557.

10. Bhagwat, S. A., Willis, K. J., Birks, H. J. B. & Whittaker, R. J. Agroforestry: a refuge for tropical biodiversity? *Trends Ecol. Evol.* **23**, 261–267 (2008).

11. Wanger, T. C. *et al.* Integrating agroecological production in a robust post-2020 Global Biodiversity Framework. *Nat. Ecol. Evol.* 1–3 (2020) doi:10.1038/s41559-020-1262-y.

12. Fitzherbert, E. B. *et al.* How will oil palm expansion affect biodiversity? *Trends Ecol. Evol.* **23**, 538–545 (2008).

13. Li, T. M. Securing oil palm smallholder livelihoods without more deforestation in Indonesia. *Nat. Sustain. 2024 74* **7**, 387–393 (2024).

14. Kalischek, N. *et al.* Cocoa plantations are associated with deforestation in Côte d'Ivoire and Ghana. *Nat. Food 2023 45* **4**, 384–393 (2023).

15. Garibaldi, L. A. & Pérez-Méndez, N. Positive outcomes between crop diversity and agricultural employment worldwide. *Ecol. Econ.* **164**, 106358 (2019).

16. Seneduangdeth, D., Ounmany, K., Phommavong, S., Phouxay, K. & Hathalong, K. Labor employment opportunities in coffee production in southern lao people democratic republic. *J. Asian Rural Stud.* **2**, 16–36 (2018).

17. OECD. *Agricultural Policy Monitoring and Evaluation 2022 Reforming Agricultural Policies for Climate Change Mitigation*. (OECD Publishing, 2022). doi:https://doi.org/10.1787/7f4542bf-en.

18. Batáry, P., Dicks, L. V., Kleijn, D. & Sutherland, W. J. The role of agri-environment schemes in conservation and environmental management. *Conserv. Biol.* **29**, 1006–1016 (2015).

19. Boetzl, F. A. *et al.* A multitaxa assessment of the effectiveness of agri-environmental schemes for biodiversity management. *Proc. Natl. Acad. Sci. U. S. A.* **118**, (2021).

20. Candel, J. J. L., Lakner, S. & Pe'er, G. Europe's reformed agricultural policy disappoints. *Nature* **595**, 650 (2021).

21. Pe'er, G. *et al.* Action needed for the EU Common Agricultural Policy to address sustainability challenges. *People Nat.* **2**, 305–316 (2020).

22. Nicholson, E. *et al.* Scientific foundations for an ecosystem goal, milestones and indicators for the post-2020 global biodiversity framework. *Nat. Ecol. Evol. 2021 510* **5**, 1338–1349 (2021).

23. Pimentel, D. *et al.* Annual vs. perennial grain production. *Agric. Ecosyst. Environ.* **161**, 1–9 (2012).

24. Batello, C. *et al. Perennial crops for food security: Proceedings of the FAO expert workshop*. *Proceedings of the Perennial crops for food security Proceedings of the FAO expert workshop* (Food and Agriculture Organization of the United Nations (FAO), 2014).

25. Crews, T. E., Carton, W. & Olsson, L. Is the future of agriculture perennial? Imperatives and opportunities to reinvent agriculture by shifting from annual monocultures to perennial polycultures. *Glob. Sustain.* **1**, e11 (2018).

26. Kleijn, D. *et al.* Ecological Intensification: Bridging the Gap between Science and Practice. *Trends Ecol. Evol.* **34**, 154–166 (2019).

27. Myers, N., Mittermeler, R. A., Mittermeler, C. G., Da Fonseca, G. A. B. & Kent, J. Biodiversity hotspots for conservation priorities. *Nat. 2000 4036772* **403**, 853–858 (2000).

28. Tang, F. H. M. *et al.* CROPGRIDS: a global geo-referenced dataset of 173 crops. *Sci. Data 2024 111* **11**, 1–14 (2024).

29. Sonwa, D. J., Weise, S. F., Schroth, G., Janssens, M. J. J. & Shapiro, H. Y. Structure of cocoa farming systems in West and Central Africa: a review. *Agrofor. Syst.* **93**, 2009–2025 (2019).

30. Tarifa, R. *et al.* Agricultural intensification erodes taxonomic and functional diversity in Mediterranean olive groves by filtering out rare species. *J. Appl. Ecol.* **58**, 2266–2276 (2021).

31. Winter, S. *et al.* Effects of vegetation management intensity on biodiversity and ecosystem services in vineyards: A meta-analysis. *J. Appl. Ecol.* (2018) doi:10.1111/1365-2664.13124.

32. Valencia, V., García-Barrios, L., West, P., Sterling, E. J. & Naeem, S. The role of coffee agroforestry in the conservation of tree diversity and community composition of native forests in a Biosphere Reserve. *Agric. Ecosyst. Environ.* **189**, 154–163 (2014).

33. Schroth, G. & Harvey, C. A. Biodiversity conservation in cocoa production landscapes: An overview. *Biodivers. Conserv.* **16**, 2237–2244 (2007).

34. Rey, P. J. *et al.* Landscape-moderated biodiversity effects of ground herb cover in olive groves: Implications for regional biodiversity conservation. *Agric. Ecosyst. Environ.* **277**, 61–73 (2019).

35. Sonwa, D. J. *et al.* Diversity of plants in cocoa agroforests in the humid forest zone of Southern Cameroon. *Biodivers. Conserv.* **16**, 2385–2400 (2007).

36. Bruggisser, O. T., Schmidt-Entling, M. H. & Bacher, S. Effects of vineyard management on biodiversity at three trophic levels. *Biol. Conserv.* **143**, 1521–1528 (2010).

37. Clough, Y. *et al.* Combining high biodiversity with high yields in tropical agroforests. *Proc. Natl. Acad. Sci. U. S. A.* **108**, 8311–8316 (2011).

38. Kavvadias, V. & Koubouris, G. Sustainable soil management practices in olive groves. in *Soil Fertility Management for Sustainable Development* 167–188 (Springer Singapore, 2019). doi:10.1007/978-981-13-5904-0_8.

39. Cerda, R. *et al.* Effects of shade, altitude and management on multiple ecosystem services in coffee agroecosystems. *Eur. J. Agron.* **82**, 308–319 (2017).

40. Ewing, P. M. *et al.* Smallholder farms have and can store more carbon than previously estimated. *Glob. Chang. Biol.* **29**, 1471–1483 (2023).

41. Batsi, G., Sonwa, D. J., Mangaza, L., Ebuy, J. & Kahindo, J. M. Preliminary estimation of above-ground carbon storage in cocoa agroforests of Bengamisa-Yangambi forest landscape (Democratic Republic of Congo). *Agrofor. Syst.* **95**, 1505–1517 (2021).

42. Perfecto, I. & Vandermeer, J. The agroecological matrix as alternative to the land-sparing/agriculture intensification model. *Proc. Natl. Acad. Sci. U. S. A.* **107**, 5786–5791 (2010).

43. Kremen, C. & Merenlender, A. M. Landscapes that work for biodiversity and people. *Science (80-.).* **362**, (2018).

44. González del Portillo, D., Arroyo, B. & Morales, M. B. The adequacy of alfalfa crops as an agri-environmental scheme: A review of agronomic benefits and effects on biodiversity. *J. Nat. Conserv.* **69**, 126253 (2022).

45. Glover, J. D. *et al.* Increased food and ecosystem security via perennial grains. *Science (80-.).* **328**, 1638–1639 (2010).

46. DeHaan, L. R. *et al.* Discussion: Prioritize perennial grain development for sustainable food production and environmental benefits. *Sci. Total Environ.* **895**, 164975 (2023).

47. Zhang, S. *et al.* Sustained productivity and agronomic potential of perennial rice. *Nat. Sustain. 2022 61* **6**, 28–38 (2022).

48. Jha, S. *et al.* Shade Coffee: Update on a Disappearing Refuge for Biodiversity. *Bioscience* **64**, 416–428 (2014).

49. Harvey, C. A. *et al.* Transformation of coffee-growing landscapes across Latin America. A review. *Agron. Sustain. Dev.* **41**, 1–19 (2021).

50. Guerrero-Casado, J., Carpio, A. J., Tortosa, F. S. & Villanueva, A. J. Environmental challenges of intensive woody crops: The case of super high-density olive groves. *Sci. Total Environ.* **798**, 149212 (2021).

51. Morgado, R. *et al.* Drivers of irrigated olive grove expansion in Mediterranean landscapes and associated biodiversity impacts. *Landsc. Urban Plan.* **225**, 104429 (2022).

52. Kopittke, P. M., Menzies, N. W., Wang, P., McKenna, B. A. & Lombi, E. Soil and the intensification of agriculture for global food security. *Environ. Int.* **132**, 105078 (2019).

53. Wolkovich, E. M., García De Cortázar-Atauri, I., Morales-Castilla, I., Nicholas, K. A. & Lacombe, T. From Pinot to Xinomavro in the world's future wine-growing regions. *Nat. Clim. Chang. 2017 81* **8**, 29–37 (2018).

54. Dempewolf, H., Krishnan, S. & Guarino, L. Our shared global responsibility: Safeguarding crop diversity for future generations. *Proc. Natl. Acad. Sci. U. S. A.* **120**, e2205768119 (2023).

55. Kühn, S. Global employment and social trends. *World Employ. Soc. Outlook* **2018**, 5–10 (2018).

56. Kleijn, D. *et al.* Bending the curve of biodiversity loss requires rewarding farmers economically for conservation management. *ARPHA Prepr.* **4**, e104881- (2023).

57. Scheper, J. *et al.* Biodiversity and pollination benefits trade off against profit in an

intensive farming system. *Proc. Natl. Acad. Sci. U. S. A.* **120**, e2212124120 (2023).

58. Hayes, T., Murtinho, F., Wolff, H., López-Sandoval, M. F. & Salazar, J. Effectiveness of payment for ecosystem services after loss and uncertainty of compensation. *Nat. Sustain. 2021 51* **5**, 81–88 (2021).

59. Malekpour, S. *et al.* What scientists need to do to accelerate progress on the SDGs. *Nat. 2023 6217978* **621**, 250–254 (2023).

60. Zinngrebe, Y. *et al.* Prioritizing partners and products for the sustainability of the EU's agri-food trade. *One Earth* **7**, 674–686 (2024).

61. Waarts, Y. R. *et al.* Multiple pathways towards achieving a living income for different types of smallholder tree-crop commodity farmers. *Food Secur.* **13**, 1467–1496 (2021).

62. Gaudaré, U. *et al.* Soil organic carbon stocks potentially at risk of decline with organic farming expansion. *Nat. Clim. Chang. 2023 137* **13**, 719–725 (2023).

63. Wijerathna-Yapa, A., Henry, R. J., Dunn, M. & Beveridge, C. A. Science and opinion in decision making: A case study of the food security collapse in Sri Lanka. *Mod. Agric.* **1**, 142–151 (2023).

64. Asitoakor, B. K. *et al.* Influences of climate variability on cocoa health and productivity in agroforestry systems in Ghana. *Agric. For. Meteorol.* **327**, 109199 (2022).

65. Jamal, A. M. *et al.* Gendered perceptions and adaptation practices of smallholder cocoa farmers to climate variability in the Central Region of Ghana. *Environ. Challenges* **5**, 100293 (2021).

66. Afriyie-Kraft, L., Zabel, A. & Damnyag, L. Adaptation strategies of Ghanaian cocoa farmers under a changing climate. *For. Policy Econ.* **113**, 102115 (2020).

67. Antwi-Agyei, P. *et al.* Perceived stressors of climate vulnerability across scales in the Savannah zone of Ghana: a participatory approach. *Reg. Environ. Chang.* **17**, 213–227 (2017).

Fig. 1: Overlap between the main perennial woody crops and hotspots of biodiversity. Orange shading indicates areas where any of the following perennial crops are grown: oil palm, bananas and plantains, cacao, coffee, coconut, olives, grapevine, cashew nuts, mangoes, apple, orange [28]. Green shading indicates the main biodiversity hotspots according to Myers et al., 2000 (revised version, 2016)[27].

Fig. 2: The importance of perennial woody crops worldwide. A) World map showing six of the most important perennial crops in terms of area coverage and socio-economic impact. The world map and plant icons were modified from https://freesvg.org. B) Main ecosystem services provided by perennial crops worldwide. C) Area covered in the year 2021 by each crop (the production area of bananas, including plantains and cooking bananas, reaches 12 M ha), and potential for biodiversity conservation and ecosystem services provision by key perennial crops worldwide. Although not woody, we include bananas as they are ecologically and socio-economically important tree-like perennial crops. See Supplementary Figure 1 for a fully referenced version.

Fig. 3: Scientific attention received by perennial woody crops and annual crops. The figure illustrates the total number of publications indexed in the Web of Science (grey) and the subset of publications within the field of Environmental Sciences (blue) that are related to specific keywords like 'annual crop' or 'wheat'. The search was done in June 2024. Note that high scientific attention does not necessarily imply that effective measures are properly deployed.

Fig. 4: Effects of agricultural practices in perennial crops along the sustainability gradient. Environmental and socio-economic negative effects driven by unsustainable production in perennial crops, showcased by extremes of sustainability in three key perennial crops worldwide (coffee, olive, and grapevine). Coffee pictures courtesy of Jacques Avelino. Pictures of olive farms courtesy of Pedro J. Rey. Pictures of grapevines courtesy of Sophie Chamont (top) and Sylvie Richart Cervera (bottom).

Fig. 5: Main threats to the sustainability of key perennial crops worldwide. Principal risks facing specific perennial woody crops were highlighted by experts on each crop. 'Environmentally less sustainable practices' refer to actions under the control of farmers, whereas 'Economically less sustainable practices' and broader 'Threats to sustainable production' require the involvement of multiple stakeholders, including scientists, society, and politicians. This list is not exhaustive; only the priority threats are highlighted for each crop and other secondary threats may also apply. *Although bananas are not woody, they are included due to their ecological and socio-economic importance as tree-like perennial crops.

Fig. 6: Agricultural practices and farming models that could be incentivized by new agricultural policies. These actions could help to increase the ecological and socio-economic long-term sustainability of key perennial crops worldwide. The proposed solutions are based on expert knowledge and scientific literature (see Supplemenyst for an extended commentary on each one, with supporting citations). 'Agricultural practices to incentivize' are actions under the

control of farmers, whereas ‘Goals and areas of priority policy investment’ require the involvement of multiple stakeholders including scientists, civil society, and politicians. ‘SDGs enhanced’ indicates the environmental and socio-economic realms that each action would improve. SDGs: 1 (no poverty), 6 (clean water and sanitation), 8 (decent work and economic growth), 10 (reduced inequality), 12 (responsible production and consumption), 13 (climate), and 15 (life on land). * Although not woody, we include bananas and plantain as ecologically and socio-economically important tree-like perennial crops. Other details are analogous to those in Fig. 5.