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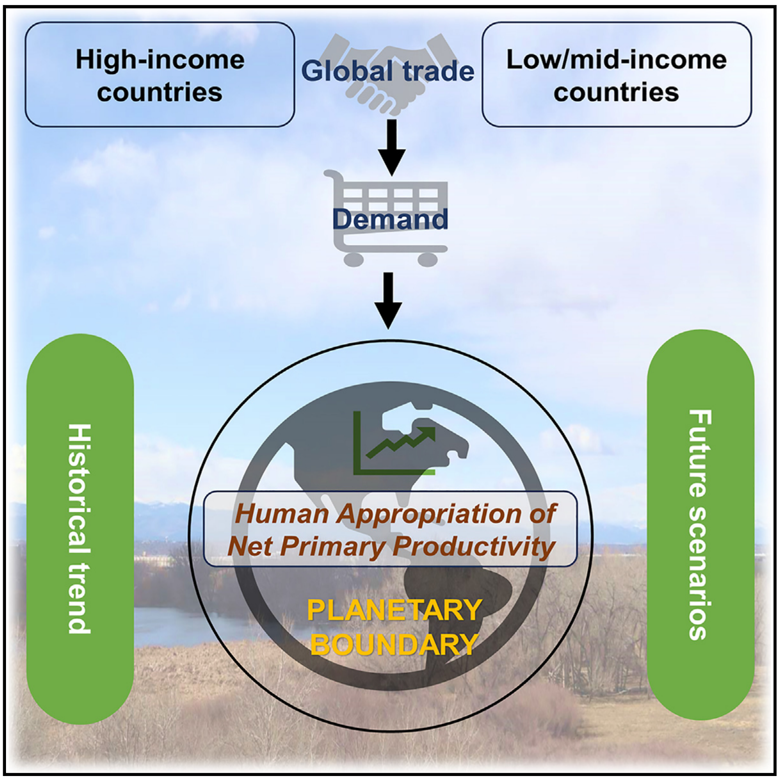
Demand-side insights for steering human appropriation of net primary productivity within planetary boundaries

Graphical abstract



Highlights

- The remaining space for global HANPP shrank significantly in the recent decade
- Many high-income countries transgressed their per-capita-based boundary allocations
- Future pressure on the HANPP boundary mainly comes from low-/mid-income countries
- Need for restructuring global supply chains and sharing agricultural technologies

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In brief

In a world of increasing population and economic growth, this study quantifies humanity's impact on Earth's finite ecosystem services using HANPP. It highlights a notable reduction in global HANPP expansion capacity, mainly due to high-income countries' overconsumption and the growing needs of low-/mid-income countries. The research underscores the urgent need for collaborative international efforts in supply chain restructuring and technology for sustainably managing HANPP and ensuring the stability of the ecosystem.

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Demand-side insights for steering human appropriation of net primary productivity within planetary boundaries

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SCIENCE FOR SOCIETY Balancing the rising demand for land and biomass caused by economic and population growth with Earth's finite resources is a critical challenge for society today. Crossing a certain limit, known as the "planetary boundary," may cause irreversible harm to the Earth's capacity to support life. The human appropriation of net primary productivity (HANPP) measures how much of the Earth's natural growth humans use and is considered a suitable metric for establishing planetary boundaries for land system change and biosphere integrity. We access the HANPP consumption by country and project its growth under several future scenarios. Our findings show that overconsumption in high-income countries and growing demand from low-/mid-income countries are rapidly closing the window for keeping HANPP within planetary boundaries. Shifting imports to countries with higher land-use efficiency and sharing agricultural techniques between countries can help to alleviate this challenge.

SUMMARY

Human activities are increasingly pressuring the land system and biosphere integrity, highlighting the urgency to manage this pressure—measured as human appropriation of net primary productivity (HANPP)—within a safe limit (planetary boundary) to avoid catastrophic consequences. Prior studies have suggested that solutions lie in demand management, yet the HANPP consumption by country and its future trends remain unclear. Understanding these aspects is vital for identifying hotspot regions and proposing potential solutions. Here, by developing a model for country-level HANPP consumption accounting and projections, we find that nearly half of high-income countries have surpassed their per-capita HANPP limits. Meanwhile, HANPP consumption in low- and middle-income countries is set to rise rapidly, posing future challenges. We emphasize the necessity for global cooperation in restructuring supply chains and sharing agricultural technologies. Our findings offer insights into how to diminish stresses on the land system and biosphere integrity from the demand side.

INTRODUCTION

Sustained growth in the global population and economy has increased demand for the planet's limited natural resources and ecosystem services. A way to measure the extent to which humans dominate the landscape and put pressure on ecosystems is through the concept of "human appropriation of net primary production" (HANPP).[1,2] HANPP measures the amount of the Earth's NPP—the energy that plants and other organisms produce through photosynthesis—that is used by humans for economic purposes; it is proposed as a suitable control variable for determining planetary boundaries for functional biosphere integrity and land system change.[3–8] The question of how to prevent further increases in global HANPP levels is receiving increasing attention within the scholarly community. It is striking that while global HANPP levels doubled during the 20th century,[2] the supply of global potential NPP has remained relatively stable in recent decades.[7,9] This indicates that managing HANPP primarily depends on demand management through measures that ensure sustainable production and consumption patterns.[10,11]

For demand-side environmental and resource management, an essential factor that we need to consider is international trade. Because of the teleconnections caused by international trade activities, the HANPP that is required to meet a country's final demand (consumption-based HANPP, here referred to as "cHANPP") comes not only from that country's own territory but also from other countries along the global supply chains. Although the amount of global cHANPP equals the amount of global territorial HANPP, the geographical distribution of cHANPP and territorial HANPP at the country level may differ significantly. Focusing on countries' cHANPP could help us identify potential demand-side solutions for stabilizing HANPP. Despite the extensive literature on territorial HANPP and the HANPP flows embodied in agricultural trade (often referred to as "eHANPP"),[1,2,12–17] the indirect HANPP consumption in non-agricultural product production has not been fully explored.[3,18–22] Additionally, the growing disparities between a country's territorial HANPP and cHANPP have not been thoroughly examined. Furthermore, little is known about the demand-side drivers of historical cHANPP changes.[20]

Another remaining problem, as highlighted by Running,[7] is the question of whether current population and economic growth trends will cause the HANPP levels to exceed planetary boundaries. To the best of our knowledge, most previous research has focused on the historical pattern of HANPP and has not investigated how HANPP will evolve in relation to future socioeconomic circumstances. One way to project future HANPP trends is to design a range of plausible socioeconomic scenarios (e.g., shared socioeconomic pathways [SSPs]).[23,24] Studying future HANPP trends under various socioeconomic pathways constitutes a critical task for contemporary scholarship: projections help us understand how future demographic and economic growth may impact the land system and functional biosphere integrity. Such trends can also assist in determining whether more radical efforts are needed to ensure that HANPP remains within planetary boundaries.

The main methods used in existing demand-side HANPP analyses can be classified, following Erb et al.[18] and Haberl et al.,[25] as conforming to either "top-down" or "bottom-up" approaches. While top-down methods calculate a country's HANPP consumption by adding together the HANPP within the territory and the HANPP embodied in biomass imports and then subtracting HANPP for export production, bottom-up approaches are product-based and proceed by way of process-based life cycle analysis. Both methods, however, are physical trade flow methods; as such, they are unable to fully uncover the HANPP supply chains that extend from production to consumption across countries. This problem can be mitigated by introducing environmentally extended multi-regional input-output (EEMRIO) analysis to the top-down approach. EEMRIO analysis can avoid the system boundary cutoff by tracking resource use across the entire global supply chain.[19,26–28] Of course, as Kastner et al.[29] have emphasized, the EEMRIO model also has certain weaknesses in comparison to physical trade flow methods, including its highly aggregated sectoral classification and homogeneous price assumption for products within the sector. The present paper, however, attempts to cover the indirect HANPP impacts of all demands in a country. Measuring cHANPP with the EEMRIO model includes not only the HANPP embodied in the agriculture sector but also the HANPP embodied in the manufacturing and service sectors. Thus, EEMRIO was chosen as the model best suiting our research question.

To deepen our understanding of countries' cHANPP and to discern how that cHANPP changed in the past and is likely to evolve in the future, we coupled a dynamic global vegetation model and an EEMRIO model to estimate territorial HANPP and cHANPP at the country level. Then, we projected the future cHANPP growth along various plausible demographic and economic growth trajectories aligned with the SSPs and explored the driving factors of historical changes in cHANPP. Specifically, we answered the following questions. (1) How does international trade link countries' HANPP supply to countries' cHANPP? (2) Downscaling the global HANPP planetary boundary based on the per-capita shares, what is the relative position of countries' cHANPP compared to their allocated share of the total HANPP planetary boundary? (3) In which countries will demand growth contribute most to future HANPP growth? (4) What are the primary causes of historical cHANPP changes? Our findings indicate that high-income countries have already transgressed or are close to transgressing their share of the HANPP planetary boundary allocated by population size, while the rapid growth of cHANPP in low- and middle-income countries will put massive pressure on the global land system and biosphere integrity in the coming decades. Considering that 30% of global HANPP is transferred between countries through international trade, this study shows that controlling global HANPP increases relies on international collaborations in supply chain management and technological cooperation. In concluding the paper, we point out the key limitations in our analysis and summarize future research directions. Overall, our analysis provides the first assessment of current and future cHANPP at the country level, thus shedding light on the demand-side solutions for keeping HANPP within planetary boundaries.

RESULTS

Transfers of HANPP across countries

Using MRIO tables derived from the Global Trade Analysis Project (GTAP) database (v.11),[30] this study tracked cHANPP in 141 countries/regions for the years 2004, 2007, 2011, 2014, and 2017. Our results show that substantial amounts of HANPP were embodied in cross-border trade flows of goods and services during the study period. In 2017, the amount of HANPP

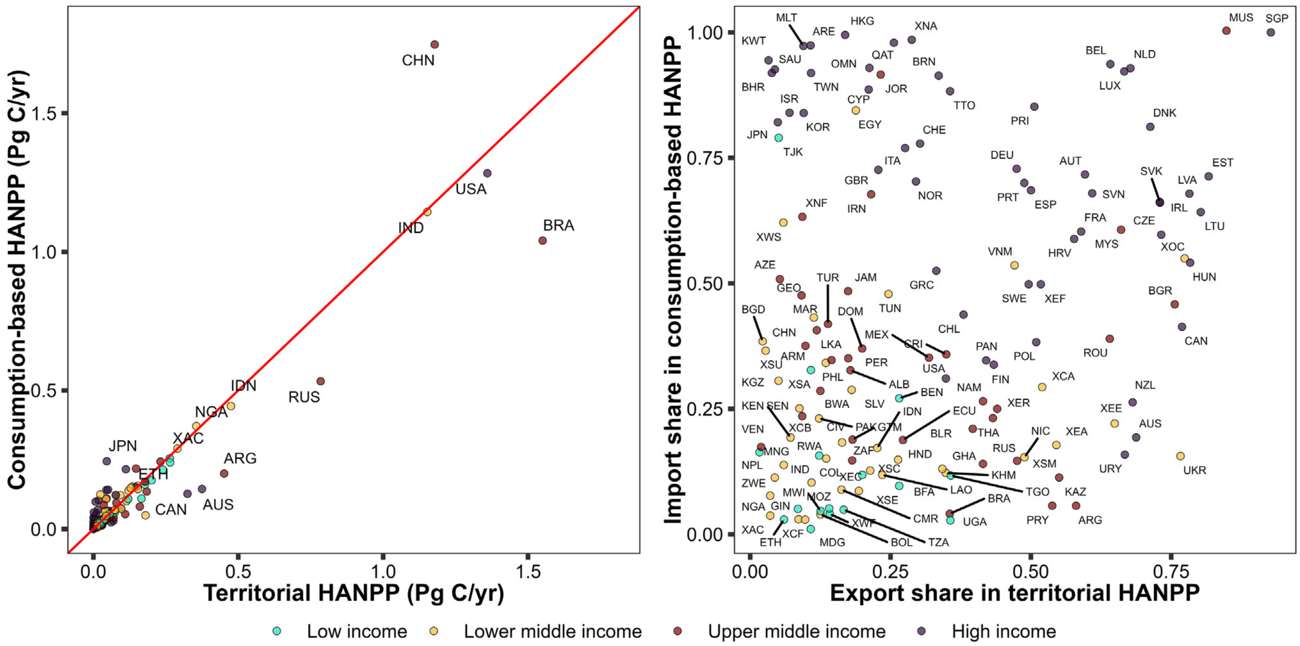

Figure 1. Territorial HANPP, consumption-based HANPP, and the role of trade
Left: territorial HANPP and consumption-based HANPP. The distance of the point from the diagonal line reflects net exports (below the red line) or net imports (above the red line). Right: the import share in consumption-based HANPP and the export share in territorial HANPP. The import share in consumption-based HANPP is the percentage of consumption-based HANPP that is met through imports from other countries. The export share in territorial HANPP is the percentage of territorial HANPP exported to other countries to meet their final demand. The data are for 2017. Countries are classified into four income groups according to the World Development Indicators, World Bank. Countries are denoted by abbreviations (refer to Table S1 for full names).

embodied in global trade (4.40 Pg C/year) accounted for 30% of global HANPP (14.86 Pg C/year).

Figure 1 shows the divergence between cHANPP and HANPP that is caused by international trade and the share of imported/exported HANPP in cHANPP/territorial HANPP in 2017. It shows that five major countries are dominant in terms of both cHANPP and territorial HANPP levels: China, the United States, India, Brazil, and Russia. However, trade has resulted in considerable differences between cHANPP and territorial HANPP in some countries. China and Japan lead as the largest net HANPP importers, with cHANPP levels exceeding their territorial HANPP by 48% and 430%, respectively. Conversely, among the primary net HANPP exporters, Brazil, Russia, and Argentina have cHANPP levels that are 33%, 32%, and 56% lower than their territorial HANPP, respectively. Moreover, Australia and Canada have cHANPP levels that are 61% lower than their territorial HANPP.

The impact of trade on HANPP is strongly related to the country's development level. High-income countries are more likely to engage in HANPP trade, whereas low-income countries are less likely to do so. In 2017, exports accounted for 45% of territorial HANPP in high-income countries, while imports accounted for 71% of their cHANPP. In contrast, only 16% of territorial HANPP is exported and 15% of cHANPP is imported in low-income countries. Comparing Figure 1 with the results for 2004, 2007, 2011, and 2014 (Figure S1), we can find that the basic characteristics of HANPP's global transfer via international trade remained unchanged during the study period. However, HANPP exports from low- and middle-income countries have increased rapidly since 2004.

Figure 2 depicts the cHANPP per gross domestic product (GDP) and cHANPP per capita to make countries with different economic and population sizes comparable. Because agriculture is the mainstay of low-income countries' economies, low-income countries tend to have higher cHANPP per GDP. On average, the cHANPP per GDP of low-income countries is 4.38 kg C/$, while that of high-income countries is 0.12 kg C/$. Regarding cHANPP per capita, high-income countries tend to have higher HANPP per capita (3.36 t C/person), which is 25% higher than the other countries. The countries with the highest cHANPP per capita are Paraguay, Uruguay, and Mongolia, all of which are small, pastoralist countries with extremely low population densities.

The HANPP planetary boundary

The concept of planetary boundaries attempts to delineate a "safe operating space" for human activities. Staying within the planetary boundaries is likely to keep the risk of destabilizing the Earth system low, while going beyond these boundaries would drive the Earth system into a zone of increasing risk.[8,12] A specific planetary boundary for HANPP has been put forward by Running,[7] who estimated that 53% of the total potential NPP is not harvestable, implying that the HANPP boundary should be 47% of the total potential NPP. This specification of the HANPP planetary boundary was also adopted by Wilson.[31] In the definition of the HANPP planetary boundary as proposed by Running,[7] the non-harvestable component encompasses plant growth occurring in root systems, as well as growth in protected areas such as national parks, which are vital for ecosystem services

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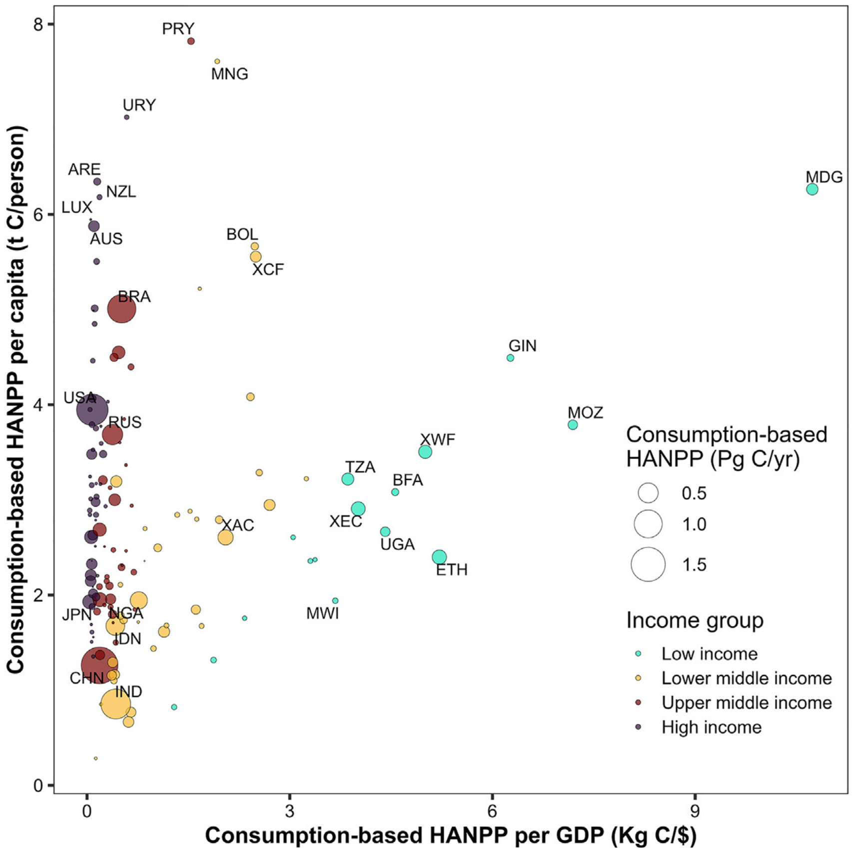

Figure 2. The consumption-based HANPP per GDP and consumption-based HANPP per capita

The data are for 2017. The size of the circle represents the consumption-based HANPP in 2017.

and biodiversity, and in remote wilderness regions inaccessible for harvesting due to lack of transportation.

Figure 3 (left) shows that the global total amount of HANPP has been increasing since the beginning of the 21st century, resulting in a shrinking of the current space between global HANPP and the planetary boundary. The remaining space decreased from 11.42 Pg C/year (18.02% of potential NPP) in 2004 to 11.03 Pg C/year (16.99% of potential NPP) in 2017. This finding implies that our space for action to sustain the land system and biosphere integrity has been further compressed in a short period.

The Sustainable Development Goals (SDGs) aspire to reduce inequality with the pledge to leave no one behind. Based on an egalitarian understanding of justice and fairness, we proportionally allocated the HANPP planetary boundary to each country according to its population size (per-capita share).[6,32] When the global HANPP planetary boundary is assigned to individual countries, cHANPP in nearly half of the high-income countries (22 out of 53) exceeded the country's portion of the boundary (Figure 3, right). In contrast, cHANPP in most low- and middle-income countries (71 out of 88) stayed within the country's portion of the boundary.

Australia, one of the high-income countries with the largest consumption of cHANPP, has exceeded its allocated HANPP planetary boundary by 70%. Brazil and Argentina, two large upper-middle-income countries, had cHANPP that surpassed their located planetary boundaries by 45% and 32%, respectively. However, China and India, representing the largest economies in the upper-middle and lower-middle-income categories, respectively, successfully maintained their cHANPP well within their allocated planetary boundary, offering a buffer of about 70% before reaching their thresholds.

We also computed low-estimate and high-estimate HANPP datasets based on different parameter settings for robustness (Note S1). Figure S2 shows that even with the low estimate of HANPP, there are still 16 countries that have already exceeded the planetary boundary. Under the high estimate of HANPP, 71 countries have exceeded the planetary boundary.

cHANPP projection under future socioeconomic pathways

Here, we sought to answer the following question: if the improvements of production technical trends (changes in cHANPP intensity of products) continue at the current pace, how will global HANPP change under various possible future demographic and economic growth pathways?

The SSPs are commonly used in the literature to project the impact of future socioeconomic evolution on environmental indicators.[23] Thus, we considered five demographic and economic growth scenarios that are in line with the five SSPs (Figure 4), including SSP1 (taking the green road), SSP2 (middle of the road), SSP3 (a rocky road), SSP4 (a road divided), and SSP5 (taking the highway). For each pathway, the HANPP growth is projected by the current trend of changes in sectoral cHANPP intensity (the HANPP embodied in $1 products) and the sectoral demand growth projected by population and GDP growth trajectories implied in the narrative of each SSP (see experimental procedures for more details).

At the global level, SSP5 is associated with the highest HANPP growth, while SSP3 and SSP4 witnessed the lowest HANPP growth. In SSP1 and SSP5, the HANPP will exceed the planetary boundary in 2040 and 2035. This may place humans in a "zone of increasing risk."[8] Under SSP2, HANPP levels will also be close to transgressing the planetary boundary. In SSP3 and SSP4, even though HANPP will remain within planetary boundaries by 2050, remarkable growth will significantly narrow the maneuvering space, implying that even in the most optimistic scenarios, the current rate of sectoral cHANPP decline is insufficient to offset the rapid growth of demand. Moreover, according to the definition of SSPs, the narratives portrayed in SSP3 and SSP4 imply low economic growth rates, slow social development in low-income countries, and growing international inequality.[23]

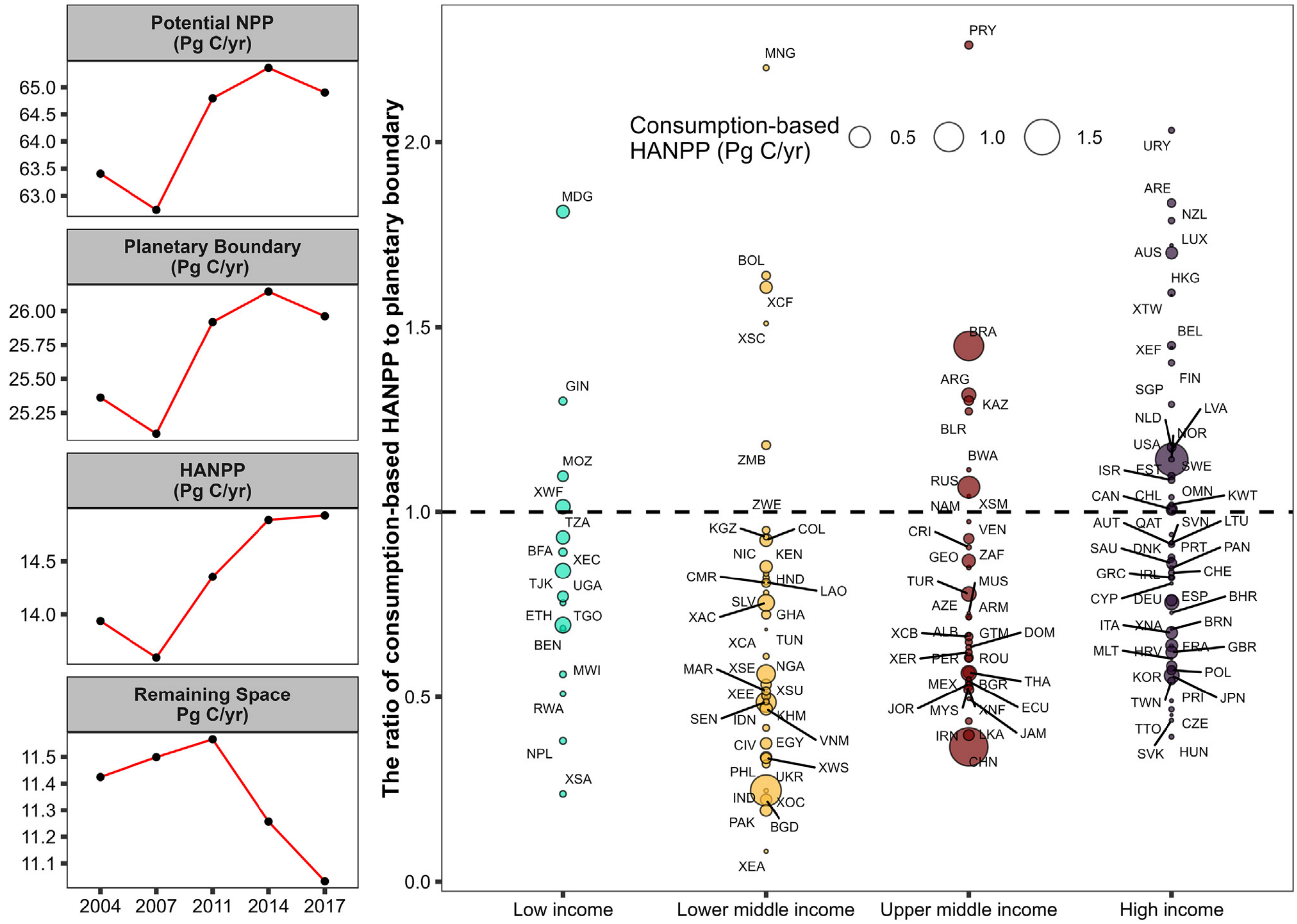

Figure 3. Global and country-level HANPP planetary boundary analysis

Left: the potential NPP, planetary boundary, HANPP, and remaining space for 5 years. The planetary boundary is 47% of the potential NPP (suggested by Running[7]). Right: the ratio of consumption-based HANPP to the planetary boundary for each country in 2017. The calculation is based on the principle of equality, with population numbers used to allocate the total global planetary boundary to countries.[6] The size of the circle represents the consumption-based HANPP in 2017.

With the low estimate of HANPP (Figure S3), the global HANPP will also exceed the planetary boundary in SSP5 in 2050. It is worth emphasizing that this paper has adopted the most lenient setting among the currently proposed HANPP planetary boundaries.

The contribution of demographic and income factors to HANPP growth varies across SSP scenarios (Figure S4). In SSP1 and SSP5, the global population shows a declining trend at the end of the century. HANPP growth is mainly caused by rapid income growth. In contrast, in SSP3 and SSP4, the income growth is relatively slow, and the HANPP growth is primarily caused by population growth. In SSP2, where the population and economic trends follow the historical pattern, both income and population growth will contribute significantly to the HANPP growth.

Low-income and lower-middle-income countries will witness fast growth in cHANPP. Even though low-income and low-middle-income countries only accounted for 40% of global HANPP consumption in 2017, their faster economic and population growth is bound to increase their share in global HANPP. By 2050, these countries will account for 48%–62% of global HANPP under five SSPs.

Driving forces of historical changes in cHANPP

Figure 5 (left) shows the changes in territorial HANPP and the HANPP consumption for each country from 2004 to 2017. Even though the global HANPP equals the global cHANPP, the change in countries' cHANPP was much more pronounced than in countries' territorial HANPP. This reflected that the geographic distribution of global cHANPP had been undergoing tremendous changes over time. The simultaneous rise of territorial HANPP and cHANPP occurred mainly in middle-income countries such as Brazil, India, and Indonesia. This implies that these countries have increased domestic and abroad ecosystem pressure along upstream supply chains. Countries in the third quadrant, such as the United States and Russia, experienced a simultaneous decline in both territorial HANPP and cHANPP, implying a simultaneous reduction in the pressure on domestic and foreign ecosystems. China and Japan's territorial HANPP remain stable, but China's cHANPP has

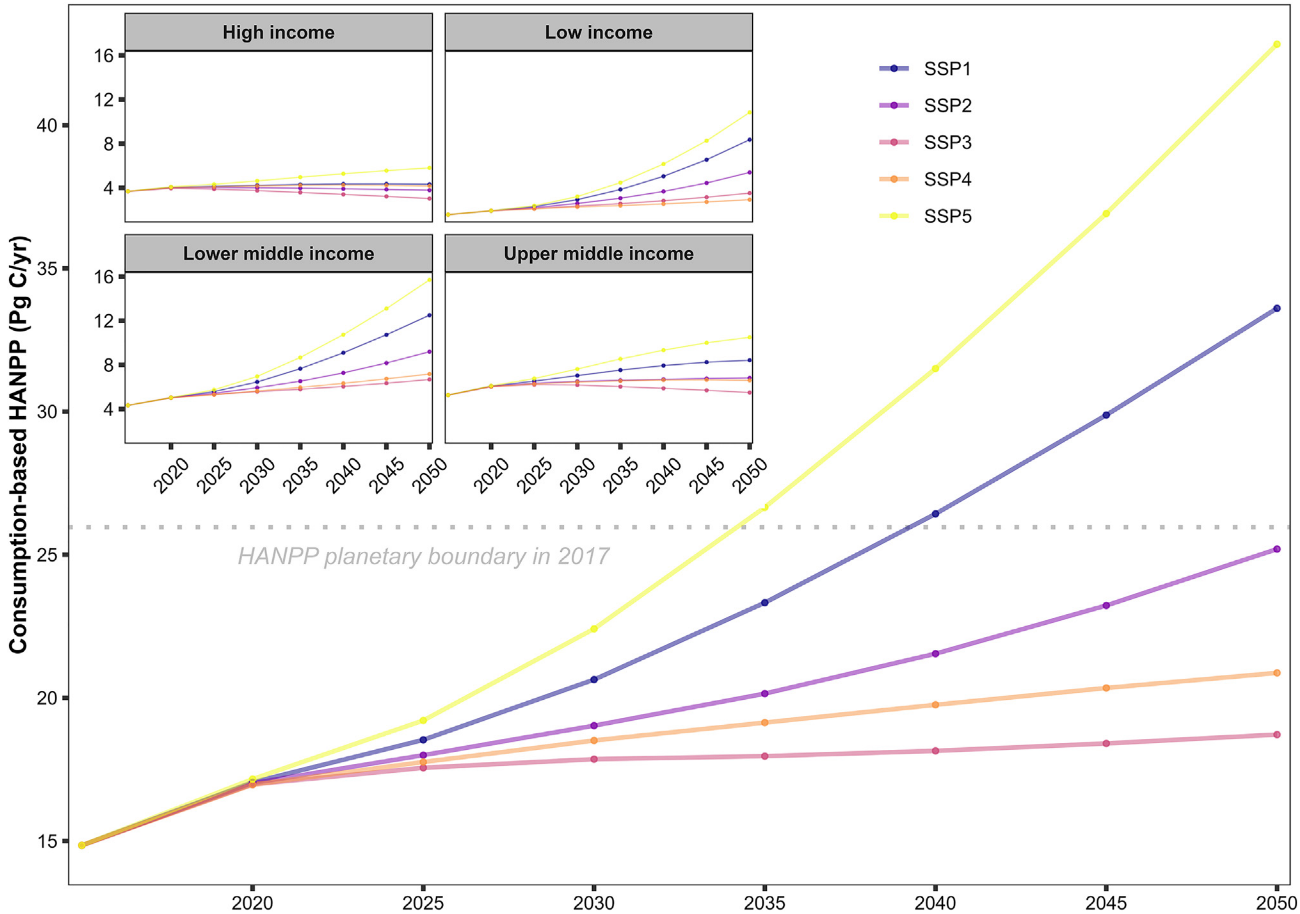

Figure 4. Consumption-based HANPP projection under future socioeconomic pathways
The dotted gray line represents the global potential NPP in 2017, while the solid gray line represents the global HANPP planetary boundary in 2017. The population and GDP trajectories to generate cHANPP projections are obtained from the base elements section of the IIASA SSP Database (v.2.0).[24,33,34]

increased significantly, while Japan's cHANPP has decreased significantly.

We used structural decomposition analysis (SDA) to investigate the detailed driving factors of changes in cHANPP to explain why countries experienced different cHANPP changes in the past. Figure 5 (right) shows the results for the four countries with largest cHANPP changes (Brazil, China, the United States, and Japan).

The rising demand for domestic and foreign products in a country typically promotes the growth of the country's cHANPP, which is especially true for low- and middle-income countries. Stimulating domestic consumption is often a top policy priority for low- and middle-income countries. Therefore, these countries will continue to catch up, and the HANPP conservation efforts in these countries need to focus on reducing the cHANPP intensity of economic activities via technological progress and structural change. By contrast, the current cHANPP per capita in high-income countries is higher than the global planetary boundary per capita. Thus, high-income countries need to reduce their cHANPP by further decoupling economic growth and cHANPP. Taking Japan and the United States as examples, from 2004 to 2017, we observed a relatively moderate increase in their consumption levels and a noticeable decline in their cHANPP. The main reason for the cHANPP reduction in Japan was the declining HANPP intensity in its import source countries. The main reasons for cHANPP reduction in the United States were the declining HANPP intensity in the country as well as in its import source countries.

Changes in a country's domestic HANPP intensity and production structure also lead to changes in cHANPP in other countries through international trade. For example, in 2017, more than 82% of cHANPP in Japan was met by its imports. Thus, we can see that foreign HANPP intensity was the biggest driving force for the cHANPP decline in Japan. In contrast, only 4% of cHANPP in Brazil was met by imports in 2017. As a result, the cHANPP of Brazil was mainly determined by domestic factors, and the reduction of domestic HANPP intensity can effectively reduce its cHANPP. In addition, Brazil was the largest exporter of HANPP during the study period. Reducing domestic HANPP intensity in Brazil will be conducive to cHANPP reduction in its downstream trading partners. Table S3 reports cHANPP intensity by sector and country.

In emerging middle-income countries that have experienced rapid cHANPP growth and are aspiring to raise consumption

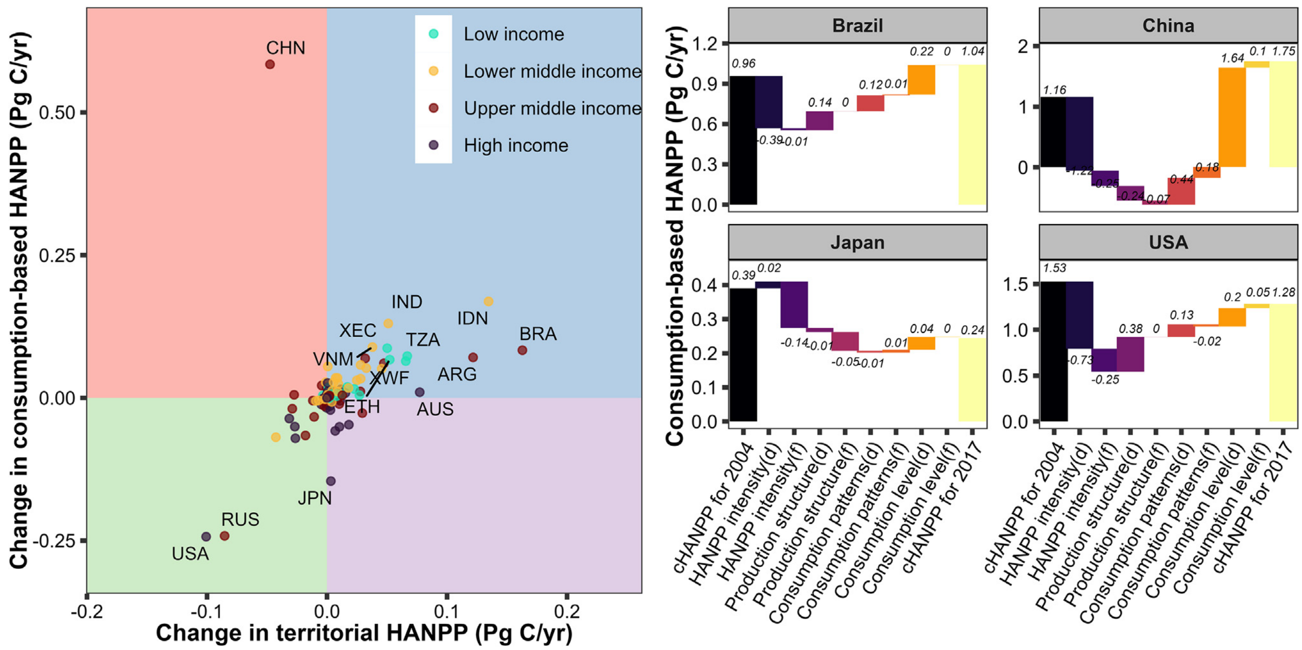

Figure 5. The changes in consumption-based HANPP for 2004–2017 and contributions of different factors

Left: the changes in territorial HANPP/consumption-based HANPP at the country level. Right: the contribution of eight factors to the changes in consumption-based HANPP from 2004 to 2017. The number shows the amount of change in consumption-based HANPP. Four representative countries are selected. Table S2 includes the decomposition results for all countries.

levels, our results indicate the efforts to improve consumption patterns, adjust production structure, and adopt technology toward less HANPP-intensive lifestyles and production processes will contribute to curtailing the pace of cHANPP growth. For example, in China, changes in domestic and foreign HANPP intensities as well as improvements in domestic consumption patterns and production structure all contributed to offsetting a considerable proportion of cHANPP growth driven by rising consumption levels. However, in Brazil, changes in domestic production structure and consumption patterns had the opposite effect. This is because the changes in Brazil's production patterns during the study period increased the use of intermediate inputs such as vegetables, fruit, nuts, oil seeds, sugar cane and sugar beet, and forest products, and thus HANPP-intensive products accounted for a larger proportion of total domestic output in 2017 compared to 2004.

DISCUSSION

While the findings from previous studies implied that keeping HANPP within planetary boundaries mainly relies on demand management,[2,9] most existing research has focused on the territorial HANPP or HANPP embodied in the agricultural trade flows (eHANPP); less is known about the cHANPP (the HANPP required to meet a country's final demand) at the country level. Furthermore, inadequate attention has been paid to the interaction between future demographics and economic dynamics and cHANPP growth and the drivers of historical changes in cHANPP—this is necessary information for identifying demand-side solutions. Our research fills these critical research gaps. First, we provided a country-level cHANPP accounting and revealed each country's position compared to its share of the global HANPP planetary boundary, based on per-capita shares. Also, we projected future HANPP growth under five socioeconomic pathways and investigated the drivers of historical cHANPP changes.

Our findings underscore the vital role of international cooperation in stabilizing global HANPP to maintain the anthropogenic perturbations on the land system and functional biosphere integrity within the safe operating space. The results show a large divergence between countries' territorial HANPP and cHANPP. In 2017, international trade transferred 30% of global HANPP between countries. Although the contribution of demographic and income factors differs across SSP scenarios, the global HANPP will transgress the HANPP planetary boundary or significantly compress the remaining maneuvering space, mainly driven by the cHANPP growth of low- and lower-middle-income countries. Based on the findings, we summarized three insights on how international cooperation can contribute to slow HANPP growth.

First, shifting the sourcing of goods to countries with a lower HANPP intensity could decrease the overall HANPP necessary to satisfy demand. The production of the same product in different countries has different embodied HANPP (*EH*). Such variation generates comparative advantages in terms of HANPP across countries. However, current international trade activities are primarily driven by comparative economic advantages rather than comparative environmental advantages, and the marginal economic productivity of land often does not reflect the environmental costs associated with land use. International trade may not optimize land use, owing to trade-offs with other social and natural inputs.[20] Therefore, this solution is subject to appropriate governance and pricing mechanisms in natural resource use. There are already many experiences to draw on, especially in relation to greenhouse emissions. Similar policies could be designed for other environmental variables. As summarized by Salzman et al.,[35] programs have considerably increased that include payments for ecosystem services in land management practices in recent decades. However, there is still a long way to go to scale up these programs and improve the accounting methods for ecosystem services' value in policy design.[36] Moreover, we must recognize that shifting international trade patterns can only partially alleviate the challenges due to supply capacity constraints in countries with low HANPP intensity.

Second, joint technical cooperation between low- and middle-income countries and developed countries will be essential. Our results show that the HANPP intensity in low- and middle-income countries is much higher than in high-income countries. The rapid growth of cHANPP in low- and middle-income countries has exerted, and may continue to exert, significant pressure on the global land system and biosphere integrity, making it particularly challenging to keep global HANPP within the planetary boundary unless low- and middle-income countries take effective action to force their HANPP growth to deviate from its current trajectory. Meanwhile, as a considerable part of cHANPP in high-income countries is satisfied by imports from low- and middle-income countries, the HANPP intensity of production in low- and middle-income countries has an important impact on cHANPP in high-income countries. Considering there is a huge gap in land productivity between the Global North and the Global South,[37] global sharing of agricultural know-how and technology will not only help reduce cHANPP by closing the yield gaps in low- and middle-income countries but will also promote the reduction of cHANPP in developed countries. In practice, even though the partnership for sustainable development is emphasized by SDG 17 (partnerships for the goals), most international technical assistance and investment are focused on renewable energy and energy-efficiency projects.[38] The current discourse on policy often does not prominently feature discussions about sustainable farming and land management technologies. Thus, international communities should go beyond the climate goal and pay more attention to the other dimensions of sustainability.

Third, the different roles of countries in governing global HANPP warrants examination. Considering that the high-income countries have already exceeded or are close to exceeding their allocated planetary boundary for cHANPP, while most low- and middle-income countries are still well within their allocated planetary boundary, we believe that the high-income countries should reinforce the decoupling between their cHANPP and economic growth and thus provide ecological space for low- and middle-income countries to grow. At the same time, low- and middle-income countries should also try to slow down the growth of their cHANPP as much as possible. However, there is no common consensus on the principle for allocating responsibility between countries in ecosystem reservation. While we adopted a per-capita share approach to allocating the global HANPP planetary boundary among individual countries, it is important to recognize the existence of other viable alternatives. Similar to the varied strategies used in allocating carbon emissions budgets, these alternative methods might allocate the HANPP budget according to varied criteria encompassing responsibility, capability, equity, and efficiency.[39–42]

We acknowledge certain limitations in our research, particularly with respect to two aspects.

First, the planetary boundary of HANPP is currently subject to ongoing debate. While some researchers believe that HANPP is a reliable indicator of the planetary boundary, the precise threshold for this boundary remains inconclusive.[6–8,31,43] Our analysis is based on the highest planetary boundary proposed by Running[7] and adopted by Wilson,[31] which is 47% of the total potential NPP. In contrast, O'Neill et al.[6] suggested that the HANPP planetary boundary is 33% of the global potential NPP. Richardson et al.[8] set it as 10% of pre-industrial Holocene mean NPP. Therefore, our research may even underestimate the severity of the problem caused by HANPP growth. Nonetheless, our analysis allowed us to draw meaningful conclusions regarding future HANPP growth and the role of various factors in its changes.

Second, the EEMRIO model used for measuring cHANPP also has limitations. Although the EEMRIO model offers several advantages over other physical trade flow methods in tracing environmental impact along the entire supply chain and calculating the HANPP footprint for non-agricultural sectors,[28] the highly aggregated sector classification employed by the EEMRIO model introduces new uncertainties into the accounting process.[44] For example, the agriculture sector in GTAP is aggregated into eight sectors, which cannot distinguish the impact of different products aggregated into one sector. Concurrently, the trade and macroeconomic statistics underpinning the GTAP database may encompass certain statistical inaccuracies. The GTAP MRIO tables used in our study are already the best available data. Further improving the precision of cHANPP accounting (also for other environmental and material footprints accounting) requires an MRIO database with greater sectoral and regional detail.[45] However, it faces significant challenges due to the data availability caused by the differences in statistical capacity and standards between countries. Moreover, since the EEMRIO model cannot project future changes in economic structure and production technology, it can only determine how global HANPP will change under various scenarios if current technical trends continue and whether accelerated technological improvement is necessary to keep HANPP within planetary boundaries.

Some important issues need further research. First, unlike greenhouse emissions, which already have a clear scientific consensus on the planetary boundary (the 1.5/2°C goal), the specific boundary for HANPP is still under debate. Second, although we believe that directing economic activity to reduce the intensity of HANPP is necessary, it remains unknown what the social costs of HANPP are (the economic and social costs as a result of the reduction in the amount of NPP available to support the biosphere), and, further, what the cost-effective policy tools are for reducing the HANPP remain unknown.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Xiaoping Liu (liuxp3@mail.sysu.edu.cn).

Materials availability

This study did not generate new unique materials.

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Data and code availability

All necessary data and code required to reproduce the results of this study are publicly available and deposited at Zenodo under the DOI 10.5281/zenodo.10724823.https://XJChenUMD/HANPP_MRIO_2023_OneEarth Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

Territorial HANPP

Widely accepted definitions of HANPP[3,13] describe the variable as consisting of two parts: human-harvested NPP ($HANPP_{harv}$) and changes in NPP induced by land use/cover change ($HANPP_{lucc}$), where $HANPP_{harv}$ is calculated as the difference between potential NPP (NPP_{pot}) and actual NPP (NPP_{act}). It can be described as the following formulas:

$$HANPP = HANPP_{harv} + HANPP_{lucc} \quad \text{(Equation 1)}$$

$$HANPP_{lucc} = NPP_{pot} - NPP_{act} \quad \text{(Equation 2)}$$

Three necessary parameters thus need to be assessed: $HANPP_{harv}$, NPP_{pot}, and NPP_{act}.

NPP_{pot} refers to the productivity of natural vegetation without human interference under given climatic conditions.[3] Previous studies of HANPP indicate that the Lund-Potsdam-Jena Dynamic Global Vegetation Model (LPJ-DGVM)[46] is suitable for calculating NPP_{pot}.[2,47,48] The driving data of LPJ-DGVM include meteorological data (temperature, precipitation, cloud cover, and wet day), soil texture data, and CO_2 data. The data sources used in the LPJ-DGVM are shown in the data section. To verify the reliability of the utilized LPJ-DGVM, our estimated results were compared with the potential NPP in 2000 calculated by Haberl et al.[1] using the LPJ-DGVM. We selected the areas where plant functional types did not change from 2000 to 2014 for sampling. Significant correlations were found between the potential NPP obtained in our study and the previous study ($R = 0.868$; $n = 5,475$; $p < 0.001$) (Figure S5). Additionally, the calculation of the NPP_{pot} for different land cover types was based on the History Database of the Global Environment (HYDE v.3.2), which is in good harmony with the FAO (Food and Agriculture Organization of the United Nations) statistics.[49]

$HANPP_{harv}$ refers to the harvested biomass within 1 year, including biomass destroyed during harvest.[1,3] Biomass harvest from cropland mainly consists of two parts: (1) primary product harvest and (2) harvest of residues. The original production data were obtained from FAO. They were transformed into dry weight basis values according to the moisture contents. Further, used and unused aboveground harvest residues were extrapolated from production data using specific harvest factors. Grazed biomass refers to the amount of biomass consumed by ruminants either directly through grazing or indirectly through the harvest of hay or silage.[2] Livestock production data were also obtained from FAOSTAT. The value of the feed conversion rate was used to calculate the biomass demand. For forest harvest, we considered biomass for wood material and energy. The FAO forestry production database provides information on industrial roundwood production and fuelwood. We assumed an average carbon content of dry matter biomass of 50% to convert harvested biomass into $HANPP_{harv}$ for these three land covers.

$HANPP_{lucc}$ represents the NPP variation resulting from land use/cover change, calculated by subtracting NPP_{act} (NPP of the currently prevailing vegetation in ecosystems[3,50]) from NPP_{pot}.[2,3] $HANPP_{lucc}$ on cropland was calculated as the difference between NPP_{pot} and NPP_{act} on the cropped area. FAO provided the cropland area temporarily fallow in each country, so we divided the NPP_{pot} of cropland (calculated based on HYDE data) into two parts according to the fallow and cropped area proportion. NPP_{act} on the cropland was calculated as the sum of $HANPP_{harv}$ and pre-harvest losses due to herbivory and weeds. A loss expansion factor[2] for calculating pre-harvest losses was allocated according to the amount of fertilizer use provided by FAO. As for $HANPP_{lucc}$ on grassland, we calculated it in two parts[1,3]: (1) NPP loss caused by the conversion from potential forests to artificial grasslands and (2) NPP loss caused by human-induced soil degradation in grazing lands. Information on the degree of soil degradation came from the Global Assessment of Human-Induced Soil Degradation (GLASOD). Furthermore, following Krausmann et al.,[2] we assumed that in forests and other natural areas, NPP_{act} equals NPP_{pot}; that is, $HANPP_{lucc}$ in these areas is defined as zero.

Note S1 explains the detailed methodology for calculating NPP_{pot}, $HANPP_{harv}$, and $HANPP_{lucc}$ and describes the uncertainty analysis of HANPP estimation.

cHANPP

Consumption-based accounting based on EEMRIO models has been frequently applied to account for embodied environmental impacts in global trade and capture the total impacts of final consumption along the entire supply chain.[51–54] In the EEMRIO framework, HANPP is embodied in product flows with the cross-border flow of products. The EH of the final demand can be characterized by Equation 3,[55]

$$\begin{bmatrix} EH_{11} & EH_{12} & \cdots & EH_{1n} \\ EH_{21} & EH_{22} & \cdots & EH_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ EH_{n1} & EH_{n2} & \cdots & EH_{nn} \end{bmatrix} = \begin{bmatrix} f_1 & 0 & \cdots & 0 \\ 0 & f_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & f_n \end{bmatrix} \begin{bmatrix} B_{11} & B_{12} & \cdots & B_{1n} \\ B_{21} & B_{22} & \cdots & B_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ B_{n1} & B_{n2} & \cdots & B_{nn} \end{bmatrix} \begin{bmatrix} Y_{11} & Y_{12} & \cdots & Y_{1n} \\ Y_{21} & Y_{22} & \cdots & Y_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ Y_{n1} & Y_{n2} & \cdots & Y_{nn} \end{bmatrix} \quad \text{(Equation 3)}$$

where the diagonal f matrix presents HANPP intensity by sector and country and the B matrix is the Leontief inverse matrix, which captures both direct and indirect inputs to satisfy one unit of final demand. The Y matrix is the final product export from the various sectors of the country s to the country r. More details about the derivation of Equation 3 can be found in Note S2.

The row vectors of the EH matrix indicate the final destination of the territorial HANPP in a region. The sum of the row vectors is equal to the territorial HANPP. The columns vector of the EH matrix represents the source of cHANPP in a region. The sum of the column vectors is the total amount of cHANPP, which can be written as

$$cHANPP_r = fBY_{*r} \quad \text{(Equation 4)}$$

HANPP projection

According to Equation 4, the future cHANPP is impacted by the changes in sectoral cHANPP intensity (fB) and the final demand. We estimate the average annual change rate of sectoral cHANPP intensities using a log-log model and data from 2004 to 2017. Maintaining the same rate of change in sectoral cHANPP intensities in the future as that from 2004 to 2017 allows us to examine whether the current rate of technical improvement is sufficient to counteract the effects of demand growth caused by demographic and economic growth.

To project future demand growth, we used the demographic and economic growth trajectory that aligns with the five SSPs, which are designed to cover a range of possible future development pathways.[23,24] The five SSPs are SSP1 (taking the green road), SSP2 (middle of the road), SSP3 (a rocky road), SSP4 (a road divided), and SSP5 (taking the highway). They are also employed by the IPCC AR6[56] to model the impacts of future socioeconomic development on climate change and are widely used in research for projecting further environmental and resource stress induced by demand growth.[57–59] Each SSP describes a distinct set of demographic and economic growth trends.[23] Dellink et al.[33] and KC et al.[34] have developed country-level GDP and population growth projections for each SSP narrative.

As explained in Dellink et al.[33] and KC et al.,[34] in SSP1, all countries will experience relatively rapid income growth. Additionally, it assumes that rich OECD countries will have a medium fertility rate and that all other countries will have a low fertility rate. In SSP2, current trends more or less continue. Some emerging economies catch up relatively quickly, whereas economic growth is much slower in the least-developed countries. All countries will have a medium fertility rate in terms of population dynamics. In SSP3, economic growth is assumed to be much slower in all countries. Meanwhile, population growth is assumed to be high in developing countries and low in industrialized countries. SSP4 refers to a world of high inequalities, where high-income countries will witness fast economic growth. In contrast, low-income countries will have slow economic growth. As global growth is less rapid than in SSP1, the long-run growth prospects for high-income countries diminish over time. Additionally, countries with high fertility will continue to have high fertility, whereas countries with low fertility will continue to have low fertility. Finally, SSP5 depicts a scenario in which countries focus entirely on economic development. As a result, all countries will have rapid economic growth. Meanwhile, relatively high fertility is assumed for rich OECD countries, and low fertility is assumed for all other countries.

Based on the population and GDP projection in SSPs, we can project the final demand for each country. When projecting demand growth caused by GDP and population growth, we use the income elasticity dataset provided by GTAP to forecast the inter-sectoral distribution of demand growth.

It should be noted that this paper only attempts to answer the question: if the production technical trends continue at the current pace, how will the global HANPP change under various possible future demographic and economic growth pathways? Thus, we do not consider other potential factors that might impact the HANPP, such as the deployment of bioenergy with carbon capture and storage technology, the dietary change caused by non-income factors (e.g., environmental awareness, policies, and regulations), and changes in global trade patterns. Also, when discussing the relationship between HANPP growth and HANPP planetary boundary, we follow the perspective outlined by Running,[9] which posits that potential NPP is expected to stay relatively stable. This stance is taken despite some studies indicating that global potential NPP may increase with climate warming.[60,61]

SDA

The SDA approach is used to identify the underlying causes of historical changes in cHANPP. The change in the cHANPP in the country r between two points in time (indicated by the subscripts 0 and 1) can be expressed as

$$\Delta cHANPP_r = cHANPP_r^1 - cHANPP_r^0 = f^1B^1Y_{*r}^1 - f^0B^0Y_{*r}^0 \quad \text{(Equation 5)}$$

Equation 5 shows that the cHANPP will be affected by the three basic factors (f, B, and Y). The final demand Y can be further disassembled into two factors: the consumption patterns ($Ystr$) and the consumption level ($Ylev$). Following the methods of previous studies,[62,63] we separated the domestic and foreign factors and used the average of two polar decompositions to disentangle the changes in cHANPP into contributions of eight components, including domestic HANPP intensity, foreign HANPP intensity, domestic production structure, foreign production structure, consumption patterns for domestic products, consumption patterns for foreign products, consumption level for domestic products, and consumption level for foreign products.

$$\Delta f^+ = 0.5 \times \left(f^{1+} - f^{0+}\right)\left(B^1Y_{*r}^1 + B^0Y_{*r}^0\right) \quad \text{(Equation 6)}$$

$$\Delta f^- = 0.5 \times \left(f^{1-} - f^{0-}\right)\left(B^1Y_{*r}^1 + B^0Y_{*r}^0\right) \quad \text{(Equation 7)}$$

$$\Delta B^+ = 0.5 \times \left[f^1\left(B^{1+} - B^{0+}\right)Y_{*r}^0 + f^0\left(B^{1+} - B^{0+}\right)Y_{*r}^1\right] \quad \text{(Equation 8)}$$

$$\Delta B^- = 0.5 \times \left[f^1\left(B^{1-} - B^{0-}\right)Y_{*r}^0 + f^0\left(B^{1-} - B^{0-}\right)Y_{*r}^1\right] \quad \text{(Equation 9)}$$

$$\Delta Ystr^+ = 0.5 \times \left[f^1B^1\left(Ystr_{*r}^{1+} - Ystr_{*r}^{0+}\right)Ylev_{*r}^{0+} + f^0B^0\left(Ystr_{*r}^{1+} - Ystr_{*r}^{0+}\right)Ylev_{*r}^{1+}\right] \quad \text{(Equation 10)}$$

$$\Delta Ystr^- = 0.5 \times \left[f^1B^1\left(Ystr_{*r}^{1-} - Ystr_{*r}^{0-}\right)Ylev_{*r}^{0-} + f^0B^0\left(Ystr_{*r}^{1-} - Ystr_{*r}^{0-}\right)Ylev_{*r}^{1-}\right] \quad \text{(Equation 11)}$$

$$\Delta Ylev^+ = 0.5 \times \left(f^1B^1Ystr_{*r}^{1+} + f^0B^0Ystr_{*r}^{0+}\right)\left(Ylev_{*r}^{1+} - Ylev_{*r}^{0+}\right) \quad \text{(Equation 12)}$$

$$\Delta Ylev^- = 0.5 \times \left(f^1B^1Ystr_{*r}^{1-} + f^0B^0Ystr_{*r}^{0-}\right)\left(Ylev_{*r}^{1-} - Ylev_{*r}^{0-}\right) \quad \text{(Equation 13)}$$

where "+" indicates domestic factors and "−" indicates foreign factors.

It should be noted that there are other types of structural decomposition besides the average of two polar decompositions. Theoretically, if there are n elements in matrix multiplication, there will be n! different types of decomposition. Some studies argue that an alternative is the average of all possible first-order decompositions.[64,65] Thus, we also calculated the SDA results based on the average of all possible first-order decompositions to test the robustness (Note S3; Table S4). In our case, the average of all possible first-order decompositions was similar to the average of two polar decompositions.

Data

The driving data of LPJ-DGVM includes meteorological data (temperature, precipitation, cloud cover, and wet day), soil texture data, and CO_2 data. Table S5 provides more details on all the data that drive the LPJ-DGVM. The data used to calculate $HANPP_{harv}$ are mainly from the FAO (http://www.fao.org/faostat/). Sub-categories and the biomass item codes in FAOSTAT are shown in Table S6. HYDE v.3.2 can be downloaded from https://dataportaal.pbl.nl/downloads/HYDE/. GLASOD can be downloaded from https://files.isric.org/public/other/GLASOD.zip.

Our MRIO tables and population data were derived from the latest released GTAP data (v.11),[30] which include 141 regions and 65 sectors (Table S1) in 2004, 2007, 2011, 2014, and 2017. There are several potential choices for MRIO tables, including WIOD, EXIOBASE, OECD ICIO, and Eora. However, compared to WIOD and EXIOBASE, GTAP MRIO tables have broader country coverage. Compared to Eora, which is compiled based on a highly automated data reconciliation approach, the original data source of GTAP MRIO tables is based on bilateral trade statistics and thus possesses higher quality. Additionally, GTAP MRIO tables include a more detailed sector classification (65 sectors) compared to Eora's 26 sectors. These attributes of GTAP can reduce errors from spatial aggregation and sectoral aggregation.[44,66] Furthermore, the double-deflator method[67] and the producer price index (PPI) ($ at 2010 constant prices) are used to make the results of different years comparable. The PPI data were obtained from the National Account Main Aggregates Database, which provides pricing information for seven board categories that can be mapped to the 65 sectors in GTAP (Table S7).[68]

We developed a HANPP satellite account that matches the GTAP MRIO tables. First, the HANPP data of grassland were divided into GTAP's animal husbandry (S09), and the HANPP data of various forest land were divided into GTAP forestry (S13). Second, GTAP contains eight agricultural sectors. We split the HANPP of cropland based on the farming areas of the eight agricultural sectors by using the production area data provided by the FAO, the concordance table between GTAP sectors and CPC classification (central product classification), and the concordance table between agricultural products and CPC classification (Table S8).

Demographic and GDP growth trajectories for the five SSPs were obtained from the IIASA SSP Database (v.2.0).[24] In fact, in the IIASA SSP Database, each SSP scenario contains a collection of different economic and demographic projections produced by various integrated assessment models. All these modeled projections begin with the same basic elements of the SSPs ("reference scenarios" in Dellink et al.[33]) but use different technology assumptions and climate scenarios. This paper does not consider the effects of future climate change and additional technological change. We solely focused on the effects of demographic and GDP growth evolution. Thus, we adopted the demographic and GDP growth trajectory depicted in the basic elements section in the IIASA SSP Database (https://tntcat.iiasa.ac.at/SspDb) (Figure S4).[33,34] Furthermore, the income elasticity for simulating sectoral demand growth came from the GTAP database.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2024.02.010.

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AUTHOR CONTRIBUTIONS

Conceptualization, S.W., X.L., K.F., C.F., and L.S.; methodology, X.C., K.L., J.W., C.W., and Y.Y.; investigation, X.C., R.X., and K.L.; resources, S.W., K.F., and Z.L.; writing – original draft, S.W., X.C., and R.X.; writing – review & editing, S.W., X.C., R.X., and J.W.; visualization, X.C. and K.L.; supervision, S.W., X.L., K.F., K.H., and C.F.; project administration, S.W. and C.F.; funding acquisition, S.W.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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