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Integrated food-system and conservation measures enhance functional connectivity of global protected areas while advancing food security and health

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Abstract

Functional connectivity of protected areas (PAs) is critical to global biodiversity but is increasingly threatened by agriculture expansion, which isolates species and heightens extinction risk. Using an integrated framework, we evaluate how functional connectivity, measured by mammal movement probability (MMP) and protected area isolation (PAI), responds to food-system transformation and ecosystem stewardship (EcoS). Without intervention, global functional connectivity deteriorates from 2020 to 2070 (-2.0% in MMP and + 3.7% in PAI), alongside substantial regional variability (PAI ranging from 8.5% decline in Europe to 16.9% increase in Africa). Food-system transformation and EcoS each mitigate this deterioration, but neither alone can simultaneously address biodiversity conservation, food security, and health. Integrated interventions deliver the largest ecological benefits while advancing food security and health, supporting biodiversity conservation and sustainable food-system.

Introduction

Protected areas (PAs) are cornerstones of global biodiversity conservation, yet their effectiveness is constrained when they are isolated[1]. As many PAs are too small to sustain viable populations over the long term[2], their conservation outcomes hinge on functional connectivity between PAs, namely, the capacity of landscapes to support species movement and adaptation under rapidly changing environments[3,4]. Without such functional connectivity, isolated populations are more vulnerable to local extinction because of demographic instability, reduced recolonization potential, and genetic erosion[5]. Given the importance of functional connectivity for biodiversity conservation, it has been increasingly emphasized in global policy frameworks. For example, the Kunming–Montreal Global Biodiversity Framework (KM-GBF) explicitly recognizes the importance of ecosystem connectivity, setting targets that by 2030 at least 30% of degraded terrestrial, inland water, coastal, and marine ecosystems should be under effective restoration, and by 2050 the integrity, connectivity, and resilience of all ecosystems should be maintained, enhanced, or restored[6]. These targets emphasize the key strategic importance of managing PAs as interconnected ecological networks for sustaining migratory species[1].

The functional connectivity of PAs is under threat by agricultural expansion and intensification over the last two centuries[7] and which now accounts for ~ 40% of the Earth's ice-free surface[8]. Agricultural activities do not only encroached upon protected areas[9], but they also degraded the connectivity between them[10]. The next few decades will likely see continually increased threats from agriculture to global PAs and their functional connectivity, because of the growing demand for food, fuel, and fiber propelled by population and economic growth[11]. In particular, global diets continue to shift toward animal-sourced proteins, with per-capita consumption of red meat increasing from 27 g/day in 1990 to 53 g/day in 2020 (96.3% increase)[12]. Animal-sourced proteins are, however, substantially more resource- and emission-intensive than plant-based foods, with, for example, the land footprint of red meat such as beef ~ 75 times that of plant-based proteins such as soybeans per unit of protein provided[13]. Under current trends, global agricultural land use is expected to further expan[14] and consequently drive even greater extents of habitat conversion and degradation[15,16], jeopardizing their capacity to sustain the ecological processes they underpin[17–19], including functional connectivity.

To mitigate the anthropogenic pressures that drive habitat and biodiversity loss[20,21], previous studies have proposed interventions to transform food systems. These interventions include dietary transition[22], sustainable production and technological innovations[23], food-waste reduction[24], and more liberalized agricultural trade[25]. However, these efforts have primarily focused on the extent of land-sparing from food system transformation, overlooking how the spatial distribution of the spared land might enhance or disrupt ecological connectivity[26]. This oversight is critical: agricultural land often competes with forests and other natural ecosystems that serve as corridors or stepping-stone habitats where animals can move more freely owing to cover, resources, and lower levels of human disturbance. Evidence shows that agricultural expansion has interrupted migratory pathways[3,27] and thereby eroded the function of protected areas through reducing connectivity and isolating species.

In addition, food-system transformation pathways can interact with conservation targets, generating synergies and/or trade-offs with potentially significant implications for functional connectivity at global and regional scales[28]. Yet, these effects remain unquantified. While combining such interventions with conservation targets could reduce land-use pressure and strengthen connectivity in some regions, the opposite may occur in others, particularly where food demand is projected to continue rising[29]. Understanding these interactions is essential for informing targeted policy packages at regional and local scales that can both support the implementation of the KM-GBF and advance broader Sustainable Development Goals (SDGs), including food security, climate mitigation, and water sustainability[30–32].

Here, we provide an integrated assessment of how food-system transformation and biodiversity conservation interventions affect the functional connectivity of global PAs, measured by protected area isolation (PAI) and mammal movement probability (MMP), as well as food security and other sustainability goals[3,33]. First, we use the Model of Agricultural Production and its Impact on the Environment (MAgPIE, v4.8.2) to simulate global land-use trajectories from 2020 to 2070. We then use the Spatial Economic Allocation Landscape Simulator (SEALS) model[34,35] to downscale the 0.5° land-use outputs to 300m resolution, enabling fine-grained representation of landscape patterns relevant for functional connectivity analysis. Finally, we combine these downscaled land-use trajectories with average movement responses of mammals (624 individuals of 48 mammalian species) to construct a global resistance-to-movement surface[36]. Based on this surface, we apply the Circuitscape[37] to estimate the two key metrics of functional connectivity: PAI and MMP. We design 8 scenarios that incorporate supply-side, demand-side, and conservation interventions, both individually and in combination, to assess their impacts on functional connectivity and broader sustainability outcomes (Table 1 and Methods in the Supplementary Information). Comparing outcomes across scenarios allows us to identify pathways that reduce agricultural land demand while enhancing functional connectivity and supporting food security and other sustainability goals (Fig. S1; see Methods in the Supplementary Information).

Table 1

Key attributes and assumptions of the scenarios considered in this study; The 'X' indicates the measure in the corresponding row is activated in the scenario.

Scenarios	Supply-side (Sup)		Demand-side (Dem)		Ecosystem stewardship (EcoS)		
	High productivity growth rate	Increased food trade	Reduced food loss and waste	Diet changes	Restore 30% of degraded ecosystems	Maintain 20% semi-natural vegetation	No net biodiversity loss
Baseline							
BAU	—	—	—	—	—	—	—
Single-action							
Sup	X	X	—	—	—	—	—
Dem	—	—	X	X	—	—	—
EcoS	—	—	—	—	X	X	X
Combined-action							
Sup-Dem	X	X	X	X	—	—	—
Sup-EcoS	X	X	—	—	X	X	X
Dem-EcoS	—	—	X	X	X	X	X
Integrated	X	X	X	X	X	X	X

Detailed information on protected areas, conservation priority areas, model settings, and scenario-specific data is provided in Figs. S2–S14 and Tables S1–S6.

Results

Mammal movement probability (MMP)

The global median MMP, estimated from cumulative current density via circuit theory to represent terrestrial mammalian dispersal, is projected to decline by about 2.0% between 2020 and 2070 under the baseline (BAU) scenario (Fig. 1a-1b). Although the net global decline is modest, it reflects offsetting changes across regions rather than uniformly weak change. Under the BAU scenario, MMP declines across nearly half of the terrestrial surface (Figs. 1b-1c & S15), with losses concentrated in regions that overlap existing critical connectivity areas (CCAs), including northwestern Canada, southern Siberia, the Sahel and northern Central Africa, and the Amazon Basin through the eastern foothills of the Andes. In these regions, forest conversion to agriculture, together with projected growth in population and food demand, is expected to intensify habitat isolation and further fragment semi-natural landscapes (Figs. S5-S6 & S16-S17). Additional declines are evident across the North American Midwest and adjacent agricultural regions, where intensive agriculture, urban expansion, and transport infrastructure jointly erode connectivity in areas that historically served as important movement corridors[3]. By contrast, gains are concentrated in mountainous regions, ecotones, and humid–arid transition zones, notably in the East African Highlands, along the eastern margin of the Congo Basin, and across the

Hengduan–Himalayan region, where lower human pressure and greater habitat heterogeneity favor stronger landscape connectivity (Fig. S15).

Compared with the 2070 BAU, all intervention strategies improve MMP to varying degrees. Food-system transformation alone has modest effects, with Supply-side, Demand-side, and Sup-Dem increasing MMP by 0.7–1.9%. However, none restore MMP to its 2020 level, indicating that food-system transformation alone is insufficient to reverse the overall decline. Generally, Demand-side interventions increase MMP in high meat-consuming regions, including Brazil, Argentina, central North America, northern Europe, and parts of Asia, because reduced demand for feed crops and grazing land alleviates pressure on natural habitats. However, Demand-side interventions reduce MMP in parts of the Global South, particularly Africa and South Asia, as well as in major food-producing regions, where growing demand for plant-based foods drives cropland expansion (Fig. 1f). Conversely, Supply-side interventions generate more spatially limited gains, mainly in Africa and parts of Eurasia, while MMP continues to decline across several major food-producing regions where intensified production increases pressure on natural habitats (Fig. 1e).

EcoS (Table 1 and Methods in the Supplementary Information) and interventions generate greater improvements, increasing MMP by 2.6% compared to BAU and raising it above the 2020 level. The largest gains occur in relatively intact landscapes, including the Congo Basin, the East African Highlands, and northern Eurasia, but remain limited in highly fragmented agricultural regions such as Brazil and Argentina, where severe habitat loss constrains recovery (Fig. 1g).

Combining EcoS interventions with food-system transformation further enhances MMP, with increases of 2.7% under Sup-EcoS, 3.1% under Dem-EcoS, and 3.2% under Integrated interventions (Fig. 1b). The MMP is projected to increase across 55.6–58.0% of the global terrestrial surface in these scenarios. Compared with food-system transformation or ecosystem stewardship implemented alone, these combined interventions produce broader and more spatially continuous improvements, especially in regions where semi-natural habitat remains, while confining residual declines to more fragmented and intensively used landscapes (Fig. 1d, 1i-j).

Protected area isolation (PAI)

We further evaluate the isolation of terrestrial protected areas worldwide under different scenarios using the median PAI within national or regional boundaries as the corresponding indicator. Under the BAU scenario, global PAI is projected to increase by 3.7% from 2020 to 2070, with 83 countries showing higher PAI and the largest increase reaching 206.7% relative to 2020, indicating an overall decline in connectivity, (Fig. 2b). Increases in PAI are concentrated in sub-Saharan Africa and South and Southeast Asia, including several countries containing globally important biodiversity strongholds and protected area networks[3]. The most severe increases are observed in the Congo, East Africa, and Madagascar, where rapid population growth and rising food demand are expected to drive cropland expansion and intensify fragmentation of remaining semi-natural landscapes. Although declining populations and slower growth in food demand in parts of Europe and Asia are projected to facilitate some natural land recovery and reduce PAI, these localized improvements are not expected to offset the global trend of deterioration.

Consistent with the MMP results, all interventions also improve projected PAI trajectories, reducing the global median PAI by 0.04–5.5% relative to the 2070 BAU, with slightly larger effect than those observed for MMP

(Fig. 2d). Supply-side interventions have the weakest effect on PAI, lowering the global median by only 0.04% relative to the 2070 BAU. This limited gain reflects offsetting regional responses, as agricultural investment drives cropland expansion and thereby increases PAI in parts of Africa (+ 0.3%), Asia (+ 0.4%), and Europe (+ 1.0%), while trade liberalization intensifies reliance on South American food exports and increases PAI in the region (+ 0.8%). Demand-side and Sup-Dem interventions have stronger effects, lowering the global median PAI by 0.8–1.4%, largely because diet changes and reduced food waste ease land-use pressure. As with MMP, neither of these interventions brings PAI back to its 2020 level.

EcoS interventions have a stronger effect on PAI than food-system transformation, reducing the global median PAI by 5.4%, largely through protected-area expansion and the retention of at least 20% semi-natural vegetation. Moreover, coupling food-system transformation with EcoS interventions can achieve comparable or even greater reductions in PAI (4.6–5.5%), although the magnitude of these effects varies across regions. Overall, Integrated interventions perform best, reducing the global median PAI by 5.5% and producing the largest regional declines in Oceania (-9.5%), North America (-9.3%), and South America (-3.4%), highlighting the synergistic benefits of combining Supply-side interventions, Demand-side interventions, and ecological restoration. In Europe and Asia, Dem-EcoS interventions perform best. Relative to Integrated interventions, the absence of Supply-side interventions helps restrain agricultural expansion and reduce food export pressure in Asia (Fig. S16), thereby allowing greater reductions in PAI in these highly fragmented landscapes. In Africa, Integrated interventions are also not the most effective pathway (-6.6%), whereas EcoS interventions alone achieve the largest reductions in PAI (-7.3%). This pattern reflects the larger gap between current and healthier diets in the region, under which Demand-side interventions increase food demand, while Supply-side interventions further stimulate cropland expansion to meet this demand, thereby offsetting part of the connectivity gains achieved under Integrated interventions.

Achieving food security without compromising biodiversity protection

Beyond gains in functional connectivity, Integrated interventions are projected to generate substantial multidimensional co-benefits by narrowing regional disparities in dietary intake, reducing food waste by 44.1%, lowering per capita food expenditure to USD 1,646.3 (24.8% below BAU), and decreasing undernutrition and obesity by 570 million and 1.79 billion people, respectively. Integrated interventions also achieve the highest Biodiversity Intactness Index (BII) among all scenarios, surpassing even conservation-dominant pathways and highlighting its potential to align ecological restoration with broader Sustainable Development Goals (Fig. 4f). By contrast, interventions implemented alone tend to yield narrower and less coordinated benefits. EcoS interventions can deliver substantial improvements in biodiversity and functional connectivity, and in some regions even produce the greatest gains, but they do not alleviate food-security or health pressures and may even increase food-expenditure burdens (Fig. 4a–e). Likewise, Supply-side and Demand-side interventions can improve specific dimensions, such as reducing food expenditure, land-use pressure, or food waste, but their ecological benefits remain relatively limited and are insufficient to reverse the overall trend of decline (Fig. 4f). This suggests that neither food-system transformation nor ecosystem stewardship alone is sufficient to address the multiple pressures shaping future sustainability outcomes[28]. By integrating ecological restoration with production- and demand-side interventions, Integrated interventions offer a more robust pathway for sustaining both environmental integrity and human well-being.

Discussion

This study is the first to explicitly link food-system transformations with biodiversity targets through spatially explicit metrics of MMP and PAI in human-dominated landscapes[3,33]. This novel integrative framework aligns food and biodiversity objectives within multifunctional, resilience-centered land governance—contributing directly to the implementation of the 2050 Vision of the Convention on Biological Diversity[38] and aligning closely with broader global sustainable-development governance. Unlike previous studies that focused primarily on protected areas themselves, our analysis shows that integrating food-system transformation with ecosystem stewardship can generate synergies between conservation and development, underscoring the need to embed connectivity-informed land-use planning into food system reform as countries implement the KM-GBF and respond to IPBES recommendations. Although no previous studies have directly validated our full modelling framework, we compared the 2020 baseline MMP and PAI with existing global connectivity assessments and observed strong spatial agreement[3], lending additional confidence to the robustness of our approach. In addition, we test our projections under alternative socio-economic assumptions, including population and income growth under the SSP1 and SSP3 trajectories, with details provided in the Supplementary Information (Figs. S18–S26).

Across the scenarios assessed, single-lever interventions, whether Demand-side, Supply-side, or conservation-focused, improve specific dimensions but remain insufficient to simultaneously support functional connectivity, food security, and human well-being. EcoS interventions, for instance, deliver substantial improvements in MMP and PAI. However, because these measures operate primarily through habitat protection rather than changes in consumption patterns, they may cause trade-offs with efforts to achieve food security and end hunger, particularly in regions with substantial nutritional deficits. Similarly, Supply-side and Demand-side interventions can reduce cropland expansion or shift consumption patterns, but they are less consistent in generating broad biodiversity gains[28]. By contrast, Integrated interventions perform best overall. Our results suggest that achieving food security, including ending hunger, does not substantially deteriorate biodiversity, while reducing malnutrition, obesity, and diet-related health risks can generate additional, albeit modest, biodiversity benefits. Yet these gains alone are insufficient to substantially improve MMP and PAI, highlighting the need for targeted action to restore functional connectivity and better align SDGs 2 (Zero Hunger), 3 (Good Health and Well-being), and 15 (Life on Land). Even so, trade-offs under Integrated interventions remain across regions. In Africa, for example, rising food demand together with greater agricultural investment may stimulate cropland expansion, thereby moderating the benefits achieved under Integrated interventions. These regional differences suggest that strategic priorities should vary by context. In high-consumption regions, demand-side interventions combined with ecological restoration may offer the greatest potential to reduce land pressure and enhance connectivity, whereas in low- and middle-income regions with rising nutritional demand, production-oriented measures need to be coupled with conservation safeguards to prevent further habitat loss. Such differentiated land-use interventions are also closely linked to the mitigation goals of the Paris Agreement, as both food-system transformation and targeted ecosystem stewardship can contribute not only to biodiversity conservation but also to climate mitigation and resilience[39]. Our findings strongly support recent literature that argues for the necessary implementation of ambitious supply- and demand- side food system interventions alongside conservation measures in order for humanity to stay within key environmental limits[40].

Despite the clear potential of Integrated interventions to reconcile ecological connectivity with food security, translating this pathway into policy remains constrained by multiple real-world barriers. In many low- and middle-income countries, limited institutional capacity, financial constraints, and fragmented governance systems pose major obstacles to implementing spatially targeted land-use interventions, particularly those requiring coordination across conservation, agriculture, and nutrition sectors[31,41]. Political inertia, resistance from vested interests within food systems, and entrenched dietary preferences further hinder transformative change[42,43]. These barriers are compounded by uneven access to spatial data, limited technical capacity for integrated planning, and the short-term political costs of reforms whose ecological and social benefits often emerge only over longer time horizons[44,45]. Overcoming these constraints will require stronger cross-sectoral governance, more predictable financing, and policy frameworks that align biodiversity, food, and health objectives rather than treating them in isolation. Biodiversity finance[46], together with long-term financing for food-systems and targeted development assistance[47], could help offset the upfront costs of ecological restoration, sustainable agricultural investment, and nutrition-sensitive food-system reform. At the same time, improved spatial monitoring, scenario-based planning tools, and region-specific implementation strategies will be essential for identifying where integrated interventions are both ecologically effective and socially feasible. Phased policy design, including producer incentives, social protection, and public engagement, may further improve political feasibility and reduce resistance to dietary and land-use transitions.

This study has several limitations. Although the SEALS model downscales MAgPIE land-use outputs using information on adjacency, biophysical suitability, and conversion eligibility, it remains an allocation algorithm rather than a full land-use change model such as Dyna-CLUE[48] or CLUMondo[49]. This means, SEALS model largely reproduces historical land-use patterns when allocating fine-scale grid cells and does not consider connectivity. If connectivity was considered in future scenario design, connectivity could be probably largely improved. In addition, owing to the lack of future data on transport networks and night-time lights, the Human Footprint Index (HFI) under different scenarios is estimated by varying only cropland, pasture, population density, and urban extent[50], while holding other components constant (see Method). This simplification may underestimate scenario-specific changes in human pressure. Moreover, our future land-use simulations do not explicitly capture climate-change effects on agricultural productivity, particularly climate-driven shifts in crop suitability, the growing influence of extreme events, and potential CO2 fertilization effects. Because these effects can influence crop yields and thereby alter land demand and allocation, excluding them may affect the projected extent and spatial distribution of cropland[51]. Finally, our analysis is restricted to mammals and does not encompass other taxa whose dispersal abilities and habitat sensitivities may differ substantially. Extending the analysis to birds, amphibians, pollinators, and invertebrates would provide a more complete picture of ecosystem responses.

Despite these limitations, our analysis demonstrates that food-system transformations are not peripheral to biodiversity conservation, but fundamental to whether connectivity is maintained or eroded across human-dominated landscapes. More broadly, our results suggest that safeguarding the functional connectivity of global protected areas will require going beyond protected-area expansion alone and embedding connectivity-informed land-use planning within wider food-system reform. Such integration will be essential to addressing the intertwined crises of biodiversity loss, malnutrition, and climate change in the Anthropocene.

Method

Model of Production and its Impacts on the Environment (MAgPIE)

The Model of Production and its Impact on the Environment (MAgPIE, v4.8.2)[52] is an open-source, modular framework designed to model land systems. It operates at two spatial levels: a coarse level that divides the world into twelve regions based on socioeconomic characteristics, and a finer subregional level that clusters regions according to biophysical properties relevant to agricultural production. The coarse regions primarily define socioeconomic constraints, such as food demand, trade patterns, and interest rates, with smaller economies aggregated and larger ones, like the USA, China, and India, represented individually. At the finer scale, land competition, agricultural production, and irrigation processes are modelled using spatial clusters derived from biophysical data at the 0.5° grid cell level. Key inputs include crop and pasture yield potentials, terrestrial carbon densities, and water availability, which are sourced from the Lund-Potsdam-Jena managed land (LPJmL) model[53]. For presenting the results, the 12 world regions are aggregated into six continental regions based on their geographic distribution (Table S1). Further details are provided in the Supplementary Methods.

Spatial Economic Allocation Landscape Simulator (SEALS)

The spatial arrangement of land cover and its changes play a crucial role in determining the functional connectivity of protected areas[3], which is fundamental to maintaining biodiversity and ecosystem resilience by facilitating species movement and gene flow[1,36,54]. However, land-cover change—driven by anthropogenic land-use transitions—can lead to habitat fragmentation[4], disrupting ecological corridors[55] and isolating conservation sites. Assessing these impacts requires spatially explicit land-cover data at fine resolutions. Yet, the coarse spatial resolution (0.5°) of the original MAgPIE model limits its ability to capture such landscape-scale dynamics that influence connectivity patterns under global land-use change. To overcome this limitation, we integrate the SEALS (Spatial Economic Allocation Landscape Simulator) model, which downscales projected land-use changes in MAgPIE to a field-scale resolution of 10 arc-seconds (~ 300 m). Further details are provided in the Supplementary Methods.

Projection of Human Footprint Index (HFI)

We constructed a Human Footprint Index (HFI) based on a hybrid approach integrating both dynamic scenario-based layers and static infrastructure assumptions. Dynamic variables including Built Environments (urban), Croplands, Pastures, and Population density were sourced from MAgPIE model outputs and SSP databases (Supplementary Fig. 11–12), aligned with Shared Socioeconomic Pathways (SSPs). Static variables such as roads, railways, night lights, and navigable water were assumed constant over time due to the lack of forward projections (Table S4). All layers were resampled to a uniform spatial resolution before aggregation. All variables were normalized to a 0–10 scale before aggregation (Table S5), following the methodology in Venter et al.[50]. Further details are provided in the Supplementary Methods.

Circuit-theoretic computations for landscape ecology (Circuitscape)

We assessed global connectivity using Circuitscape[37], an open-source software developed in Julia that is widely applied in ecological connectivity analyses and conservation planning (https://circuitscape.org/). This approach treats a gridded resistance-to-movement surface as a conductive layer where neighboring grid cells are connected by resistors, whose level of resistance represents the friction of the landscape to animal movement (i.e., low-resistance grid cells are most likely to be traversed). Electrical current, injected at a source node representing a source of animal movement, flows across all neighboring landscape grid cells (resistors) in the circuit to a ground node representing the destination of animal movement. Connectivity is then evaluated in two distinct ways: (a) from the effective resistance between nodes on a circuit (i.e., protected area (PA) isolation), measuring the degree to which the source node is isolated from the ground node and (b) from the pattern of electrical current flow (i.e., mammal movement probabilities) across the resistance-to-movement surface. Further details are provided in the Supplementary Methods.

Scenario description

We adopted the “middle-of-the-road” Shared Socioeconomic Pathway (SSP2) as our reference scenario. SSP2 assumes continued moderate population growth, reaching a global peak of 9.4 billion by 2070, coupled with uneven economic growth, ongoing globalization, and gradual socioeconomic convergence across countries, while also incorporating currently implemented land-use regulations. In six additional scenarios, we evaluated different combinations of supply-side, demand-side, and conservation measures aimed at enhancing the functional connectivity of global protected areas; all scenarios were implemented within the SSP2 pathway. The additional scenarios correspond to each action separately and to combined-action scenarios, in which actions are paired or combined as the integrated action portfolio of all three actions. Further details on the intervention components are provided in the following section. Further details on the intervention components are provided in the following section.

Supply-side (Sup) actions

The supply-side actions comprise two components: improving agricultural production efficiency and increasing trade in agricultural goods. Improvements in production efficiency include lowering interest rates in low-income countries, facilitating investment and thereby increasing agricultural output, and enhancing livestock productivity by aligning production efficiency and feed-use profiles with the SSP1 trajectory. The trade component reduces self-sufficiency rates for livestock products by 10% by 2030 and by an additional 10% after 2050, while crop self-sufficiency rates are reduced by 20% by 2030 and by a further 10% after 2050.

Demand-side (Dem) actions

The demand-side actions consist of two components: diet changes and reductions in food waste. The diet changes are guided by the minimum and maximum recommended daily intakes for different food groups, while allowing substantial cross-country variation in dietary patterns within these recommended ranges (Table S6). Minimum per capita intakes are specified for legumes, fruits, vegetables, and nuts. In countries where current intake levels fall below these thresholds, consumption is increased to meet the minimum recommendations. Maximum intake thresholds are set for sugar, oils, poultry, eggs, red meat, and dairy products. Where current

intake exceeds these levels, consumption is reduced accordingly. In addition, we assume convergence toward a healthy body mass index of 20–25. The food-waste reduction component constrains current food losses and waste to a maximum of 20%.

Ecosystem stewardship (EcoS) actions

The ecosystem-stewardship intervention comprises a suite of conservation measures designed to strengthen biosphere integrity. Relative to the BAU scenario, the extent of protected areas is expanded by 2055 Mha to achieve the GBF commitment of conserving at least 30% of global terrestrial land by 2030. The expansion prioritizes regions of highest global conservation value (Supplementary Fig. 14), including Key Biodiversity Areas (KBAs), Biodiversity Hotspots (BHs) and Ecoregions with high beta-diversity (EBDs)[56], as well as the Critical Connectivity Areas (CCAs) identified by Brennan et al.[3]. Our choice to expand protected areas within KBAs, BHs, EBDs, and CCAs is guided by current evidence on global conservation priorities and reflects an effort to balance multiple conservation objectives, including the protection of globally important regions and the maintenance of species movements[3,56]. Nonetheless, this represents only one plausible pathway for implementing the GBF 30×30 target, intended to illustrate how strategic land protection could support global biodiversity conservation. We assume that, within these conservation priority areas, restoration targets for different land-cover types follow pre-industrial (1750) reference conditions derived from the LUH2 (v2) dataset[57]. In addition, the *EcoS* actions incorporates a set of interventions aimed at addressing major drivers of biodiversity loss outside protected areas. These measures include retaining at least 20% semi-natural vegetation (SNV) in managed landscapes by 2030 and implementing a no-net-biodiversity-loss scheme at the biome level after 2030[58]. The requirement to maintain at least 20% SNV within managed landscapes is directly implemented in the MAgPIE model by reserving 20% of potentially cultivable cropland for SNV. Further methodological details can be found in Jeetze et al.[59]. The no-net-biodiversity-loss mechanism prevents any decline in the Biodiversity Intactness Index (BII)[28] for each biome[58] within a given MAgPIE region and biogeographic realm. Consequently, any reduction in the biome-level, area-weighted mean BII, such as that caused by cropland expansion or urban development, must be compensated by increasing the extent of land-use categories with higher BII scores within the same biome. In this way, the no-net-loss rule functions as an additional safeguard for areas outside designated conservation priorities, discouraging avoidable conversions to agricultural land. The BII coefficients associated with individual land-use classes in MAgPIE follow Leclère et al.[28], with additional methodological details described in Jeetze et al.[59].

Declarations

Data availability

Data supporting the findings of this study are available within the article and its Supplementary Information files or are available on figshare (https://doi.org/10.6084/m9.figshare.32083284).

Code availability

The model code of the MAgPIE model is openly available under GNU Affero General Public License, version 3 (AGPLv3), and is accessible via GitHub at https://github.com/magpiemodel/magpie. The release version (MAgPIE 4.8.2) on which this work is based is available via Zenodo at

https://doi.org/10.5281/zenodo.13833444. MAgPIE 4.8.2 is accompanied by technical model documentation (https://rse.pik-potsdam.de/doc/magpie/4.8.2/), which was compiled using the GAMS code documentation toolkit goxygen. The SEALS code is accessible via GitHub at https://github.com/jandrewjohnson/seals_dev/ and the accompanying documentation is available at https://justinandrewjohnson.com/earth_economy_devstack/seals_overview.html. The Circuitscape code is also accessible via GitHub at https://github.com/Circuitscape and the accompanying documentation is available at https://docs.circuitscape.org/Circuitscape.jl/latest/.

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Author contributions

ZW conceptualized the study and acquired funding. ZW, YY, and WL designed and supervised the research. ZD, SC, PvJ, BLB, XXW, and JAJ developed the methodology. CC, YH, KL, GZ, and WZ contributed to data collection. ZD, CL, WZ, and JW prepared the visualizations. ZD wrote the original draft. All authors reviewed and edited the manuscript.

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Figures

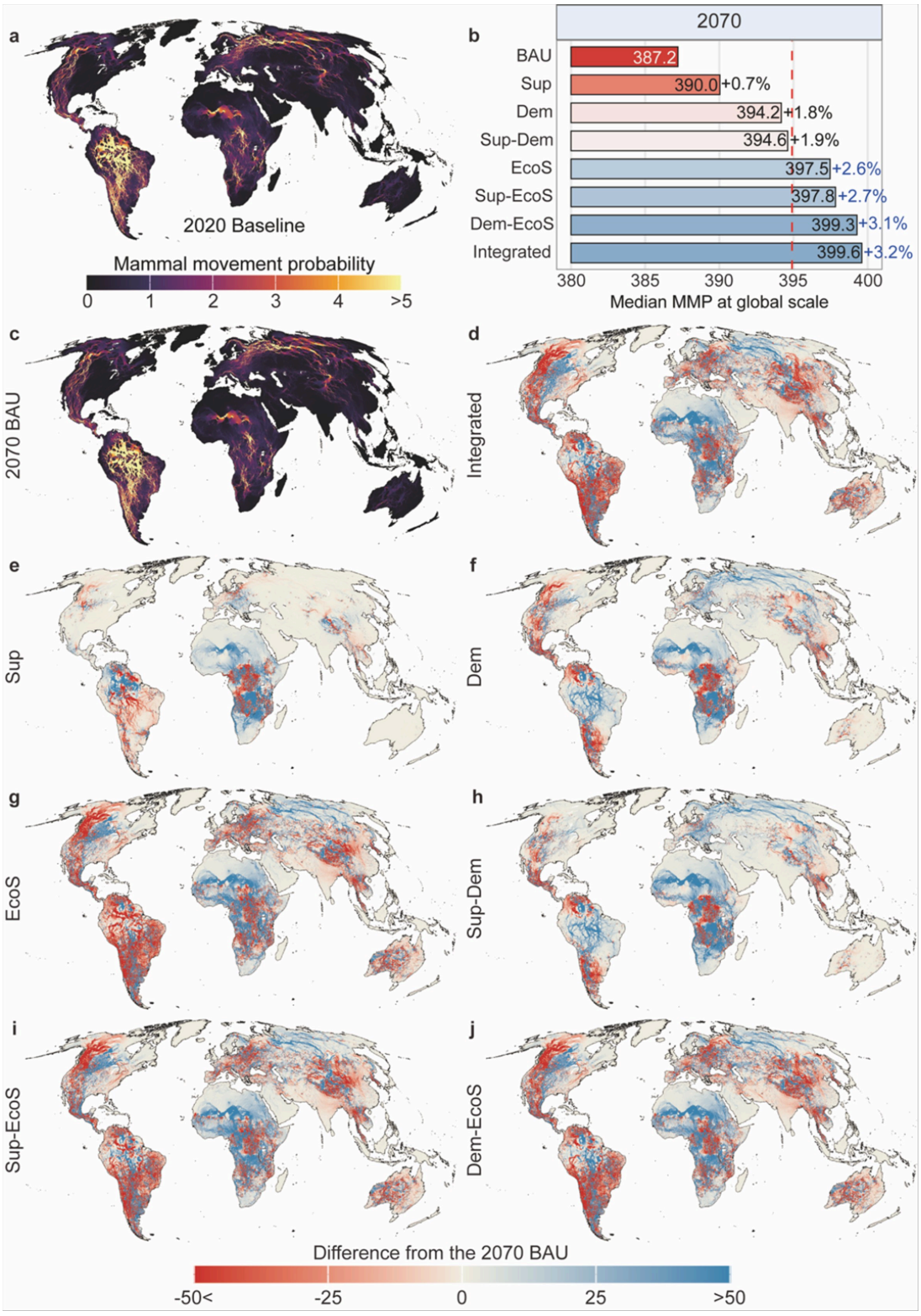


Figure 1

Mammal movement probability (MMP) in the baseline and seven action scenarios, and differences from 2070 BAU. a) shows MMP under the baseline scenario in 2020; **b)** Global median MMP outcomes across scenarios. The red dashed line denotes the global median MMP value under the 2020 BAU, and the percentage numbers represent changes relative to the 2070 BAU; **c)** shows MMP under the baseline scenario in 2070;**d-j)** shows differences from 2070 BAU under the different action in 2070. **Note:**Areas with high MMP represent zones of

concentrated animal movement, often along corridors linking less permeable regions, or within expansive tracts of undisturbed habitat situated among large, interconnected protected areas.

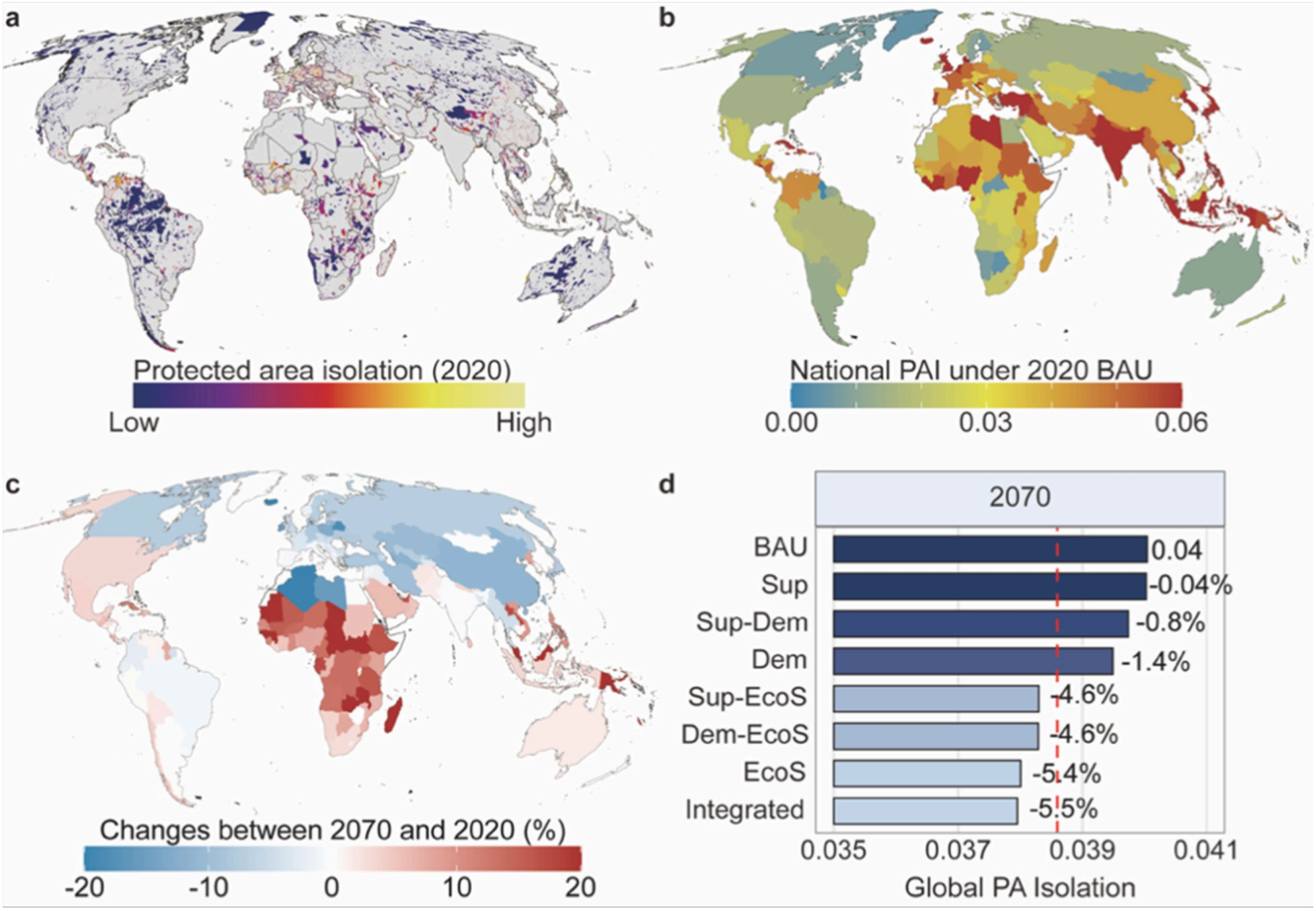


Figure 2

Global projections of protected area isolation (PAI). A national PAI was determined by the median PAI value of all protected areas within its national boundaries. a) isolation of the world's terrestrial PAs. **b)** national PAI under 2020 BAU. **c)** Changes in national-scale PAI between 2020 and 2070 under the BAU scenario. Positive percent change indicates increased PAI, i.e., reduced connectivity. **d)** Global outcomes across scenarios. The red dashed line denotes the global PAI value under the 2020 BAU, and the percentage numbers represent changes relative to the 2070 BAU.

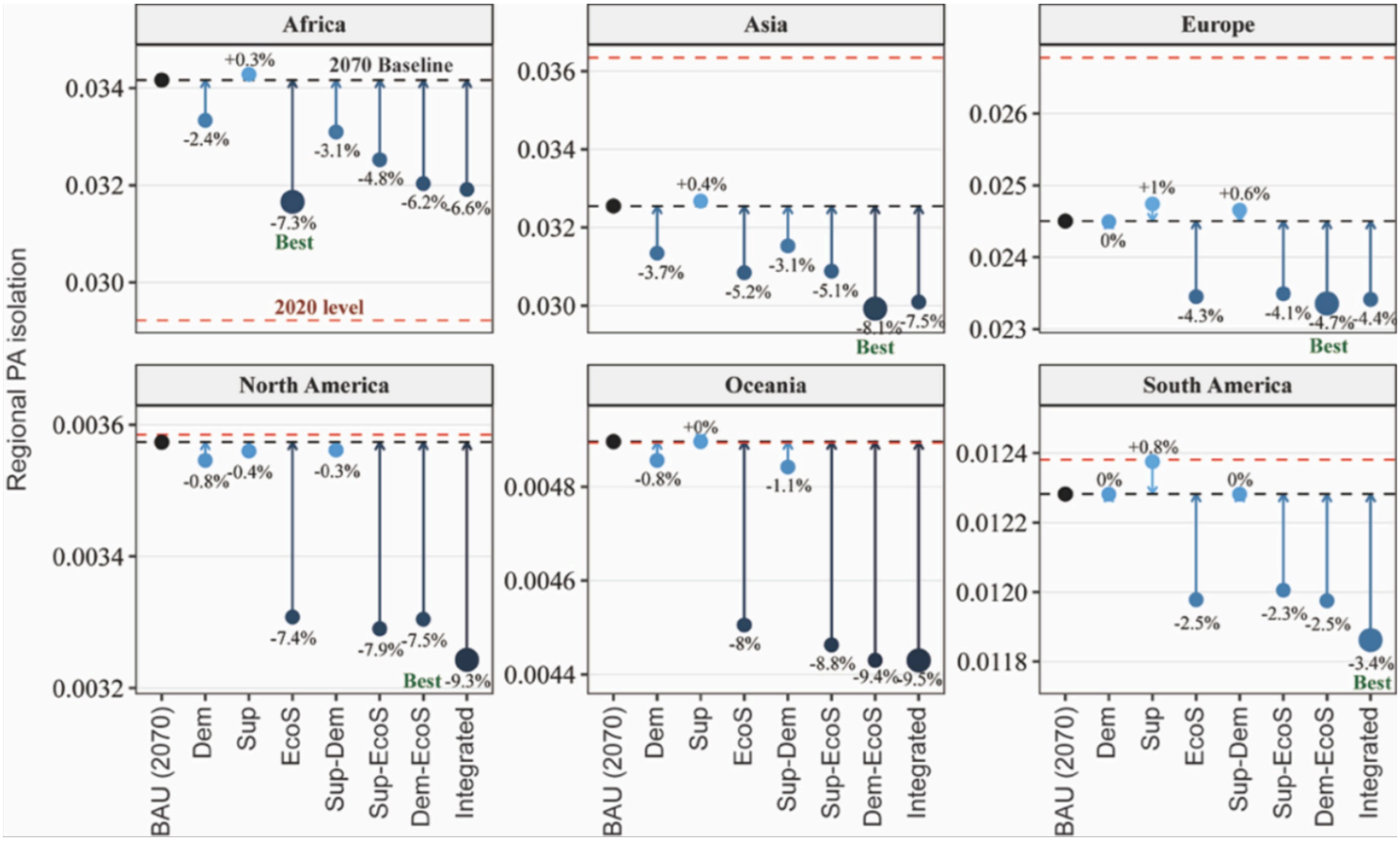


Figure 3

Regional-level projections of protected area isolation (PAI) across scenarios. Larger downward shifts of dots indicate greater improvements in PAI, i.e., stronger reductions in isolation and enhanced functional connectivity.

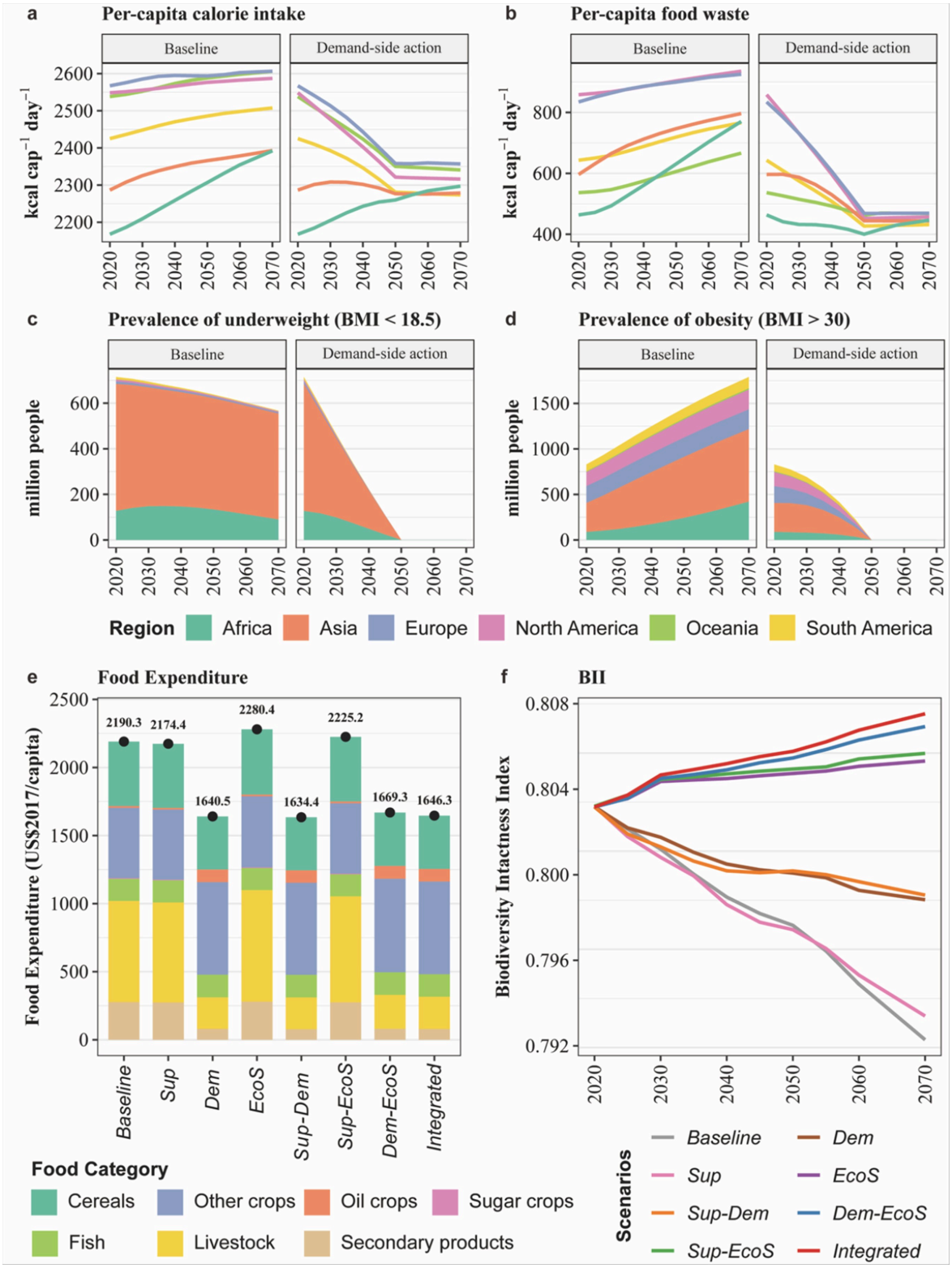


Figure 4

Key socio-economic drivers and developments. a) per-capita calorie intake at regional level; **b)** per-capita food waste; **c)** prevalence of underweight (body mass index <18.5) and **d)** prevalence of obesity (BMI > 30); **e) f**ood expenditure at global level and **f)** biodiversity intactness index (BII) at global level. Note: Panels a–d include only the Baseline and demand-side actions, as interventions without demand-side measures do not change dietary intake or food waste, and thus do not affect underweight or obesity.

Supplementary Files

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