

RESEARCH ARTICLE

ENVIRONMENTAL ENGINEERING

Assessing the land resource–food price nexus of the Sustainable Development Goals

Michael Obersteiner,^{1*†} Brian Walsh,^{1*‡} Stefan Frank,¹ Petr Havlík,¹ Matthew Cantele,¹ Junguo Liu,^{1,2} Amanda Palazzo,¹ Mario Herrero,³ Yonglong Lu,^{4,5} Aline Mosnier,¹ Hugo Valin,¹ Keywan Riahi,¹ Florian Kraxner,¹ Steffen Fritz,¹ Detlef van Vuuren^{6,7}

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The 17 Sustainable Development Goals (SDGs) call for a comprehensive new approach to development rooted in planetary boundaries, equity, and inclusivity. The wide scope of the SDGs will necessitate unprecedented integration of siloed policy portfolios to work at international, regional, and national levels toward multiple goals and mitigate the conflicts that arise from competing resource demands. In this analysis, we adopt a comprehensive modeling approach to understand how coherent policy combinations can manage trade-offs among environmental conservation initiatives and food prices. Our scenario results indicate that SDG strategies constructed around Sustainable Consumption and Production policies can minimize problem-shifting, which has long placed global development and conservation agendas at odds. We conclude that Sustainable Consumption and Production policies (goal 12) are most effective at minimizing trade-offs and argue for their centrality to the formulation of coherent SDG strategies. We also find that alternative socioeconomic futures—mainly, population and economic growth pathways—generate smaller impacts on the eventual achievement of land resource-related SDGs than do resource-use and management policies. We expect that this and future systems analyses will allow policymakers to negotiate trade-offs and exploit synergies as they assemble sustainable development strategies equal in scope to the ambition of the SDGs.

INTRODUCTION

The Sustainable Development Goals (SDGs) agenda adopted by the United Nations General Assembly in September 2015 articulates conditions for sustainable management of social, physical, and ecological elements of the Earth system in the Anthropocene (1, 2). In aggregate, these 17 goals and 169 targets comprehend a road map to “the future we want” in terms of human welfare and environmental sustainability (3). Their underlying development agenda demands inclusive and sustainable policies promoting the welfare of the most vulnerable people and ecosystems (1–4) while avoiding the transgression of planetary boundaries (5–7).

The scientific community has generated an impressive body of literature directly and indirectly informing SDG formulation by sector-specific assessments covering climate change mitigation (8), energy systems (9), food security (10, 11), agricultural productivity (12–14), terrestrial ecosystem management (15), biodiversity conservation (16), land-use change emissions mitigation (17), and sustainable consumption (18). However, these studies are sector-specific and typically ignore the synergies and trade-offs identified in multisectorial assessments (19–23). This is a major shortcoming because the direct and indirect effects of policies in service of specific goals can affect the suc-

cess or failure of others (24, 25). Outside of policy silos, the interdependencies among goals can be identified and integrated into the negotiation and operationalization of the SDGs.

In this analysis, we begin by identifying seven policy clusters, each of which is defined by a set of closely related sustainable development goals or targets coupled with three policies, or discrete global responses to these goals (cf. Fig. 1). Within each cluster, policies are mutually exclusive and span a range of ambition from inaction [business as usual (BAU)] to committed action toward the relevant goals. The policies are described briefly in Table 1 and in full detail in section S1.3. Integrated SDG strategies are constructed by specifying exactly one policy from each of the seven policy clusters. Strategies are subsequently combined with one of three Shared Socioeconomic Pathways (SSPs), or projections of population and economic growth and other drivers (26), to form scenarios. The Global Biosphere Management Model (GLOBIOM), a spatially explicit partial equilibrium model of the agricultural, bioenergy, and forestry sectors (27–31), projects the effects of each scenario on global food prices and environmental indicators decennially through 2050.

RESULTS

Siloed SDG strategies

We begin with 14 single-policy strategies (active policy in exactly one policy cluster and BAU in the remaining six: 2 active policies per cluster × 7 clusters). These generate 42 GLOBIOM scenarios (14 single-policy strategies × 3 SSPs) that project futures in which the global community musters a discrete policy change in service of some subset of goals and nothing further. Single-policy strategies are siloed insofar as the collective response to the comprehensive SDG agenda is limited to action on the goals in a single cluster (cf. Fig. 1). For each scenario, environmental

¹International Institute for Applied Systems Analysis, Ecosystem Services and Management Program, Schlossplatz 1, A-2361, Laxenburg, Austria. ²School of Environmental Science and Engineering, South University of Science and Technology of China, Shenzhen 518055, China. ³Commonwealth Scientific and Industrial Research Organisation, Brisbane, Queensland, Australia. ⁴International Resource Panel of the United Nations Environmental Program, 15 rue de Milan, 75441 Paris Cedex 09, France. ⁵Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing, China. ⁶PBL Netherlands Environmental Assessment Agency, Oranjestraat 6, 2511 VE The Hague, Netherlands. ⁷Copernicus Institute for Sustainable Development, Utrecht University, Utrecht, Netherlands.

*Co-first authors.

†Senior author.

‡Corresponding author. Email: walsh@iiasa.ac.at

index (EI) scores are calculated and compared with food price projections (c.f. Materials and Methods). This provides an integrated measure of siloed strategies' effects on conservation and food security agendas within a particular SSP or socioeconomic pathway.

Overall, the EI scores for these scenarios confirm that each single-policy strategy is a direct and constructive policy response to the goals and targets within its cluster. However, comparison against the global food price index reveals a significant, positive correlation between EI

scores and food prices in year 2030 (cf. Fig. 2, left). That is, more effective conservation policies also lead to greater food price increases. The trade-off intensity, or ratio of food price cost to EI score benefit, of most strategies falls within a narrow range (c.f. the slope of the linear regression in Fig. 2, left).

Single-policy strategies exhibit similar trade-off intensities despite being distinguished by diverse goals and levels of ambition. From this, we conclude that "success" defined in the context of policy clusters

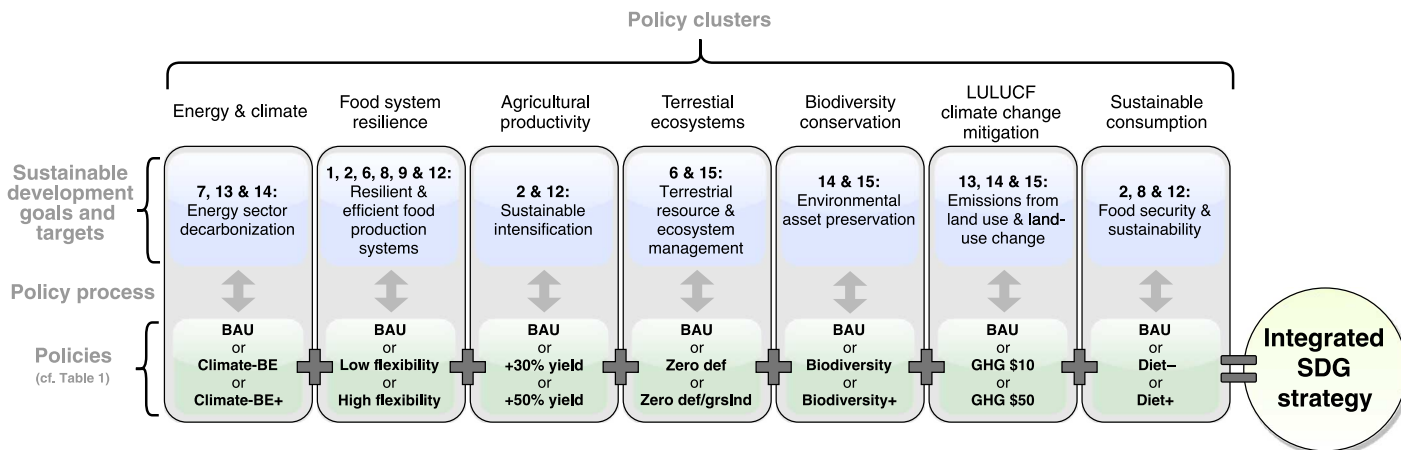


Fig. 1. Schematic diagram of the construction of SDG strategies. We begin with seven policy clusters, each consisting of (A) a subset of SDGs relevant to a specific theme, (B) two active policies reflecting different ambition levels associated with specific SDG targets, and (C) one null policy (BAU), which represents inaction on the relevant goals. Integrated SDG strategies are defined by specifying exactly one policy in each cluster. The BAU strategy is composed of the BAU policy in all seven domains. SDG strategies are subsequently combined with an SSP to form a complete, unique GLOBIOM scenario, and their results are projected decennially through 2050. LULUCF, land use, land-use change, and forestry.

Table 1. Description of the policies within each cluster. One policy from each cluster is specified to construct an SDG strategy, which is subsequently combined with an SSP to form a complete GLOBIOM scenario. The expected pressurizing effect of each policy on food prices is indicated in the far right column, where "P" indicates pressurizing policies expected to raise food prices, and "D" indicates depressurizing policies expected to decrease food prices.

Policy cluster	Policy	Description	Food effect
Energy and climate (SDGs 7, 13, and 14)	BAU	Nominal primary energy profile: no climate target	—
	Climate-BE	Moderate bioenergy and nuclear energy: $\Delta T < 2^{\circ}\text{C}$	P
	Climate-BE+	High bioenergy and no nuclear: $\Delta T < 2^{\circ}\text{C}$	P
Food system resilience (SDGs 1, 2, 6, 8, 9, and 12)	Low flexibility	Slow production system shifts and high waste	P
	BAU	Nominal production system shifts and waste	—
	High flexibility	Rapid production system shifts and low waste	D
Agricultural productivity (SDGs 2 and 12)	BAU	Nominal input-neutral agricultural yield growth	—
	+30% yield	Nominal input-neutral yield growth + 30%	D
	+50% yield	Nominal input-neutral yield growth + 50%	D
Terrestrial ecosystems (SDGs 6 and 15)	BAU	No restrictions on land-use change	—
	Zero def	No gross forest loss	P
	Zero def/grslnd	No gross forest or grassland loss	P
Biodiversity conservation (SDGs 14 and 15)	BAU	Unrestricted conversion of biodiversity hotspots	—
	Biodiversity	Moderate protection of biodiversity hotspots	P
	Biodiversity+	No conversion of biodiversity hotspots	P
LULUCF climate change mitigation (SDGs 13–15)	BAU	No tax on LULUCF emissions	—
	GHG \$10	LULUCF emissions tax: US \$10/tCO ₂ eq	P
	GHG \$50	LULUCF emissions tax: US \$50/tCO ₂ eq	P
Sustainable consumption (SDGs 2, 8, and 12)	Diet–	Western diet globalization	P
	BAU	FAO diet projections	—
	Diet+	Reduced meat demand	D

inevitably belies problem-shifting and trade-offs with other clusters, in this case, food security. Further, joint EI score–food price outcomes are limited to this narrow range of trade-offs even under distinct SSPs. This result suggests that the policies governing land resource use and management are more critical to the success of the SDG agenda than are future population and economic growth trends.

The correlation between EI scores and food prices can be interpreted as an efficiency frontier of the trade-offs between conservation and food security agendas. This frontier largely constrains the possible outcomes of single-policy strategies and serves as a useful benchmark against which compound SDG strategies can be evaluated. Two reference frames can be introduced for measuring distances: parallel to the ordinate and perpendicular to the regression. For example, measurement parallel to the ordinate reveals that reduced meat consumption (Diet+) returns a 15% lower food price than would be expected on the basis of its EI score, whereas inflexible agricultural production systems (Low flexibility) and strong biodiversity protections (Biodiversity+) return prices 7% higher than is expected for their respective EI scores. Perpendicular deviations yield the regression residuals, which measure efficiency gains or losses with respect to the joint outcome of EI score and food price.

The fit residuals from each of the single-policy strategies under nominal socioeconomic conditions (SSP2) are ranked and plotted in Fig. 2 (right). Policies that promote sustainable consumption (for example, Diet+) and production—for example, input-neutral agricultural intensification (+50% yield)—simultaneously boost EI scores and lower food prices relative to the overall correlation. This indicates that Sustainable Consumption and Production (SCP) policies reduce the intensity of trade-offs among goals. Conversely, locked-in agricultural production systems (Low flexibility) and restrictive land-use policies (for example, Biodiversity+) intensify trade-offs or increase the marginal food security costs of prospective conservation initiatives. Generally, SDG policies modulate the intensity of trade-offs among goals

through their net effects on total resource consumption, land-use change, and associated emissions.

Compound SDG strategies

The interdependencies that arise within compound SDG strategies (active policies in multiple policy clusters) are similarly governed by the net effect of their component policies regarding the trade-offs in the land system. These effects may either build on or counterbalance each other. To examine this in our analysis, we consider two sets of three-policy strategies. The first of these includes sustainable consumption and energy sector decarbonization (Diet+ and Climate-BE) as two of the three policies. Following from the single-policy strategy residuals in Fig. 2 (right), these policies are expected to create lower-pressure scenarios because reduced demand for animal proteins offsets increased demand for bioenergy and improves the assimilative capacity of food production systems. The second set couples locked-in agricultural systems with energy system decarbonization and denuclearization (Low flexibility and Climate-BE+) and is constructed to exemplify higher-pressure scenarios. To fill out each set, we combined the two named policies with a third active policy from exactly one of the five remaining policy clusters (30 GLOBIOM scenarios = 2 active policies per cluster × 5 clusters × 3 SSPs).

Figure 3 compares the results for the low- and high-pressure strategy sets to the single-policy strategy results for 2030 and 2050 (cf. Fig. 3, left and right, respectively). Within each set of strategies, EI scores maintain significant correlations with food prices. However, the intensities of trade-offs between environmental and food production systems, as represented by the slopes of the regression fits, vary widely across the three distinct futures, implying that it is possible to “break away” from the standard trade-offs.

Among the benchmark set of single-policy strategies, EI scores range from 0.18 to 0.78, and food price projections range from –14% to +7% in 2030. In the low-pressure set, EI scores show improvement (0.45 to

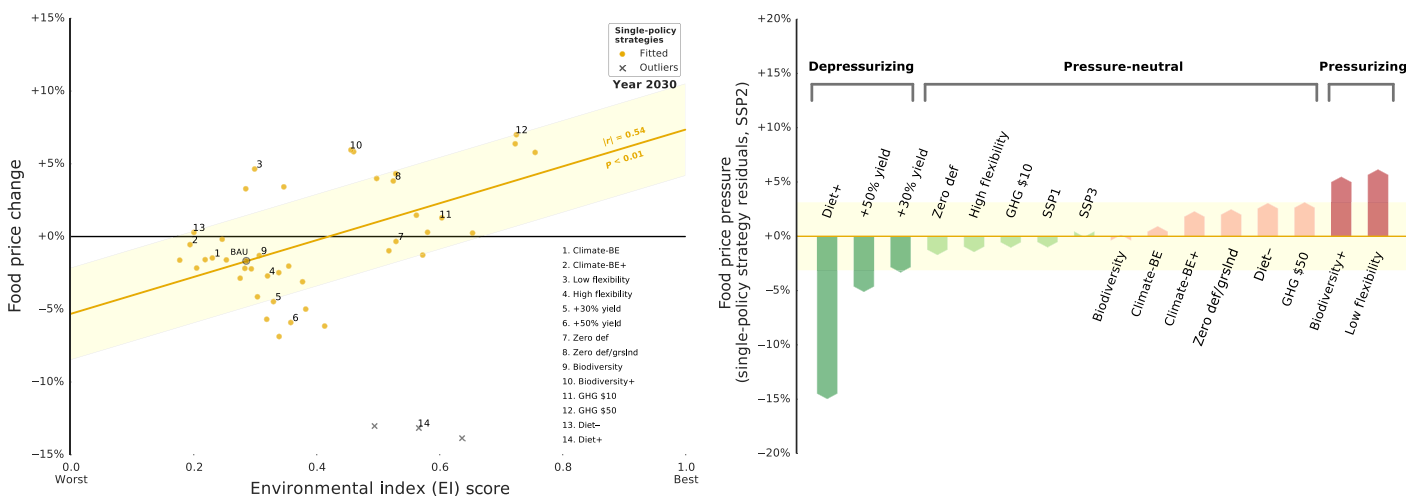


Fig. 2. GLOBIOM model results describe a trade-off efficiency frontier between EI scores and food prices. (Left) EI scores plotted versus global food price increases for single-policy strategies. Each single-policy strategy consists of an active policy from exactly one policy cluster and the null policy in the remaining six clusters, and each generates three GLOBIOM scenarios (one for each SSP). Food price changes are expressed in percent change relative to 2010. SSP2 scenario results are individually labeled. The linear regression fit includes all three SSPs and returns a statistically significant correlation between food prices and EI scores ($N = 39$). **(Right)** The fit residuals from single-policy SSP2 strategies characterize each policy’s deviation from the overall trade-off efficiency frontier. From left to right, policies are ranked in order of increasing ratio of food price cost to EI score benefit. Policies with low (high) cost-benefit ratios are interpreted as having depressurizing (pressurizing) effects on food production systems.

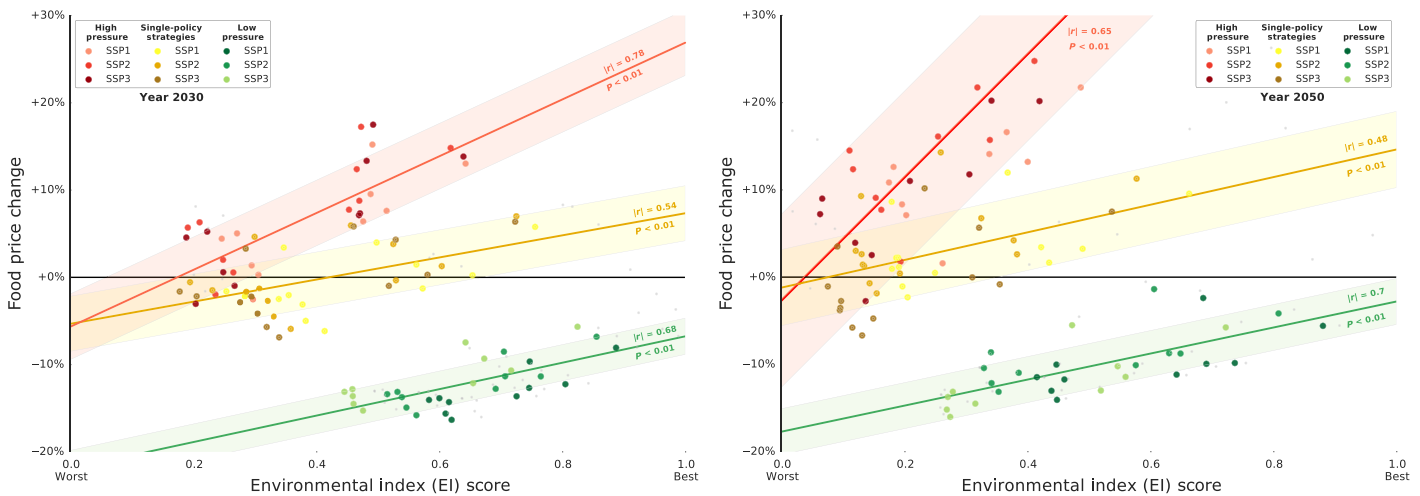


Fig. 3. EI scores plotted against global food price increases. Food price changes are expressed in percent change relative to 2010 for low-pressure, single-policy, and high-pressure strategies in years 2030 (left) and 2050 (right) of the indicated scenarios. Results from unique socioeconomic scenarios are indicated separately in each legend, but linear regression fits include all three SSPs within each strategy set ($N = 30$). Fit statistics are reported for each set.

0.89), whereas food prices decrease (-7% to -16%). This beneficial shift in the trade-off efficiency frontier persists through 2050. Conversely, high-pressure strategies return lower EI scores (0.07 to 0.48) coupled with higher costs to food security ($+1\%$ to $+17\%$). Further, the food price costs of conservation initiatives steepen markedly for high-pressure strategies by 2050. In general, SDG strategies that achieve their goals by shifting pressure onto food production systems intensify the trade-offs between conservation agendas and food security. These trade-offs intensify further with the ambition of SDG strategies and over time. On the other hand, policies that manage food system pressure mitigate trade-offs by simultaneously increasing the availability of land, water, and food for the full range of SDG priorities.

The model results used to calculate EI scores for low-pressure (Diet+ and Climate-BE) and high-pressure (Low flexibility and Climate-BE+) strategies are disaggregated and presented in Fig. 4 as percent changes relative to 2010 for each indicator. In the left (right) hemisphere of each circle, strategies are ranked from top to bottom according to EI score (food price). Within each circle, policy rankings are not perfect inverses, suggesting that a common ground can be found even between agendas that prioritize either sustainability or development. For example, comparison between the left hemispheres of the two circles indicates that greenhouse gas (GHG) pricing schemes (GHG \$10 and GHG \$50) result in the highest EI scores regardless of the other policies enacted. The right hemispheres indicate that the benefits of input-neutral yield growth ($+30\%$ yield and $+50\%$ yield) are similarly independent of accompanying policies. As a result, these types of policies or investments would be attractive as foundational components of SDG strategies.

Closer examination of trade-offs quantified in Fig. 4 indicates that SCP policies (for example, yield growth, agricultural resilience, and waste mitigation) generate the greatest and most broadly distributed benefits to nutrient cycling, water use, and overall food security outcomes. Land-use change restrictions (that is, policies in the biodiversity conservation and terrestrial ecosystems clusters) work as designed to mitigate the destruction of natural forests and habitats as well as GHG emissions but can pressurize water cycles by increasing reliance on irrigation. This is indicative of significant trade-offs among water,

land conservation, and climate mitigation SDGs. GHG pricing, a cross-sectorial policy, leads to broadly improved environmental outcomes while maintaining efficient food price trade-offs.

DISCUSSION

Land is a fixed resource at all scales, although it can be managed to serve a multitude of goods and services. However, this inherent flexibility is constrained by path dependencies; land-use change today has implications for the services it can provide in the subsequent decades. These essential properties of land induce strong spatial, temporal, and intersectorial interactions and make land management an ideal laboratory to study the internal consistency of siloed and integrated policy responses to the SDG agenda (24). Here, we analyze interactions among multiple SDG policy options for the management of land-based resources on a global scale. This is carried out by sorting land-related SDGs into seven policy clusters, which map in a rough sense to current, weakly coordinated policy processes among the ministries, departments, and panels of national governments, international organizations, and civil society.

Our analysis establishes that path dependencies, competition, and pressure—all functions of fixed resource endowments in the land system—create trade-offs among coeval goals. Although single-sector policies are typically easier to conceive and implement in actual policy processes, piecemeal approaches to SDG implementation create policy incoherence to the overall detriment of environmental and food security outcomes. Failure to evaluate policy responses in integrated systems contexts leaves these interdependencies hidden and may limit policy planning to zero-sum trade-offs (25).

Trade-offs within the global SDG agenda will manifest as obstacles to progress at regional and national levels. In the Congo Basin, for example, analyses based on satellite data have identified agricultural expansion and fuel wood and timber extraction as leading drivers of deforestation and habitat degradation (32). Longitudinal research in Sumatra similarly concluded that rising agricultural commodity prices

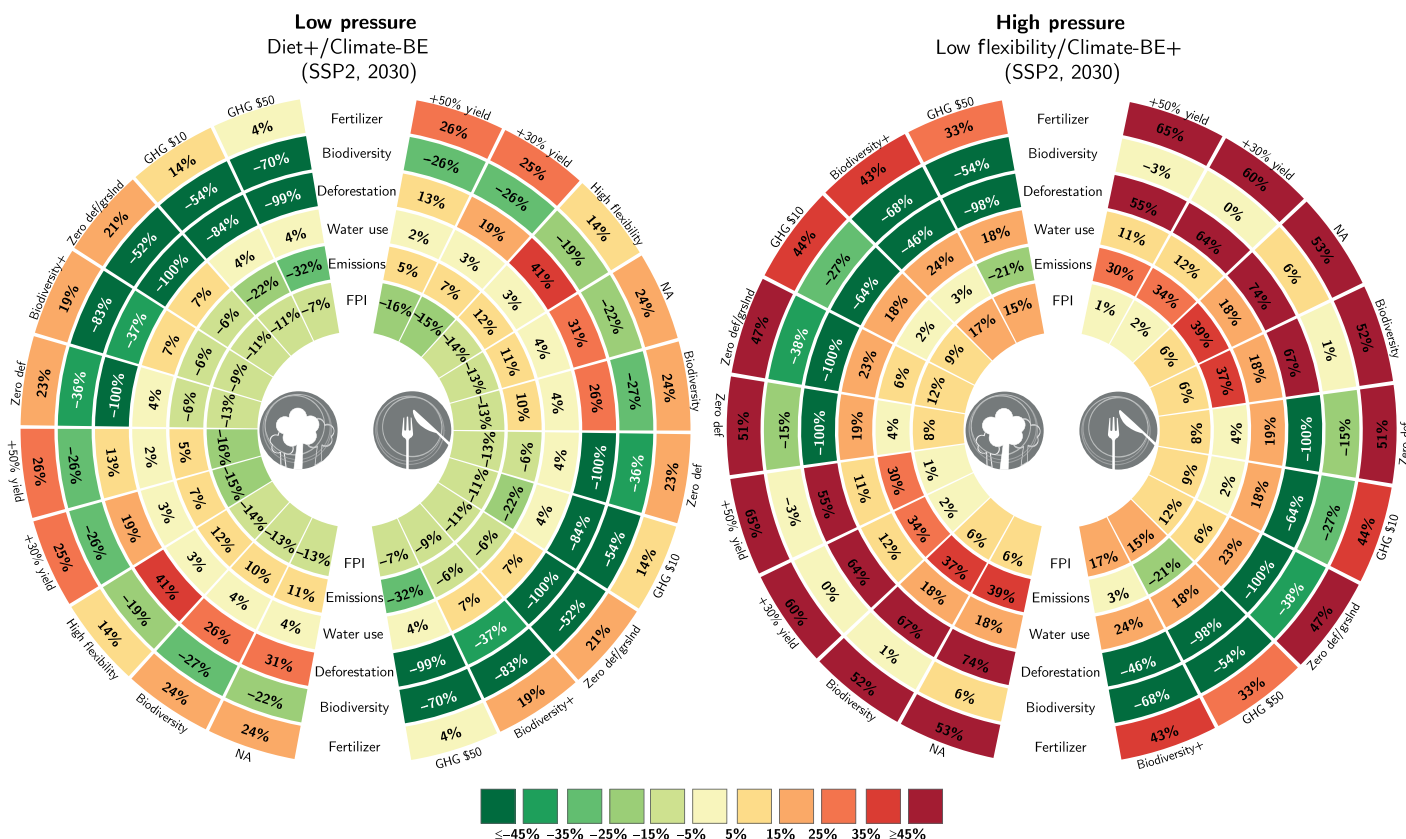


Fig. 4. Circular plots illustrating the projected consequences of low- and high-pressure SDG strategies. Strategy outcomes are measured by five environmental indicators—LULUCF carbon emissions, agricultural water use, deforestation, biodiversity loss, and fertilizer use—and a global food price index (FPI). Policies on the outer ring of each circle indicate the third policy in each strategy. In the **left (right)** hemisphere of each circle, strategies are ranked from top to bottom by El score (food price). Colors and percentages in each cell indicate the deviation for each indicator in year 2030 of the simulation relative to 2010.

are detrimental to tropical forests and their biodiversity (33). Conversely, case studies of biodiversity protection initiatives in low-income nations have demonstrated that deforestation restrictions can lead directly and indirectly to reductions in average household incomes in the vicinity of protected areas (34). GLOBIOM model results are consistent with these empirical observations, concluding in a fourth study that international agreements could mitigate Congo Basin deforestation, carbon emissions, and biodiversity loss but would also increase food prices by as much as 60% in the region (35).

Last, our quantitative assessment shows that land system interdependencies are more significant determinants of joint environmental and food security outcomes than are population and economic growth scenarios. This suggests that mounting trade-offs are not our demographic destiny but rather the predictable consequence of siloed policies, initiatives, and choices accreting into incoherent SDG strategies.

Application to the policy process

On the basis of these insights, we argue that SDG policy formulation at national, regional, and international scales should be more inclusive: Policy options developed by sectorial and technical specialists must also be subjected to assessments of total system effects outside the bounds of their silos. Based on the results of these assessments, strategies for SDG implementation can be classified as incoherent, neutral, or coherent.

The first class, incoherent strategies, includes any constellation of policies that magnify trade-offs in the land system due to inefficient production systems or implied restrictions on resource consumption. For example, sustainable bioenergy production and biodiversity conservation measures—both essential components of the overall SDG agenda—exacerbate trade-offs by creating opportunity costs for international and local stakeholders (34). Trade-offs can be hidden when policy planners neglect the interests of, for example, smallholder farmers, leading to the underestimation of policies’ costs and their disproportionate distribution among and within national economies (36). SDG strategies crafted without the benefit of an integrated systems perspective are unlikely to anticipate these trade-offs, leading to problem-shifting and potentially magnifying the challenges facing sustainable development agendas. In the worst cases, incoherent strategies could put many of the SDG objectives out of reach by 2030.

The second class includes neutral strategies, which seek merely to avoid intensifying trade-offs between land and food systems. As shown in Fig. 2 (right), half-measures in most policy clusters negotiate but do not transform the efficiency frontier of trade-offs between environmental and food systems. In particular, GHG pricing (GHG \$50) avoids magnifying trade-offs even when implemented ambitiously by incentivizing resource-use efficiency and land sparing across multiple economic sectors and spatial regions. This is consistent with

the recent experience of China, which established its emissions trading systems in part to distribute the high economic costs of national energy intensity targets (37).

Pressure-neutral policies can also be used to prioritize the rehabilitation and sustainable management of critical ecosystems and ecosystem services. For example, “hotspot” strategies, which identify and prioritize conservation of ecosystems that support the highest concentrations of endemic species, may be able to avoid mass extinctions by setting aside less than 2% of global land area (38). In pursuit of food security, researchers have similarly identified “leverage points” or location- and crop-specific strategies for boosting global food production while minimizing environmental impacts (39). These approaches seek to maximize the contribution of initial economic and natural resource outlays to long-term conservation or food security agendas and should be pursued as a first step toward SDG operationalization.

Finally, coherent SDG strategies are those that minimize trade-offs between the land and food systems. In many countries, future demand for meat and animal products will have a major impact on resource availability and food security trends. In developed economies, shifts away from these land- and water-intensive commodities (that is, Diet+) can also reduce the health-related costs of overconsumption, including mortality. At the same time, such a shift would decrease food prices in developing countries, reduce mortality and deforestation, and enable progress toward food security for all (goal 2). In the same way, investments in agricultural resource efficiency, spoilage prevention, and waste mitigation can reduce land system pressure and minimize the overall costs of SDG strategies.

Coherent SDG strategies are founded on SCP policies. They combine innovations, investments, and incentives to escape zero-sum outcomes and achieve net positive progress toward the SDGs as a whole (40). In recognition of this, the focus of the German sustainable development agenda has shifted from land, water, and soil pollution mitigation to resource productivity gains in the last decades (23). SCP policies have likewise been incorporated into national action plans for economies as diverse as South Africa, Japan, and China to manage energy and resource consumption and decouple economic growth from environmental degradation (23). Even when trade-offs between coequal goals cannot be eliminated entirely, SCP policies allow policy-

makers to manage competing pressures proactively and create simultaneous solution spaces for the largest possible number of SDGs.

Research outlook

Our analysis is a first step toward understanding the land resource nexus of the SDGs. We expect that our integrated approach can serve as a model for further research into relationships among nutrition, waste, education, energy, and environmental goals. In this field, the relative intensities of pressure, trade-offs, and cobenefits will, of course, depend on the scope of each analysis and, in particular, the indicators used to measure outcomes. However, the dynamics we have probed are real insofar as they predict *ex ante* the consequences of actual shifts to land resource policies. Within any scope, integrated systems analyses can elucidate efficiency frontiers and identify policies that minimize problem-shifting, among other obstacles, to simultaneous achievement of multiple SDGs. We expect that these efforts will contribute to coherent and comprehensive policy planning at all levels, starting with joint programming among the three Rio Conventions on climate change, biodiversity, and desertification.

Future iterations of global assessments could be improved with more abundant and more accurate global Earth observations and data sets on issues ranging from improved land cover products (41) to spatially explicit data on crop management practices. In addition, the precise effects of policy options on food security and other SDGs would bear more detailed analysis because the global indicators used here mask ecosystem-, region-, and crop-specific complexities.

Upon the formalization of the SDG targets, countries will be expected to develop strategies for SDG operationalization that reflect their individual expected contributions to global outcomes. Therefore, similar analyses should be replicated at the national level not only to evaluate and refine prospective policies but also to improve the representation of biophysical and technological parameters in global assessments. These efforts could help reveal the comparative advantages of individual countries—a dimension absent from this analysis—and lead to tailored-but-coherent strategies for managing the global commons.

MATERIALS AND METHODS

Scenario construction

This analysis connects with and builds on previous work by identifying seven thematic policy clusters, each of which is defined by a set of closely related sustainable development goals or targets (cf. Fig. 1 and Table 1). The wide-ranging goals and targets can be partitioned into any number of thematic clusters. However, the structure of this analysis reflects that of cutting-edge research on these issues as well as the agendas of nongovernmental organizations and other lobbying interests, national and supranational bodies, and international organizations. Consequently, policy clusters provide a convenient starting point for broadly integrative analyses, such as this one.

Each of the seven clusters was assigned a triplet of policies, or discrete potential responses to the goals and targets within its scope. Each triplet included a singular null policy, which projected the continuation of BAU vis-à-vis the associated environmental or developmental goals, and two active policies, which described discrete shifts from BAU undertaken on a global scale in service of the same targets.

Table 2. Indicators used to evaluate SDG strategies. Each SDG strategy is scored according to its effect on five environmental indicators of planetary boundaries—LULUCF carbon emissions, agricultural water use, deforestation, biodiversity loss, and fertilizer use—and on global food prices in years 2030 and 2050 of the simulation. The SDGs relevant to each of the planetary boundaries are indicated, thus closing the policy process and pressure-state-response (PSR) loops. All metrics refer to globally aggregated results from the GLOBIOM model.

Pressure indicator	SDG targets	Units
Food price index	2	—
LULUCF emissions	13	$\frac{\text{MtCO}_2\text{eq}}{\text{year}}$
Agricultural water use	6	km^3
Deforestation	6, 13, and 15	10^3 ha
Biodiversity loss	15	10^3 ha
Fertilizer use	2 and 13	10^3 ton

By construction, each triplet of policies spanned a range of ambition from inaction (BAU) to committed action toward the relevant targets (cf. Fig. 1 and Table 1; full description in section S1.3). As a result, the policies within each cluster are mutually exclusive.

With this arrangement, policies in distinct clusters can be combined systematically to form integrated SDG strategies, which we defined as any and all policies enacted on a global scale in response to the SDG agenda. Strategies were constructed by specifying exactly one policy from each of the seven policy clusters. In this analysis, we evaluated three types of strategies: null, single-policy, and compound. The null strategy projected a future in which zero active policies are enacted (that is, null policies in all seven clusters). Single-policy strategies were composed of exactly one active policy in one policy cluster (and null policies in the remaining six clusters). Compound strategies included active policies in two or more policy clusters (and null policies in all remaining clusters).

Last, each strategy was combined with one of three SSPs, which jointly spanned a range of assumptions about global socioeconomic drivers, including, most relevantly, population and per capita income growth (26). The pairing of any SDG strategy with an SSP formed a complete, unique scenario in the GLOBIOM, which projected the effects of each scenario on global food prices and environmental indicators decennially through 2050.

The GLOBIOM model

GLOBIOM is a recursive dynamic partial equilibrium model of the global agriculture and forest sectors (27–30). The model computes market equilibrium for agricultural and forestry products by allocating land use among production activities to maximize the sum of producer and consumer surplus within a set of dynamic demand, resource, and technological and policy constraints. The model was run over the period of 2000–2050 at decadal intervals.

To calculate the demand, GLOBIOM partitioned the world into 57 economic regions. Within each region, FAOSTAT data were used to calibrate agricultural commodity prices in year 2000 for 18 major crops (barley, dry beans, cassava, chick peas, corn, cotton, groundnut, millet, potatoes, rapeseed, rice, soybeans, sorghum, sugarcane, sunflower, sweet potatoes, wheat, and oil palm) and seven livestock products (bovine meat and milk, small ruminant meat and milk, pig meat, poultry meat, and eggs). These crops represent more than 70% of the total harvested area and 85% of the vegetal calorie supply, as reported by FAOSTAT (28).

From these initial conditions, the model calculated demand for commodities within each region and bilateral trade flows among them endogenously on the basis of population, per capita income, production costs, and equilibrium prices (including tariffs and transportation costs and capacity constraints). Demand is functionally represented by a stepwise linearized function with constant own-price elasticities from the U.S. Department of Agriculture (42).

Commodity supply was calculated using biophysical models on a grid with cells ranging from 5×5 to 30×30 arc min. Cells were delimited taking into account dominant soils, climate, topography, and national borders, which are leading drivers of spatial heterogeneity in agricultural productivities. Agricultural and forest production in each grid cell was determined by cell-specific agricultural and silvicultural yields (dependent on suitability and management), international and regional market prices and access (reflecting the level of demand), and the conditions and cost associated with land conversion and production expansion.

GLOBIOM has been used in detailed analyses of the socioeconomic and environmental impacts of land use and agricultural policy shifts, as discussed at greater length in section S2 (28–31). A full discussion of the mapping of SDG targets and policies to GLOBIOM parameters, the construction of SDG strategies from policy clusters, and the statistical methods used is included in sections S3.2 and S3.4.

Scenario evaluation

Because most of the SDG targets have not yet been quantified, we examined the GLOBIOM scenario results for a relationship between global food prices and five planetary boundaries, which collectively served as dynamic indicators of trade-offs between global agricultural and environmental systems (cf. Table 2) (6).

The food price index represented a weighted average of the equilibrium price of the 18 crops and seven livestock products modeled in GLOBIOM across all 57 regions. Food price index values were calculated in 2030 and 2050 and reported as percent changes from the 2010 value of the same index.

The five environmental indicators were normalized to the range (0 to 1), and then a simple average was taken to derive decennial EI scores for each SDG strategy. For individual indicators and EI scores, values near “0” corresponded to the worst environmental outcomes in year 2030 among the integrated SDG strategies analyzed, whereas scores near “1” signified the best.

The raw (prenormalized) values that define the “worst” and “best” outcomes for all six indicators are listed in section S3.1. Raw and normalized scenario results for all indicators in all scenarios are tabulated in section S3.5.

Statistical analysis

Linear regression statistics are reported for each fit in Figs. 2 and 3. In the set of single-policy strategies only, Diet+ strategies for each SSP are excluded as extreme outliers using Grubbs’ test for outliers at the 0.02 significance level ($N = 14$ degrees of freedom).

We used a probability plot of fit residuals to assess the appropriateness of a linear regression fit to single-policy and low- and high-pressure strategies (cf. Figs. 2 and 3). For all three sets, the test returned an r^2 value near unity (cf. figs. S13 to S15), indicating that the correlation is significant and that our finding of a linear correlation relationship between these scenario results is appropriate.

Pressure

To aid in the interpretation of GLOBIOM scenarios, we applied the heuristic concept of pressure, defined as degradation of the assimilative capacity of the land system caused by anthropogenic activities and policies (43). Major sources of pressure include air, water, and soil pollution, emissions, or other waste; overuse of environmental resources, including land; and land-use change (44, 45).

Pressure is an essential component of the PSR framework, a paradigm for tracing land system responses to both proximate causes and underlying driving forces of change (46–48). In this framework, “human activities exert pressures on the environment and change its quality and the quantity of natural resources (the ‘state’ box). Society responds to these changes through environmental, general economic and sectorial policies (the ‘societal response’). The latter form a feedback loop to pressures through human activities” (44). Variants of the PSR framework are widely used in integrated assessments of ecosystems and management strategies and have been adopted by several international

organizations, including the Organization for Economic Cooperation and Development and the World Health Organization (44, 45).

The assimilative capacity of the land system is closely related to both supply- and demand-side constraints on natural resources. These constraints are reflected in both the “normal” functioning of agricultural and environmental systems—their capacities to meet demand for food, health, resources, biodiversity, and other essential ecosystem services—and their vulnerability to future anthropogenic or natural shocks (43, 44). Through their direct and indirect effects on resource supply and demand, SDG policies can govern both the magnitude and distribution of pressure throughout the land system, and this results in linked outcomes—that is, trade-offs and cobenefits—among disparate SDG objectives.

Because SDG policies are assembled into strategies, pressure manifests in the intensity of trade-offs between coeval goals. When resource-use efficiency is held constant, global economic development spurs demand for commodities, which increases pressure on the land system and raises the prospective costs of essential conservation policies. At the same time, evolving resource limitations, whether due to conservation policies or due to natural or man-made scarcities, can generate opportunity costs that strain the assimilative capacity of agricultural and economic systems.

This analysis seeks to examine the pressure that conservation policies can place on agricultural systems and, by extension, food security. For example, land-use change restrictions in support of biodiversity and emissions mitigation can increase pressure on food production systems by limiting their capacity to expand in response to market shifts, climate change, or soil degradation. Expanded bioenergy production may further the essential goal of energy sector decarbonization, but it also increases demand for arable land, fresh water, and fertilizers and therefore increases food system pressure. Conversely, investments in resilient and high-intensity production systems, waste reduction, and reduced meat consumption can reduce pressure by improving resource-use efficiency.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at <http://advances.sciencemag.org/cgi/content/full/2/9/e1501499/DC1>

- section S1.1. Overview of the general approach to the SDG land resource nexus.
- section S1.2. Quantitative approach to modeling trade-offs and cobenefits.
- section S1.3. Developing policy clusters in association with SDG targets.
- section S1.4. Defining SDG strategies from individual policy alternatives.
- section S2.1. The analytical framework for modeling SDG scenarios.
- section S3.1. Indicators for assessing SDG strategies.
- section S3.2. Normalized scores.
- section S3.3. EI scores.
- section S3.4. Fit statistics.
- section S3.5. Complete GLOBIOM scenario results.
- fig. S1. Diagram illustrating the conceptualization of the analysis.
- fig. S2. SDG clusters, policies, and strategies.
- fig. S3. Future primary energy supply from biomass.
- fig. S4. Short-rotation tree plantation areas.
- fig. S5. Indicators of environmental performance of Global Energy Assessment scenarios.
- fig. S6. Aggregate crop yield projections by SSP.
- fig. S7. Historical and projected global food consumption.
- fig. S8. Global consumption patterns of livestock products.
- fig. S9. Diagrammatic illustration of the GLOBIOM model.
- fig. S10. Graphical representation of interactions among policy clusters.
- fig. S11. Representation of SDG scenario output and evaluation.
- fig. S12. Spider charts showing GLOBIOM results for three SDG strategies (in three SSPs).
- fig. S13. Normality test on fit residuals from single-policy strategies.
- fig. S14. Normality test on fit residuals from depressurizing strategies.
- fig. S15. Normality test on fit residuals from pressurizing strategies.

fig. S16. Circular plots for SSPs 1 and 3.

table S1. Overview of definitions for three food system resilience policy cluster policies.

table S2. Projected change in meat consumption per capita.

table S3. SDG strategy definition table.

table S4. GLOBIOM scenario results (values and normalized scores) for SSP1 scenarios.

table S5. GLOBIOM scenario results (values and normalized scores) for SSP2 scenarios.

table S6. GLOBIOM scenario results (values and normalized scores) for SSP3 scenarios.

table S7. GLOBIOM scenario results (values and percent deviation from 2010 value, at top) for SSP1 scenarios.

table S8. GLOBIOM scenario results (values and percent deviation from 2010 value, at top) for SSP2 scenarios.

table S9. GLOBIOM scenario results (values and percent deviation from 2010 value, at top) for SSP3 scenarios.

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