Global and regional health and food security under strict conservation scenarios.

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Abstract

Global biodiversity is rapidly declining and goals to halt biodiversity loss, such as the Aichi Biodiversity Targets, have not been achieved. To avoid further biodiversity loss area based protection will form part of new biodiversity targets. We use a state of the art global land use model, LandSyMM, to explore global and regional human health and food security outcomes under strictly enforced 30% and 50% land protection scenarios. We find protection scenarios cause additional human mortality due to diet and weight related changes. Low income regions such as South Asia and Sub-Saharan Africa experience the highest levels of underweight-related mortality, causing an additional 200,000 deaths related to malnutrition in these regions alone. High income regions in contrast are less affected by protection measures. Our results highlight that radical measures to protect areas of biodiversity value may jeopardise food security and human health in the most vulnerable regions of the world.

Background

The Convention on Biological Diversity committed to halting biodiversity loss [1], however international agreements, such as the Strategic Plan for Biodiversity 2011–2020 and the associated Aichi Biodiversity Targets, have been mostly unachieved [2,3]. In response to previous shortcomings and to avoid further species extinctions, high-level area-based targets form an integral part of the post-2020 Global Biodiversity Framework discussions [4]. However, conservation measures will need to be scrutinized to ensure their implementation does not compromise other Sustainable Development Goals. In particular, global area based targets will require extending protected areas and restoring natural land [5–7]. If this expansion restricts agriculture then the consequences may be felt in food production sectors with reduced food provisioning potentially compromising food security goals and human health, particularly in vulnerable regions [8]. The impacts of strict area-based conservation measures on food security and health however remain poorly understood [8,9]. Furthermore, studies of human and biodiversity interactions have been typically conducted at global scales, despite calls to ensure regional variations are considered [10,11]. Given existing food security inequalities, it is important to consider the impacts of conservation measures on human health and nutrition in a spatially explicit manner [12].

Here we use a state-of the art integrated assessment modelling framework of the land sector, LandSyMM [13], to address such gaps. LandSyMM combines spatially-explicit biophysically-derived yield responses and land constraints, such as protected areas, with socio-economic scenario data to project future land use and management inputs and demand for, and trade of, agricultural commodities. We identify priority areas that contribute the most to species extinction prevention using an optimization approach and for this study make the assumption that by 2040, 30% and 50% of the earth's terrestrial surface is strictly protected from human use. Results from the protection scenarios are compared with reference outcomes parameterised to align with the 'Middle of the Road' Shared Socio-economic Pathways scenario, SSP2; under SSP2 future socioeconomic trends largely follow historical patterns. Following the methodology of Springmann[14,15], we investigate the human health and food security consequences of stringent protection by calculating the number of additional deaths due to changes in dietary and weight-related risk factors compared to the reference scenario.

There is a gradation of views as to the role agriculture can play within conservation areas, for example, in the global safety net (GSN) proposed by Dinerstein *et al.* [16], the proposed protected areas are allocated depending upon remaining 'intact' land and species rich areas. The Three Conditions framework proposes an expansion of protected areas that are a supported by sustainable resource extraction[17]. Waldron *et al.*[18] explore a range of scenarios where human activities are excluded from protected areas or permitted at sustainable levels, while Strassburg *et al.* [19] identify agricultural lands with the greatest biodiversity potential globally if restored to their natural state [20,21]. Recently, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) have developed the Nature Futures Framework (NFF). This framework aims to provide a structure for designing normative scenarios that investigate relationships between people and nature [12]. Our stylised protection scenarios can be considered an extreme form of the 'Nature for Nature' aspect of the NFF, characterised as strict protection that separates nature from human pressures, and thus do not directly represent any existing proposals. The potential pitfalls associated with strict area-based conservation are frequently discussed[22,23], however few studies have tested hypotheses on the consequences of extended strict protection for human well-being. Here, we do not advocate for strict protection measures but rather quantify some of the impacts that such extreme potential management actions could entail.

Results

Between 2020 and 2040 in the 30% and 50% protection scenarios, biodiversity protection is gradually implemented across the terrestrial land surface such that by 2040, 30% and 50% of the Earth is assumed to be under stringent protection (Supplementary Figure 2). Such extreme levels of protection and human exclusion have repercussions in the modelled results for food production. In the 50% protection scenario 55% of protected areas lie within the subtropical belt and in the 30% protection scenario 63% lie within the subtropical belt (Supplementary Figure 2). Consequently, agricultural land is shifted away from optimal growing areas in these regions and into higher latitudes, particularly in the 50% protection scenario (Supplementary Figure 4). This has the effect of reducing food supply while demand continues to increase with population growth. When demand exceeds supply, food prices increase, which reduces food consumption. This has positive health effects through the reduction of obesity and red meat consumption but negative health effects through increasing levels of undernutrition and reduced fruit and vegetable consumption. Implicitly, reducing levels of obesity reduces the risk of cancer, stroke and coronary heart disease and especially diabetes while reducing red meat consumption is particularly important for reducing the risk of colorectal cancers (Supplementary Table 2). Conversely, reducing fruit and vegetable consumption increases the risk of cancer, stroke and coronary heart disease while being underweight increases the risk of cancer and death due to other causes (Supplementary Table 2).

Strict land protection has disparate regional health impacts

Compared to 2019, in all three scenarios, there are additional diet and weight related deaths driven by increased levels of obesity, increased red meat consumption and reduced fruit and vegetable consumption (Table 1, upper section). However, compared to the Reference scenario, the protection scenarios increase global mortality by further reducing fruit and vegetable consumption and maintaining higher levels of underweight related mortality (Table 1, lower section). In 2060, 30% and 50% land protection increases total global mortality by 4%, equivalent to an additional 31 and 28 deaths per million people, respectively (Figure 1). The additional diet and weight related mortality in the protection scenarios is caused by increased food prices relative to the Reference scenario (Figure 3). The net additional mortality is similar in the protection scenarios, despite higher prices in the 50% scenario, because of non-linear dynamics in the demand system. Both fruit and vegetable consumption and red meat consumption respond to prices in a non-linear fashion, such that there is a minimum subsistence amount of fruit and vegetable or red meat eaten, regardless of price. Thus once this threshold is reached consumption of fruit and vegetables cannot decrease further and there are no additional deaths. Thus in the 50% scenario the increase in deaths from reduced fruit and vegetables has proportionally decreased because consumption has reached minimum thresholds in some countries. Meanwhile meat intake does not reach the minimum thresholds and is at a price point in the 50% scenario where consumption is greatly reduced compared to the Reference scenario. Here we find the avoided mortality from reduced red meat consumption to increase proportionally. The proportional changes in fruit, vegetable and red meat consumption shifts the balance between additional and avoided deaths in the 50% scenario such that 81% of additional mortality is offset by avoided mortality compared to only 56% in the 30% scenario.

The protection scenarios reduce fruit, vegetable and red meat consumption compared to the Reference scenario (Supplementary Table 5, Supplementary Figure 5, Supplementary Figure 6). In both scenarios this results in a net increase in mortality, compared to the Reference scenario, from dietary causes (Table 1, lower section). While the net global and regional effects of 30% and 50% protection are similar, changes in dietary risk exposure and associated mortality are much larger in the 50% scenario compared to the 30% scenario (compare width of bars in (a) and (b) of Figure 1). Reduced fruit and vegetable consumption increases deaths globally by 377,000 in the 30% protection scenario and by 691,000 in the 50% protection scenario (Table 1). Reduced red meat consumption reduces global mortality by 93,000 in the 30% protection scenario and by 297,000 in the 50% protection scenario. Therefore in both scenarios the benefits of lower red meat consumption are overwhelmed by the negative consequences of decreased fruit and vegetable consumption.

Likewise, differences in weight risk exposure are much larger in the 50% scenario compared to the 30% scenario. At a global level, the protection scenarios reduce average BMI such that there are 167,000 and 448,000 fewer obesity and overweight related deaths in the 30% and 50% scenarios respectively (Table 1). However, reducing BMI also increases the number of underweight related deaths by 87,000 in the 30% scenario and by 236,000 in the 50% scenario compared to the Reference scenario. Thus, the increase from 30% protection to 50% protection almost triples the additional underweight related mortality in 2060.

There are clear differences in the rate of underweight-related deaths between developing and developed countries. South Asia and Sub-Saharan Africa have the largest additional underweight-related deaths in 2060 compared to the Reference scenario in both the 30% and 50% protection scenarios. In the 50% protection scenario, South Asia and Sub-Saharan Africa have an average of 75 and 44 additional underweight related deaths per million people, equivalent to 196,000 additional deaths in absolute terms (Figure 1, light blue bars). Thus additional underweight related deaths in these regions account for 83% of all global additional underweight related deaths. In contrast, developed regions such as North America and Europe and Central Asia have the lowest additional underweight-related deaths in 2060 compared to the Reference scenario, both with a rate of 3 additional deaths per million people, equivalent to 3717 additional deaths in absolute terms (Figure 1, light blue bars). In 2019, South Asia and Sub-Saharan Africa are the regions with the lowest calorie consumption and subsequently the highest underweight population fractions, 22% and 16% respectively (Supplementary Table S6). In the Reference scenario by 2060, calorie intake in these regions increases and the underweight population fraction decreases from 22% to 13% in South Asia and from 16% to 7% in Sub-Saharan Africa (Supplementary Table S6). The protection scenarios stall this decrease, however, and by 2060, the underweight population fraction in the 50% protection scenario is 14% in South Asia and 8% in Sub-Saharan Africa (Supplementary Table S6). For both regions this is a difference of 1 percentage point between the 50% protection scenario and the Reference scenario (Figure 2).

The number of underweight related deaths in South Asia explains why the difference between total mortality in the Reference scenario and the 50% scenario is greatest in South Asia, with 80 additional deaths per million people, more than double the global average. Moreover, the difference in fruit and vegetable consumption between the Reference and 50% protection scenario are greatest in South Asia (Supplementary Figure 6) and thus mortality owing to lower consumption of fruit and vegetables increases relative to the Reference scenario. This combination of additional underweight related deaths and additional deaths owing to lower fruit and vegetable consumption acts to increase the net number of additional deaths in South Asia relative to other regions.

Sub-Saharan Africa is the only region where land protection results in fewer deaths compared to the Reference scenario. In the 30% protection scenario, 10 fewer deaths occur per million people and in the 50% protection scenario, 49 fewer deaths occur per million people. Unlike other regions, the consumption of fruit and vegetables does not drop substantially in Sub-Saharan Africa compared to the Reference scenario, thus there are fewer deaths related to reduced fruit and vegetable consumption (Figure 1). The difference in fruit and vegetable consumption between the protection scenarios and the Reference scenario in Sub-Saharan Africa is smaller than other regions because of the dynamics in cross-price elasticities in food demand. Sub-Saharan Africa has the lowest income levels and experiences the greatest increase in the price of ruminant products compared to other regions. Consequently, in the protection scenarios, Sub-Saharan Africa experiences the greatest decline in ruminant product consumption compared to the Reference scenario (Supplementary Figure 6). Plant based foods are substituted for the meat products that are not consumed and, in particular, fruit and vegetables are a common substitute. Therefore, in Sub-Saharan Africa, as land protection reduces the consumption of ruminant products, levels of fruit and vegetable consumption are maintained and as such, the difference in fruit and vegetable consumption between the protection and Reference scenario is smaller for this region. While land protection may seem beneficial for Sub-Saharan Africa in terms of net mortality, Sub-Saharan Africa still experiences high numbers of additional underweight related deaths. Ultimately, net mortality falls in Sub-Saharan Africa because populations cannot afford more expensive, unhealthy meat-rich diets, this also causes greater underweight related mortality due to reduced food supply because of protection measures.

Strict land protection increases food prices and spending

Changing dietary consumption levels and weight changes in the protection scenarios are caused by increased food prices relative to the Reference scenario. Furthermore, the greater health impacts in the 50% scenario compared to the 30% scenario are driven by greater food price changes in the 50% protection scenario (Figure 3). Higher food prices in the protection scenarios also increase spending on food relative to the Reference scenario.

During 2020 to 2040, agricultural land is converted back to natural land; this reduces food production, and when demand outstrips supply, food prices increase. In the Reference scenario between 2020 and 2060 food prices decrease due to continued globalisation, climate change and improving production efficiency. With a decline in food prices, the Laspeyres price index falls for all regions (Figure 3). Between 2020 and 2040 in the protection scenarios, the food price index increases, for most regions reaches a peak in 2040. After the implementation period, post 2040, as supply and demand begin to settle and food prices start to stabilise the price index begins to drop, albeit at a slower rate than the rate of increase earlier in the time period (Figure 3). Despite the price index increase, North American and European expenditure on food remains low (Figure 3), which indicates that developed countries are buffered by price increases due to their high GDP. In contrast, Sub-Saharan Africa is still vulnerable to even small increases in food prices, as their proportional expenditure on food is the greatest. Indeed, the greatest regional spending difference between the Reference scenario and the protection scenarios is in Sub-Saharan Africa. For example, in Sub-Saharan Africa, by 2060, in the 50% scenario the percent of GDP spent on meeting food demand is 18%, compared to 12% in the Reference scenario.

Discussion

Increasing strict land protection for biodiversity causes global and regional food prices to increase, which in turn affects food security and human health. Increased food prices reduces calorie intake and the consumption of luxury food commodities, such as red meat, fruit and vegetables. Changing calorie and dietary intake has some positive health effects through the reduction of obesity and red meat consumption related deaths. However, the positive effects are outweighed across almost all world regions by increasing mortality due to increasing underweight population fractions and reduced fruit and vegetable consumption. The 50% land protection scenario results in greater levels of agricultural land resettlement and higher food prices than the 30% protection scenario. Despite this, the additional net global and regional mortality compared to the Reference scenario is similar within the two scenarios, with an additional 5.1 million deaths in 2060 alone.

Considering mortality associated with individual risk factors, rather than net mortality, is however particularly important when considering the trade-offs associated with land protection. When each of the risk factors in our analysis are considered individually, the impact of the 50% scenario is greater than the 30% scenario for all. For example, we find the levels of undernourishment are much greater as the proportion of land protection increases, with the increase from 30% to 50% protection causing an additional 149,000 underweight related deaths and almost tripling underweight related additional mortality in 2060. Similarly, the extent of protection has repercussions for spending. While both protection scenarios slow the reduction of GDP expenditure on food compared to the Reference scenario, all regions experience greater food spending in the 50% protection scenario compared to the 30% protection scenario. Thus, our results serve to highlight that area-based protection strategies will need to dissect the positive and negative repercussions for food security and health for every additional hectare of strict protection.

We find developed world regions are largely insulated from the negative effects of stringent area-based protection, and arguably reducing calorie consumption and levels of obesity is a desirable outcome; conversely, developing regions are worst affected by reduced food provisioning in terms of undernourishment. Sub-Saharan African countries currently have the highest fraction of undernourishment at a population level while countries in Asia, such as Pakistan and India, are among those with the highest absolute number of undernourished people on the planet [24]. In all of three scenarios, calorie intake increases and underweight related deaths decrease over time. However, land protection lessens the reduction of underweight related deaths, such that in the 50%

protection scenario there are an additional 236,000 deaths compared to the Reference scenario, with Sub-Saharan Africa and South Asia accounting for 83% of this additional mortality. In both the 30% and 50% scenarios, underweight related deaths per capita are highest in Sub-Saharan Africa and South Asia. Land protection therefore creates higher levels of undernourishment in regions that are already vulnerable. In a recent modelling study of area based conservation, Kok *et al.* [9] found food security risks as a result of protection measures were most prevalent in Sub-Saharan Africa and South Asia. Similarly, in our results we find that Sub-Saharan Africa and South Asia have the greatest proportion of food spending as a percent of GDP in 2019 and the impact of land protection on food spending is greatest in Sub-Saharan Africa. Our results therefore corroborate existing work that finds that food security and health impacts of strict area-based biodiversity measures are likely to be greatest in some of the most vulnerable societies of the world [8,9,25].

Despite a large number of underweight deaths, land protection results in net fewer deaths in Sub-Saharan Africa. While in our analysis reducing red meat is beneficial for reducing deaths from coronary heart disease, cancer and stroke, it is important to consider that, particularly for regions such as Sub-Saharan Africa and South Asia, access to sufficient protein is often limited. In developed regions such as North America, meat protein can be replaced by other sources because adequate food provisioning is in place. However, for the developing world the benefits from reduced rates of non-communicable disease due to reduced red meat consumption may, in reality, be outweighed by the consequences of lack of sufficient dietary protein if meat is not easily substitutable. Given the higher levels of food insecurity and underweight population fractions, we highlight that future work, that includes deaths caused by insufficient substitution of dietary protein, may find additional deaths in developing regions.

For the purpose of this study, we assume that the protection of 30% and 50% of the terrestrial land surface is stringent and agriculture is displaced from these areas. Given the current debate and uncertainty about the form that protected areas should take, our approach is clear, unambiguous but sits at the extreme end of a continuum within existing literature[4,16,18,26]. By exploring the strictest form of protection, we are nevertheless able to explore the worst-case scenario, in terms of human health. Given how extreme our assumptions are, arguably, there is a surprisingly small number of additional deaths. However, in many food insecure regions like Sub-Saharan Africa, agriculture is the main source of income for households. Economic and physical displacement of agricultural practices could further jeopardise nutrition[27] through reduced incomes and economies that we have not captured here. Conversely, relaxing the assumption of agricultural exclusion would likely reduce the detrimental effects that we, and others, find. The expansion of multi-use protected areas could in fact be beneficial for human health and well-being[28]; a recent analysis of protected areas and human well-being found households near multi-use protected areas with tourism experienced higher levels of wealth and lower likelihoods of poverty[29]. Similarly, a recent modelling exercise reported that protected areas expansion was economically beneficial through the mitigation of climate change risk and biodiversity loss[18].

The specific form of protection sought by area-based conservation is often unclear. Effective conservation will likely be determined by socio-economic, e.g. bottom-up involvement of stakeholders and land owners in planning, political and legal factors, such as country specific laws on agricultural practice within protected areas. In this regard future work could explore the consequences of protected area expansion if new protected areas reflected existing legislation and practice or if some low-impact agricultural activities are allowed to continue. Regardless of the agricultural assumptions made, global conservation prioritization methods that primarily focus on biogeography, such as the approach employed here, or degree of wilderness will commonly select regions in the tropics and indigenous lands[30]. Given that we followed a strict interpretation of the 'nature for nature' aspect of the NFF, our prioritisation maps are accordingly based on avoiding species extinctions, rather than avoiding human displacement. There are a myriad of ways land for the spatial planning of protected areas could be allocated, however, as evident by recent debates[16,27,30], the impact and role of local communities, indigenous populations and rural livelihoods will need to be explicitly considered to avoid further marginalisation of vulnerable populations[16,25,27,30]. Alternative prioritisation could be based on selecting regions with the greatest human and biodiversity co-benefits or the land most likely to be spared if yield gaps were closed. We include yield increases due to climate change and a technology change factor, but we do not explicitly test the assumption that yield gaps can be closed. If we assumed yield gaps closed then biodiversity benefits, similar to those found in existing studies[19], may be achieved without compromising food security and health.

It is clear is that the implementation and form of protected areas is a multifaceted challenge and will continue to be the subject of much contention and debate[31]. We stress that we do not here propose any type of conservation measures that will provide the optimal outcomes for meeting various SDG's. Rather our analysis can provide insight into trade-offs and upper potential impacts on global health of strict protection, thereby aiding conservation planning and negotiations involving the post-2020 Global Biodiversity Framework. We make the assumption that 'Nature for Nature' takes precedence, at the expense of agriculture activities, but this should not be taken to imply our support or advocacy for such an approach, as the design and implementation of biodiversity conservation plans at sub-national scale requires deeper considerations of local circumstances as outlined in IUCN Protected Area guidelines. Nevertheless, our analysis serves to further quantify that radical measures will lead to undesirable and unequal health and food security outcomes if implemented globally. The results from this work emphasise the need to evaluate human health and food security outcomes associated with area-based conservation, particularly in food insecure regions of the world.

Methods

LandSyMM framework

The Land System Modular Model (LandSyMM)[13], is a state of the art global land use model that couples a dynamic global vegetation model (LPJ-GUESS) with a food and land system model (PLUM). LandSyMM combines spatially-explicit, biophysically-derived yield responses with socio-economic scenario data to project future demand, land use, and management inputs. LandSyMM improves upon existing integrated assessment models (IAMs) by modelling crop yield responses in a more detailed manner at a finer grain. Furthermore LandSyMM calculates commodity demand endogenously and therefore unlike the majority of land use models, demand for commodities responds dynamically to changing commodity prices. A more detailed description of LandSyMM can be found in the SI material.

Scenarios

30% and 50% protection scenarios

The grid cell fractions designated as protected under the 30% and 50% protection scenarios are determined by a spatial conservation prioritisation approach[32]. We use vertebrate distribution data (at ~0.5° resolution) of all birds, mammals, amphibians and reptile species[33,34] . We calculate for each species the amount of area necessary for a species to qualify for a non-threatened status, thus avoiding extinction [32,35]. We then set incremental budgets of available land area (10, 20, 30, 40, and 50% of the global land surface area) and minimize for each species globally the shortfall in reaching those targets, hierarchically locking in proportions of selected grid cells from lower budgets and encompassing the existing World Database of Protected Areas (Stand April 2019). To account for intraspecific variation and to coarsely represent ecological and genetic diversity of a species, we subdivide each species' range into multiple conservation features using data on the distribution of terrestrial biomes [6]. By splitting a species range into several separate features, we thus place greater emphasis on the importance of subpopulation covering multiple biomes, which might be locally important, which resulted in shifting some importance away from tropical biomes which have usually the highest conservation value. Further details on the prioritization approach can be found in Jung et al.[32] however we highlight that we – differing from Jung et al. - assume that strict protection is to be implemented in those priority areas. All optimizations are solved using the Gurobi optimization software (ver. 8.1)[36] in an integer linear planning approach with the prioritizr package [37]. To create the protection scenarios we here take the priority areas that cover 30% and 50% of the global land surface respectively. Our analysis does not include a count of the number of people affected by economic or physical displacement of protected areas because our analysis is at the scale of individual grid cells for future scenarios up to 2060 for which – to our knowledge - there does not exist any estimates on projected human population numbers at sufficient resolution.

The socio-economic and climate settings for the protection scenarios are the same as those for the Reference scenario, detailed below. However, in the protection scenarios we assume that by 2040 30% and 50% of the terrestrial land surface is stringently protected from agricultural use. Our scenarios are therefore situated at the extreme end of conservation implementations, strictly adhering to the 'Nature for Nature' aspect of the Nature's Future Framework, characterising a form of conservation that separates nature from human pressures. Between 2020 – 2040 the protection regimes are gradually implemented. In a grid cell with sufficient natural land available to protect, the fraction of natural land requiring protection becomes immediately protected in 2020. However, in grid cells where the fraction of natural land is less than the fraction of protected area required, existing cropland or pasture are gradually removed such that by 2040 the fraction of natural land in a cell is equal to the fraction required to be protected (Supplementary Figure 2). We assume that urban areas are unaffected by protected areas. LandSyMM land covers are initialised from Land Use Harmonisation version 2(LUH2)[38]. Throughout the simulations, urban and barren (here defined as unusable for agriculture, such as water or ice covered) land areas are static while agricultural land and natural lands can change. Agricultural land is defined as land that is managed for the production of food and feed, such as cropland and pasture, while natural land is not used for agricultural production and consists of primary or secondary natural vegetation that can include afforested land. 2040 was chosen at the end of the implementation period as it is a midpoint between two commonly proposed strategies, 30% by 2030 and 50% by 2050. This also ensures that once the implementation of protection is achieved the modelled dynamics have the same length of time to settle, regardless of the area of protection, before the analysis year of 2060.

Results from the protection scenarios are compared with outcomes from a Reference, 'Middle of the Road' Shared Socio-economic Pathways (SSP2) scenario, detailed below.

Reference scenario

In the Reference scenario the proportion of protected land within a grid cell is calculated using data from the WDPA database[39]. This equates to 1933 Mha or 14.7% of the modelled land surface. In cells where agricultural land already exceeds the area specified as protected, agricultural land is permitted to remain within the protected areas however it cannot further encroach on natural land.

Socioeconomic parameters, population trajectories and GDP trajectories follow the “middle of the road” SSP scenario (SSP2), with trends largely exhibiting historic patterns [40,41]. GDP levels and endogenously calculated food prices drive per-capita demand for food. Under SSP2 GDP continues to increase, driving a shift away from staple crops towards increased consumption of meat, milk, fruit and vegetables (Supplementary Figure 1). Within SSP2 we assume moderate yield increases of 0.2% per annum due to technological development and management improvement. The climate and atmospheric CO_2 forcing scenario RCP 6.0 is used as it considers the Representative Concentration Pathway [42] most consistent with SSP2 [43]. Forcings are taken from the 1850–2100 IPSL-CM5A-MR outputs from the Fifth Coupled Model Intercomparison Project (CMIP5). While we do not explicitly model bioenergy, demand for bioenergy is important to include as it is an additional pressure on the land system. Demand for first-generation bioenergy is modelled from an observed baseline level in 2010 [44,45] after which it is adjusted to double by 2030 and thereafter remain constant. Global demand for dedicated second-generation bioenergy crops increases to 3263 Mt DM/year by 2060, in line with the SSP2 demand with baseline assumptions [46]. A Monte Carlo approach to explore uncertainty associated with input parameters is used and parameters are sampled using a Sobol sequence method with n = 30, more details about the incorporation of uncertainty can be found in the supplementary material.

Analysis

Food price index

We calculate a Laspeyres food price index (1) per country *(c)* by calculating how much it would cost to meet demand from the base period (year = 2019), for the eight food commodity groups (*f,* cereals, sugar, fruit and vegetables, ruminant meat, monogastric meat, oilcrops, pulses, starchy roots), in the current period (*t*) given current country specific prices (*p*). The Laspeyres food price index there represents the cost of a basket of goods in a given year compared to the base year.

$$food\ price\ index_{c,t} = \frac{\sum_f demand_{f,c,t=2019} \cdot p_{f,c,t}}{\sum_f demand_{f,c,t=2019} \cdot p_{f,c,t=2019}} \qquad (1)$$

Expenditure

We calculate the expenditure on food in relation to GDP to account for GDP changes over time. The expenditure is calculated as the percent of the GDP in a year in a country that is spent meeting demand for food.

$$expenditure_{c,t} = \frac{\sum_f demand_{f,c,t} \cdot p_{f,c,t}}{GDP_{c,t}} * 100 \qquad (2)$$

Population weight distributions

We calculate the proportion of the population that is underweight (BMI < 18.5), normal weight (BMI 18.5-25), overweight (BMI 25-30) or obese (BMI 30+) in each country and given year by estimating the mean BMI to use as input in a log normal distribution[15]. We estimate the mean BMI of a country's population using the following relationship:

$$meanBMI_{c,t} = 11.9 + coef_c + kcalPc_{c,t} \cdot 0.0037 + \ kcalPc_{c,t}^2 \cdot \ -0.0000002 + percAP_{c,t} \cdot 0.2276 + percAP_{c,t}^2 \cdot -0.0046 + \ \varepsilon \tag{3}$$

where $coef_c$ is a country fixed effect, *kcalPc* is the average calorie consumption per person per day in a country, *percAP* is the percentage of daily calories consumed in the form of animal products in a country, and ε represents the error term. The relationship in Eq. 3 was estimated by regressing food consumption data from FAOSTAT with WHO estimates of mean BMI for the years 2000 - 2017 (R^2 = 0.87, Supplementary Figure 3).

We use the estimated mean BMI of a country to calculate the different population weight proportions for a given timestep according to a log normal distribution with a mean:

$$mean_t = \ Log(meanBMI_{c,t}) - \frac{\sigma_c^2}{2} \tag{4}$$

and standard deviation:

$$sd = \ \sigma_c \tag{5}$$

Where σ_c is constant over time and calculated by fitting a log-normal distribution to WHO estimates of mean BMI and the prevalence of underweight, overweight and obesity in 2010 using a cross-entropy method. The cross-entropy approach estimates the parameters of the log-normal distribution by comparing two probability distributions and minimising the Kullback-Leibler Divergence.

Deaths avoided

We followed the methodology of Springmann *et al.* [14,15] to calculate the number of additional deaths a counterfactual scenario (30% protection, 50% protection) compared to a reference scenario. We isolate the effects of changes in dietary and weight-related risk factors between 2019 and 2060 by comparing the year 2060 in the three scenarios against a baseline with death rates and population structures of 2060 but diets and BMI levels from 2019. We use 2019 as a baseline year as the implementation of 30% and 50% protection begins in 2020. Calculating the mortality differences between the Reference scenario and the protection scenarios in 2060 also allows us to estimate the impacts of the 30% and 50% protection.

We considered deaths caused by coronary heart disease (CHD), stroke (STR), colorectal cancer (CRC), all cancers (TOC), type-II diabetes (DIA) and other causes (OTH) from diet and weight related risk factors. We included three dietary risk factors (reduced fruit, reduced vegetable and increased red-meat consumption) and four levels of weight-related risks (underweight, normal weight, overweight, obese). The number of deaths avoided in country (*c*) in year (*t*) for disease (d) according to risk factor (*f*) in age group (*a*) was calculated according to:

$$\Delta deaths_{c,t,d,f,a} = DR_{c,d,a} \cdot P_{c,t,a} \cdot PIF_{c,t,d,f}$$

(6)

Where DR is the death rate taken from the Global Burden of Disease Project for the year 2019 [47]. P is the population size of the age group; population size and demographic changes for each country were projected based on SSP2 from the IIASA database [21,48]. The population impact fractions (PIF) are the proportions of mortality that would be avoided if the risk exposure were changed from the Reference scenario to the protection scenarios, while the distribution of other risk factors in the population remain unchanged.

For the dietary risk factors, the PIFs were calculated as follows:

$$PIF_{c,t,d,f} = 1 - \frac{RR_{d,f}^{cm_{c,t,pr}/s_f}}{RR_{d,f}^{cm_{c,t,ref}/s_f}}, \qquad f = (red\ meat\ intake, fruitveg\ intake)$$

(7)

where RR is the relative risk of disease/mortality cause for the risk factor. The relative risk factors were taken from Springmann et al.[33] and are given in Supplementary Table 2. For the dietary risk factors, it was assumed that the whole adult (>= age 20) population of a country experiences the risks associated with its consumption level (*cm*) measured in g/capita/day. We assumed serving sizes (*s*) of 100g [15]. The relative risk is raised to the power of the consumption level over the serving size. Consumption levels are indexed by *pr* and *ref* for their levels in the protection scenarios and Reference scenario, respectively. The commodities included in the dietary risk categories are listed in Supplementary Table 2.

For the weight related risk factors the PIFs were calculated as follows:

$$PIF_{c,t,d,f} = 1 - \frac{\sum_w P_{c,t,w}^{pr} \cdot RR_{d,w}}{\sum_w P_{c,t,w}^{ref} \cdot RR_{d,w}}, \qquad w = \begin{pmatrix} underweight, normal\ weight, \\ overweight, obese \end{pmatrix}$$

(8)

where the relative risks *RR* are differentiated by disease *d* and weight category *w*. The proportions of the population (*P*) in the different weight categories are differentiated by country and year.

We calculated the combined disease and mortality burden of changes in dietary risk factors and weight risk factors using the following equation:

$$PIFtot_d = 1 - \prod_f \left(1 - PAF_{d,f}\right),\ f = \begin{pmatrix} weight, red\ meat\ intake, \\ fruit\ intake, veg\ intake \end{pmatrix}$$

(9)

where PIF_{TOT} is the final PIF for a given disease after all PIFs for risk factors (*f)* have been combined.

Data availability

The LandSyMM output data used in this study is available through figshare, doi: https://doi.org/10.6084/m9.figshare.17111687.v1. Food consumption data were accessed through FAOSTAT (https://www.fao.org/faostat/en/), BMI data were access through the WHO global health observatory database (https://www.who.int/gho/database/en/) , disease and mortality data were accessed through the global health data exchange (http://ghdx.healthdata.org/gbd-results-tool).

Code availability

LandSyMM model code is available on request from the authors.

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Contributions

RCH,AA, PA, MDR developed the idea. RH, FW, SR and MJ contributed to method development and data analysis. RCH wrote the manuscript and all authors contributed to editing and reviewing the manuscript and approved the final version for submission and publication.

Declaration of interest

The authors declare no competing interests.

Tables

Figure legends

Table 1: Upper section: Average absolute number of additional global deaths in 2060 in the Reference, 30% and 50% scenarios, using 2019 diets and weight levels as a baseline for comparison. Lower section: Additional global deaths in 2060 due to strict protection. We calculate the difference between the number of additional deaths in the Reference scenario and the protection scenarios in a pairwise manner. Equivalent model runs are paired and the mean and 95% confidence intervals of the differences calculated. The 95% confidence intervals are displayed in brackets and negative values represent fewer deaths. The sum of the individual risk factors for a region can be lower than the total deaths as individual risks can be attenuated and/or compensated when combined with other risk factors.

Figure 1: The health effects of protection measures in 2060. The results here show the difference in deaths in 2060 between the (a) 30% and (b) 50% protection and the reference scenarios. The number of additional or fewer deaths per million people for each world region are shown. Colours represent the different risk factors. Points represent the mean total change in deaths, and error bars show the 95% confidence intervals (n=30). The sum of the individual risk factors for a region can be lower than the total change in deaths as individual risks can be attenuated and/or compensated when combined with other risk factors.

Figure 2: Difference in the percentage points of each regional population in the four BMI weight categories between the Reference scenario and (a) 30% and (b) 50% protection scenarios in 2060. Y axis values not equal to zero indicate changes as a result of the protection scenarios. Columns represent the mean with 95% confidence intervals error bars (n=30). Regional values are a weighted average using country population sizes as the weighting within the region.

Figure 3: Laspeyres food price index (a,b,c) over time for different world regions in the three scenarios. Food spending as a percent of GDP (d,e,f) over time for different world regions in the three scenarios. The regional index and expenditure are calculated by taking a weighted average of the country specific price index and expenditure in a region according to country population size. The median and standard deviations are shown (n=30).

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