Climate-driven losses in soybean suitability threaten iron and zinc supply for millions in the Global South

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Climate-driven losses in soybean suitability threaten iron and zinc supply for millions in the Global South

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Abstract

Recent studies have documented the growing impact of climate change on global agriculture. Yet, the nutritional impacts of these changes remain largely overlooked, especially for key crops like soybeans, one of the world's richest plant sources of iron and zinc, nutrients for which over a billion people remain at risk of deficiency. Here, drawing on advances in spatial modelling and nutrient mapping, we present the first global assessment showing that projected climate-driven declines in soybean suitability by 2050 will substantially reduce iron and zinc supply for millions of people in sub-Saharan Africa and Southeast Asia, where deficiencies are already widespread. In Southern Africa alone, lost soybean-derived nutrients correspond to the annual requirements of more than six million people for iron and four million for zinc. By contrast, gains accrue mostly in higher-income temperate regions, where deficiency burdens are generally lower. These findings highlight a new frontier in climate adaptation: agricultural strategies must incorporate a nutrition lens, and global nutrition initiatives must integrate climate foresight.

Introduction

Concerns over feeding a growing global population stretch back centuries, from Malthusian predictions of scarcity [1,2] to twentieth-century fears of global famine [3–5]. Although scientific and technological advances have delivered substantial increases in agricultural productivity and caloric supply, gains in dietary quality and micronutrient adequacy have been uneven [6,7]. In many low- and middle-income countries (LMICs), diets remain deficient in essential micronutrients, particularly among groups with elevated nutritional needs [6,8], resulting in widespread deficiencies in iron, zinc, folate, vitamin A, calcium, and vitamin B12, with serious and lasting health consequences [9,10]. Even in high-income countries (HICs), micronutrient deficiencies, including iron deficiency, remain common, especially among women of reproductive age (WRA) [8,10].

Meanwhile, climate change, driven by decades of accumulated greenhouse gas emissions, will further heighten these pressures by warming the planet and shifting growing-season timing and length [11,12]. It is also increasing the frequency and intensity of storms, floods, droughts, and sea-level rise, with disproportionate impacts on low- and middle-income countries, particularly in the Global South [11,13–15]. Vulnerable LMIC populations already face greater exposure to climate-driven food and water insecurity, deepening malnutrition risks [16]. Using the concept of Safe Climatic Space (SCS), defined as the envelope of temperature, precipitation, and aridity conditions under which crops have historically thrived [17], recent analyses project that under a business-as-usual SSP5-8.5 pathway, approximately 31% of global crop production will fall outside its SCS by 2081–2100, with comparable risks for livestock systems. This erosion of suitability is expected to drive yield declines of between 7 – 23%[18] and increase production volatility, posing escalating threats to food and nutrition security at scales[15].

In response, research is increasingly focused on developing nutrient-dense and climate-resilient crop varieties and production systems [15,16], as incremental adaptations become increasingly urgent [19]. This shift has stimulated growing interest in broader adaptation strategies for major global staples [15,17,20–22], including soybeans, which are especially vulnerable to climate change [23–26] and play a vital role in food and nutrition security [27,28]. Under current emissions trajectories, soybean yields are projected to decline by 26 –57% by 2050 [29], with the greatest declines in low-latitude (tropical) regions [24]. Concurrently, elevated atmospheric CO_2 levels are expected to reduce iron and zinc concentrations in C_3 crops, including soybeans – by up to 5 % [30], compounding the nutritional impact of yield losses [13].

While climate impact assessments on agriculture are growing, most studies on soybean under climate change have focused on aggregate yield or economic impacts, often using multi-model ensembles and process-based simulations to map broad agroecological shifts (e.g., AgMIP crop modeling studies [21,22,31,32]). Only a handful of studies have considered nutritional implications [15,30,33,34]. Of these, several quantified climate-driven changes in seed iron and zinc [30,33,34], while one introduced a nutrition-sensitive climate risk framework linking climate extremes to micronutrient supply across food systems [15]. However, these approaches often remain crop-agnostic, overlook crop-specific suitability dynamics, and rarely validate modelled responses against established ecophysiological thresholds for soybean growth. This leaves a critical research gap at the intersection of food systems, climate resilience, and human nutrition.

Addressing this gap is especially important for soybeans, which are among the richest plant sources of iron (15.9 mg per 100 g) and zinc (4.8 mg per 100 g), and whose per-capita food-use supply has increased globally from 1.29 to 1.77 kg between 2010 and 2021[35], reflecting rising demand in both LMICs and HICs [28,36]. Yet, only about 7 % of soybean production is consumed directly by humans, with most diverted to livestock feed, highlighting untapped potential for dietary use [37]. In many LMICs, including India, Nigeria, and Southeast Asia, soy products such as tofu, tempeh, and soy milk already contribute meaningfully to dietary iron and zinc [7,36,38]. Meanwhile, upper-middle-income and high-income countries continue to increase per-capita soy consumption through plant-based milks and meat alternatives [28,39,40].

Despite these critical roles, the global consequences of climate-driven changes in soybean suitability for micronutrient delivery remain largely unexplored. This gap is critical because even modest shifts in soybean growing regions, which underpin the production of plant-based products (e.g., tofu, tempeh, soy milk) that are key sources of dietary iron and zinc, could disproportionately affect areas where micronutrient deficiencies are already severe and dietary needs remain unmet [41,42].

To fill this critical gap, we present the first global, spatially explicit assessment of how climate change may reshape soybean's contribution to dietary iron and zinc supply. We first compile high-resolution harvested-area grids from the International Food Policy Research Institute's Spatial Production Allocation Model (SPAM) [43] and biophysical suitability layers from the Global Agro-Ecological Zones (GAEZ) [44]. We then train continent-specific Maximum Entropy (MaxEnt) models to predict soybean suitability under current and mid-century (2050) conditions using the Coupled Model Intercomparison Project Phase 6 (CMIP6) "middle-of-the-road" Shared Socioeconomic Pathway 2-4.5 (SSP2-4.5) scenario [45–47]. By projecting suitability beyond current cultivated areas onto GAEZ-identified lands, we assessed both losses and potential expansion of soybean area.

Next, we integrate predicted suitability changes with country-level yield statistics and nutrient composition data to estimate shifts in iron and zinc output, and translate these into the number of people whose annual micronutrient requirements could be gained or lost, recasting yield projections as direct nutritional impacts. Model performance is evaluated using established metrics and ecological response curves, and biological realism is ensured by comparing model-derived suitability ranges to known ecophysiological thresholds for soybean growth. Finally, we map where suitability-driven gains and losses in soybean-derived nutrients may exacerbate or alleviate micronutrient deficiencies, offering insights for targeted land-use planning and nutrition-sensitive climate adaptation.

Results

Poleward expansion and tropical contraction

Our model indicates that climate change will drive a marked poleward expansion of soybean-suitable areas by mid-century, coupled with a decline in many tropical regions (Fig. 1a and b). Current high-productivity temperate zones will become even more favorable, and new areas in higher latitudes emerge as suitable, whereas several traditional soybean belts near the equator face declining suitability (Fig. 1c; SData 2 – 7). For example, North America and Eurasia show major gains in climatically suitable land for soy cultivation (Fig. 1b). In Canada, large tracts of land that were previously too cool for soybean are projected to become viable, yielding a ~204% increase in that country's potential soybean area by 2050 (relative to today; Fig. 1c). The United States, already the world's leading soybean producer, could see its suitable area expand by roughly 18%, mainly pushing further into northern states. In Europe, our projections highlight expansion particularly in Eastern and Central Europe: the Russian Federation (European part) with a 69% increase in suitable area, while countries like Germany, France, and Poland each show 10 – 26% increases, indicating new opportunities beyond their current soybean-growing zones. Northern Europe and the United Kingdom also become marginally suitable, despite having little to no current soybean production (SData 6).

Meanwhile, many countries in the tropics and subtropics are projected to lose suitable areas (Fig. 1b). Across sub-Saharan Africa (SData 2), the overall pattern is a southward retreat of soybean viability: current southern African breadbaskets are hit hardest (for instance, South

Africa's suitable area declined by an estimated 12%, Zambia by 17%, Zimbabwe by 15%; Fig. 1b and c). These losses concentrate in semi-arid regions where increasing heat and drought frequency (projected under SSP2-4.5) push conditions beyond soy's tolerance. In West Africa, baseline suitability is lower to begin with, but countries like Nigeria might actually gain some new suitable pockets (13%) in northern areas as conditions warm – an important nuance suggesting heterogeneous impacts within Africa. East Africa (e.g., Ethiopia +14%) also has potential expansion zones at higher elevations, even as lower-elevation areas become less hospitable.

Across South Asia (SData 3), we project a mixed outcome: India could gain ~6% (Fig. 1b and c) more suitable area (particularly in its northern and eastern regions), whereas Pakistan and Bangladesh lose some of their limited suitable areas due to intensified heat stress and changing monsoon patterns. Southeast Asia emerges as another vulnerable region. Tropical countries like Indonesia (−5%), Vietnam (−11%), Cambodia (−14%) and Thailand (−6%) are all expected to see declines in soybean-suitable land by mid-century. Much of Indonesia's current soybean production is already constrained by tropical conditions; further warming could make it even less viable in areas like Java and Kalimantan (Fig 1b). Similarly, parts of the Philippines and Myanmar lose suitability. Notably, East Asia (China's Manchurian Plain, etc.) does relatively well, northern and northeastern China improve (13%) thanks to milder winters and longer growing seasons, helping offset losses further south.

In South America (SData 4), the picture is patchwork but generally positive for the big producers. Brazil, which straddles tropical and subtropical zones, gains about 12% (Fig. 1b and c) in suitable area, largely in its southern states and possibly in parts of the Amazon fringe (although expansion there would raise sustainability concerns). Argentina sees a modest 3% increase overall; its core Pampas region remains suitable and southern areas become more so, though parts of the northern Argentina/Paraguay border might become too hot. Some smaller South American countries face losses: Colombia (−13%), Ecuador (−10%), and Venezuela (−8%) see contraction, which aligns with their tropical climates becoming less favorable for soy. Interestingly, Suriname and Guyana (Northern Amazon basin) show localized increases (> 15%), albeit starting from very small baselines. The Southern Cone (Uruguay, Chile's suitable zones) remains relatively stable or with slight gains, as warming may improve conditions in cooler pockets.

In Oceania, soybean cultivation is limited; Australia is projected to experience an overall decline (−13% in suitable area; Fig. 1b and c). Regions like Queensland and New South Wales, which currently grow soy, may become less reliable due to increased drought and heat (Queensland suitability −21%, for instance). On the other hand, a few cooler areas (Victoria, Tasmania) could see marginal improvements, but these are small regions that do not compensate for losses in major growing zones. Overall, the geographic analysis shows climate change "redrawing" the global soybean map: new areas opening up in temperate climates, and current tropical growing areas constricting. Next, we examine what these spatial shifts mean for nutrient production.

Projected impact of harvest area shifts on iron and zinc yield relative to population requirements

Regions with net nutrient gains

The nutritional consequences of the above shifts are substantial and highly unequal across regions. We translated changes in soybean distribution into changes in iron and zinc output, and then into "people's nutrient requirements met" to illustrate the human scale of these changes (Table 2; SData 2 – 7). On a global aggregate level, soybean-derived iron and zinc output is projected to increase by 2050, because the gains in high-yield temperate regions outweigh the losses in lower-yield regions. However, these gains accrue in places that already have ample nutrient supply relative to their population requirements. In contrast, many of the regions with losses are those where diets are already deficient in iron and zinc and with the least adaptive capacity. To illustrate, consider North America (Table 2; SData 5): with warming, the U.S. and Canada combined could produce an enormous additional quantity of nutrients from soybeans. In our projections, by 2050 the United States would produce roughly 4.0 trillion grams of iron per year more from soybeans compared to today (and about 1.2 trillion grams of zinc). This increase alone is enough iron to meet the entire annual requirement of ~482 million people, and enough zinc for ~323 million people (Table 2). Canada's expansion yields another 2.6 trillion grams of iron (790 billion g zinc) per year, which corresponds to the iron requirements of ~316 million people (and zinc needs of ~212 million). Of course, these numbers far exceed North America's actual population, highlighting that the additional nutrients, while globally significant, would be surplus relative to local requirements.

In fact, even a fraction of this extra iron, if it were accessible where deficits are common, could alleviate deficiency for hundreds of millions in other regions. Brazil, another agricultural giant, is projected to add approximately 2.9 trillion grams of iron and 88 billion grams of zinc annually from soy expansion (if fully realized) – iron sufficient for ~350 million people, zinc for 235 million (Table 2; SData 4). Argentina and Paraguay together contribute a smaller yet notable gain (458 billion g iron, 140 billion g zinc combined), enough iron for ~94 million people and zinc for ~38 million. China and India, as mentioned, also see large increases: China's gain of 570 billion g iron and 174 billion g zinc per year could cover the iron requirements of ~70 million people and zinc of ~47 million; India's 167 billion g iron and 51 billion g zinc could cover ~20 million people (iron) and ~14 million (zinc) (Table 2; SData 3). Russia (Asian part included) also benefits: its projected 707 billion g iron and 216 billion g zinc equate to iron for ~86 million people and zinc for ~58 million.

Regions with net nutrient losses

In Southern Africa, as soybean-suitable land shrinks, countries in this region collectively could lose more than 51 billion grams of iron and 16 billion grams of zinc per year from decreased soybean production (relative to current output: Table 2; SData 2). This lost output is equivalent to the iron requirements of more than 6 million people and the zinc requirements of 4 million people annually. Put plainly, millions fewer people in Southern Africa could have their nutrient needs met because of climate impacts on soy. The hardest-hit country, South Africa, alone accounts for ~36 billion g iron and ~11 billion g zinc of that loss (iron for 4.4 million people, zinc for 3.0 million). Zambia and Zimbabwe together add roughly another 13 billion g iron and 3.9 billion g zinc lost, affecting ~1.6 million people's iron requirements (~1.1 million people's zinc). These are not just numbers, they represent nutritional shortfalls that could deepen already widespread iron deficiency anemia and zinc deficiency in this region.

In Southeast Asia, the pattern is similar (SData 3). We estimate an aggregate annual loss of roughly 24 billion grams of iron and 7.4 billion grams of zinc from reduced soybean yields in countries of this region. This amount of iron would have satisfied the yearly requirements of ~2.0 million people, and the zinc loss the requirements of ~2.1 million people. For example, Indonesia's projected production decline (9.3 billion g iron, 2.9 billion g zinc per year) leaves about 1.1 million people's iron requirements and 0.76 million people's zinc requirements unmet (Table 2). Cambodia (losing ~5.9 billion g iron, 1.8 billion g zinc) and Vietnam (~5.8 billion g iron, 1.8 billion g zinc) each see on the order of 0.7–0.8 million people's worth of iron and ~0.48 million people's worth of zinc removed from their annual food supply. These countries already experience significant burdens of micronutrient malnutrition, so even modest reductions in local nutrient production can have outsized public health implications. Other regions with losses include parts of South Asia: e.g., Pakistan loses some soybean potential (translating to a ~2.1 billion g annual iron shortfall, ~260k people's iron requirements), and Bangladesh (~1.3 billion g iron lost, affecting ~160k people).

In West Africa, soybean production remains limited in most countries, although our projections suggest potential increases in some areas, particularly Nigeria (26.47 billion g of iron and 8.09 billion g of zinc, enough for over 3 million and 2 million people, respectively). However, the realization of these gains is far from certain, given persistent agronomic, economic, and infrastructural barriers. Without substantial growth in production, the region is unlikely to see meaningful improvements in soy-derived iron and zinc supply. Even where our models indicate possible gains, such as Nigeria, Benin, and Ethiopia, the translation of projected suitability into actual nutrient delivery remains uncertain. If these gains are not fully realized, the net supply of soy-derived iron and zinc across Africa may be even lower than our model suggests, potentially worsening the continent's already fragile micronutrient landscape.

Net global balance and equity

Summing gains and losses, our projections imply that global soybean iron output could increase by well over 10 trillion grams (10 million tonnes) per year, which in theory could meet the iron requirements of >1.2 billion people. However, this aggregate surplus is misleading from a nutritional equity standpoint. The additional iron and zinc are predominantly being produced in countries (like the U.S., Canada, Russia, Brazil) where per capita micronutrient supplies are already sufficient or even excessive, and where the marginal benefit to public health is small. Meanwhile, the deficits – although smaller in absolute quantity – occur in countries where even a small loss of nutrient availability can translate into many more people becoming deficient (or existing deficiencies worsening).

This spatial decoupling between production gains and nutritional needs is a major concern highlighted by our results (Table 2 quantifies this disparity by showing gains and losses in nutrients alongside the population whose needs correspond to those amounts). If no corrective measures are taken, these projected changes portend a potential widening of global micronutrient gaps. Populations in parts of Africa and Asia that are already struggling with iron and zinc deficiency could face even greater shortages as local food systems come under climate stress. On the other hand, temperate, wealthier countries might experience a glut of soy-derived nutrients (likely channeled mostly to animal feed or export markets) with little direct benefit to the undernourished. The challenge is that nutrients will not automatically flow to where they are needed; without intervention, the outcome could be a net increase in global nutrient production but a net decrease in its equitable distribution.

Discussion

We present a spatially explicit, global assessment of climate-driven shifts in soybean suitability that links changes in production potential to nutrient delivery. By coupling probabilistic habitat modeling (MaxEnt) with harvested area data from SPAM and translating changes in output into population-level iron and zinc supply, we provide a framework to evaluate the nutritional impacts of climate adaptation in agriculture.

To our knowledge, this is the first global analysis to explicitly link climate-driven shifts in crop suitability to potential changes in population micronutrient supply. Our findings build on a growing body of research demonstrating poleward shifts in crop suitability under climate change [23,24,31,32,48,49]. Previous projections using species-distribution modeling (MaxEnt under RCP4.5/8.5) [23] and data-driven regional yield forecasts (random forest under RCP4.5/8.5) [32] have consistently shown that warming climates will likely expand soybean's range into mid-to-higher latitudes while reducing its viability in many tropical regions. Other studies have highlighted declining suitability in low-latitude regions, typically framed around biodiversity loss [24] or shifts in species occurrence [49], yet rarely connect these biogeographical changes to nutritional outcomes. Even the most recent large-scale global assessments, which incorporate real-world adaptation strategies for major crops (including soybean), confirm that the most severe impacts are concentrated in low-latitude regions, but do not quantify the consequences for nutrient supply or public health [50].

By bridging these gaps, integrating actual crop distribution, nutrient composition, and human requirements, our study provides a spatially explicit and population-level assessment that reveals the nutritional dimension of climate-driven shifts in soybean suitability. We find that, while total soybean-derived iron and zinc supply is projected to increase globally by 2050 under a business-as-usual scenario, these gains accrue primarily in regions where populations already meet or exceed micronutrient needs. In contrast, countries across Southern Africa, Southeast Asia, and South Asia, many of which face widespread iron and zinc deficiencies are projected to lose suitability and nutrient output (Table 2; SData 2 and 3). In these regions, soybeans serve as a critical source of both protein and micronutrients. Thus, even relatively modest declines in soybean suitability pose major risks to local food and nutrition security [51], compounded by intensifying drought and heat stress on staple crops [38,52], and cascading impacts on livelihoods [15,22,24,27,53]. Such projections reveal a risk of nutritional maladaptation, in which climate-driven gains in crop suitability become geographically and demographically decoupled from nutritional need. If adaptation follows market or ecological inertia, nutrient-rich crops may increasingly shift toward populations with the least need, potentially deepening global nutrition inequities.

Nevertheless, there are signs of proactive adaptation within affected regions. In Southern Africa, for example, Zambia has taken deliberate steps to address these emerging risks. Recent policy initiatives, such as the National Crop Diversification Strategy and the Zambia Soybean Strategy and Investment Plan, explicitly promote crop diversification and position soybean as a strategic crop for both climate resilience and nutrition security [54]. These policies have elevated soybeans as both a cash crop and a key source of livestock feed, with broader benefits for food security and diet quality. However, cases like Zambia remain the exception rather than the rule.

Globally, integration of nutrition into climate adaptation remains limited. Despite growing recognition of the need for nutrition-sensitive agriculture, only 2% of Nationally Determined Contributions (NDCs) and 28% of National Adaptation Plans (NAPs) explicitly address nutrition outcomes [55]. This reflects a continued focus on conventional adaptation strategies that prioritize yields and economic outputs (e.g., tonnes per hectare or dollars per crop), metrics that, while vital, can obscure the nutritional vulnerabilities of at-risk communities. Recent climate shocks highlight the real-world consequences of this oversight and the urgent need to embed nutrition priorities into adaptation planning. For instance, the 2024 El Niño–linked drought in Southern Africa triggered one of the region's worst hunger crises in decades, causing widespread crop failure and affecting over 27 million people [56,57]. Similarly, intensifying monsoon variability in Southeast Asia has disrupted sowing and yields for soybean and other staple crops [58,59].

Although farmers and governments in these regions may respond with agronomic adjustments, such as altered sowing dates, drought-tolerant varieties, and improved soil management, for short-term relief, evidence suggests these measures are unlikely to fully offset the long-term impacts of climate change [24,50]. Moreover, even in regions where climate projections suggest improved suitability for soybean production, particularly in developing countries with high burdens of malnutrition, substantial adaptive barriers remain, including limited infrastructure, weak supply chains, and competition from other land uses [13,53]. In other words, favorable biophysical conditions alone will not suffice to ensure improved nutrient delivery without broader enabling conditions.

Given these intersecting challenges, a more comprehensive approach is needed. Adaptation strategies must address not only climate risks but also the nutritional vulnerabilities they create or amplify [15]. This requires moving beyond siloed or fragmented efforts towards coordinated policies that link crop adaptation with investments in value chains, infrastructure, and nutrition-specific interventions [13,55]. Effective responses must therefore operate across multiple levels.

At the value-chain level, developing fortified soy products, investing in processing and storage, promoting dietary diversification, and incentivizing smallholder production can all help ensure that gains in production translate to improved nutrition [13,60,61]. Yet, such interventions depend on institutional capacity that is often lacking in many LMICs [62,63]. Strengthening these institutional capacities, alongside fostering multi-sectoral collaboration, will be essential to ensure that adaptation efforts realize their full potential for nutrition security.

In places where climate change undercuts local production, ensuring access to imported or alternative nutrient sources becomes critical. This could involve reducing import tariffs on nutrient-rich foods, scaling up food fortification programs (e.g., adding iron and zinc to widely consumed staples), and expanding social safety nets, such as food assistance or micronutrient supplementation [15,60]. At the farm level, introducing or expanding drought- and heat-tolerant legumes (like cowpea, pigeon pea, or mung bean) and scaling up biofortified staples (e.g., iron-rich beans or zinc-fortified rice and wheat) offers another avenue for nutritional resilience, as demonstrated in countries like Rwanda, Zambia, Bangladesh, and India [64].

While these immediate and medium-term interventions can help buffer nutritional risks, sustained progress will require long-term investment in crop breeding, biotechnology, and improved farming systems, especially in climate-stressed regions such as sub-Saharan Africa and Southeast Asia. For example, scaling up the deployment of photoperiod-insensitive, heat- and drought-tolerant soybean varieties, already validated across sub-Saharan Africa through initiatives like the International Institute of Tropical Agriculture (IITA), offers promising adaptation pathways [65]. Leveraging regional frameworks, such as the Forum on China–Africa Cooperation (FOCAC) Beijing Action Plan (2025–2027), could further accelerate the development and dissemination of climate-resilient varieties [66].

Beyond varietal development, integrated farming systems have been promoted in different regions, through programs such as the Sustainable Intensification of Maize-Legume Systems for Food Security in Eastern and Southern Africa (SIMLESA) [67] and similar initiatives in Southeast Asia [68,69]. These approaches, which combine legumes, cereals, and agroforestry, have demonstrated benefits for soil fertility, yield stability, and improved nutrition outcomes [70]. However, realizing these benefits at scale will require strengthened extension services and research infrastructure, both of which are often underfunded in lower-income countries, as well as greater prioritization of climate finance, technology transfer, and development aid to support high-need contexts.

Meanwhile, in regions like the Americas and Europe (Fig. 2; Data S4–6), where climate-driven increases in soybean suitability coincide with already low iron and zinc deficiency rates [10], the priority shifts toward managing nutritional surpluses responsibly and maximizing global benefits. Recent studies demonstrate that expanding soybean production in Europe could substantially reduce greenhouse gas emissions and nitrogen fertilizer use while making the continent largely self-sufficient in soy, even under future climate scenarios [28,32]. Yet, these potential environmental and production gains will have limited nutritional impact unless policies are enacted to redirect a greater share of soybean output toward direct human consumption. Currently, more than 80% of soybeans are diverted to animal feed or bioenergy, leaving only a small fraction available for food products that could address nutrient gaps in vulnerable populations [37,71]. Therefore, aligning agricultural and trade policies to promote soy-based foods, not just for domestic use but also as part of a nutrition-sensitive global supply chain, represents a critical opportunity to leverage potential regional gains for broader public health gains, stabilizing markets and supporting dietary improvement in regions of greatest need.

One positive development is the rising interest in plant-based diets and sustainable nutrition in high-income countries [28] which could drive demand for more soy-based foods. Say these regions with gains realize their climate potential for soy, some of this output could contribute to more sustainable food products, displace animal-source foods, and free up nutrient resources for regions in need. Yet as global trade increasingly moves nutrients around the world [72], countries also face new vulnerabilities, not just from their own climate shocks, but from disruptions elsewhere [15,54]. For example, the 2012 drought in the United States, one of the world's largest soybean exporters, led to a sharp increase in global soybean prices and disrupted supply chains for many import-dependent countries [73,74]. So, while nutrition-focused trade policies can help move soy-based nutrients to regions with shortages, they must be balanced by efforts to reduce overdependence on imports and to strengthen the resilience of local food systems [53].

Nevertheless, it is essential to recognize that the insight highlighted by our globally scalable framework is bound by realities far beyond biophysical suitability. First, our modeling is based on a single scenario (SSP2-4.5) and does not capture the range of uncertainty across climate models and socio-economic trajectories. Actual outcomes could vary; for instance, if greenhouse gas emissions are higher or lower, the magnitude of shifts in suitability could correspondingly increase or decrease. Similarly, socio-economic changes (dietary shifts, trade developments, e.t.c) could mediate the impacts we projected in ways our study did not account for [75]. For a more robust risk assessment, future work should examine multiple scenarios (including worst-case SSP5-8.5 and best-case SSP1-2.6) and perhaps a multi-model ensemble for climate projections to gauge variability across plausible futures [21].

Second, the assumption that changes in climatic suitability will directly translate into expanded or reduced soybean cultivation is a simplification. In practice, land-use change depends on a range of factors, including the availability of arable land, access to capital and markets, policy incentives, and competing land uses such as food, biofuels, or reforestation [76,77]. We did not simulate these socio-economic drivers. For example, even if Canada becomes much more suitable for soy, expansion will depend on global soy demand, prices, and land availability (which in turn might be constrained by forests or urbanization). Likewise, some regions might not abandon soy immediately even if climate suitability declines, farmers could attempt to adapt in place (with irrigation, shading, switching planting dates, etc.) and delay the contraction [78]. Our results should therefore be interpreted as potential changes, assuming a direct response to climate signals, whereas real-world outcomes will reflect a broader set of human decisions and policy responses.

Relatedly, we did not consider land-use competition and sustainability concerns that could arise from expanding soy into new areas. Soybean agriculture, especially in South America, has historically been linked to deforestation, carbon emissions, and biodiversity loss (e.g., expansion into the Amazon or Cerrado) [37,79,80]. While our study identifies climatically suitable areas for soybean cultivation by 2050, it does not assess whether conversion of these areas would be environmentally desirable or socially acceptable. Incorporating a landscape approach that balances nutritional needs with biodiversity conservation and climate mitigation [81] will be essential. Some newly suitable lands may overlap with forests that serve as key carbon sinks or biodiversity hotspots; converting them to soybean could boost nutrient supply, but at the cost of undermining climate or conservation goals and creating challenging trade-offs [82].

Third, our focus on iron and zinc in soybeans provides a clear picture for those nutrients, but we recognize that diets are complex. Iron and zinc from soy might not be fully bioavailable due to phytates, and people obtain these nutrients from many foods. Climate change will affect entire diets [83], not just soy. Other staple crops (like wheat, rice, maize) have their own climate vulnerability [24], and our single-crop approach does not capture substitution effects or resilience in the broader food system. It could be, for example, that losses in soybean are partly offset by increases in another crop like cowpea in some regions – meaning the net dietary iron change is less severe than it looks from soy alone. A multicrop, systems-wide analysis would be valuable as a next step to see how total dietary nutrient availability might change under climate scenarios.

Another limitation is that we assumed current nutrient composition and yields remain constant. Climate change itself can alter crop nutritional quality, elevated CO_2 has been shown to lower the zinc and iron concentration in crops (including soy) by 5–10% in some cases, [30,33] which we did not factor into our grams of nutrient calculations (we assumed soy grown in 2050 has the same iron/zinc density as today). If nutrient density declines, then our estimates of people's requirements met would be slightly optimistic (the real number of people served by a tonne of soy could be less in the future). Contrastingly, there are efforts to biofortify and breed crops for higher nutrient content, or to improve yields despite climate stress; if successful, those could mitigate some losses [64,84]. We also did not account for possible adaptation measures by farmers that could reduce yield losses, e.g., irrigation expansion, shifting sowing dates, new cultivars – which might cushion the blow in some declining areas [84].

Finally, we note that our study addresses only the potential availability of nutrients assuming all soybean production is allocated to direct human consumption, not actual nutrition outcomes. While estimating the number of people whose requirements could be met by available supply provides a useful proxy for public health impact, it does not directly translate to prevalence of deficiencies. In reality, shortfalls in domestic supply may be offset through trade, supplementation, or dietary adjustments, meaning that not all individuals in areas of insufficient supply will necessarily become deficient [53,85]. Conversely, even if enough nutrient is available on paper, issues of access, acceptability, and utilization mean deficiencies can persist [53]. This disconnect is well-documented in nutrition literature, particularly in low- and middle-income countries where food systems may not ensure equitable access [53]. We used the population requirements metric as a way to frame the magnitude of changes, but real-world nutrition outcomes would require further analysis including socio-economic access, allocation and cultural dietary patterns, and health system factors [86].

Despite these uncertainties, our core findings are robust: climate change, if unaddressed, risks further decoupling food production from nutritional need, underlining a crucial area where health and global equity intersect. Addressing this will require breaking silos. Agricultural adaptation initiatives must adopt a nutrition lens, and global nutrition initiatives must integrate climate foresight [13,60,87]. For example, humanitarian and development programs that aim to combat micronutrient deficiency should factor in climate trends (identifying regions where local food availability of iron/zinc may dwindle and planning interventions accordingly) [53]. Likewise, climate change adaptation funding should support projects that explicitly improve nutritional outcomes, such as climate-resilient kitchen gardens, fortification during climate-related food crises, or distribution of drought-hardy, nutrient-rich crop seeds [53].

In conclusion, our findings reveal that climate change is poised to redraw the global map of soy-derived nutrient production, with profound implications for nutrition security and equity. Without deliberate and targeted interventions, "business-as-usual" adaptation strategies risk exacerbating nutritional disparities and undermining decades of progress toward the Sustainable Development Goals (SDGs), especially SDG 2 (Zero Hunger), SDG 3 (Good Health and Well-being), and SDG 10 (Reduced Inequalities). Yet, our analysis also illuminates a path forward. By identifying emerging hotspots of nutrient shortfalls, we provide a framework to prioritize resources and actions where they are needed most, enabling policy responses that directly support SDG targets. Integrating nutrition outcomes into climate adaptation policies is no longer an afterthought: it must become a defining priority for food system transformation. As the geography of global agriculture shifts, so too must our collective resolve to ensure that food systems nourish everyone, everywhere, both adequately and equitably. Ultimately, meeting the challenges of a warming world will require more than technical innovation in agricultural production. It will demand a renewed global commitment to the right to nutrition, to equity, and to solidarity, values at the heart of the SDGs. If we act with foresight and urgency, climate adaptation can become not only a defense against hidden hunger, but a catalyst for progress toward more resilient, just, and nourishing food systems for all.

Methods

Spatial modeling framework. To assess how climate change may alter soybean's contribution to global micronutrient supply, we developed a spatial modeling framework based on the MaxEnt algorithm [88,89]. MaxEnt is a presence-only machine-learning tool that estimates a species' probability distribution by relating occurrence records to environmental predictors, while minimizing assumptions about data structure. We first collated high-resolution soybean occurrence data and key bioclimatic variables from WorldClim v2.1 [90], and then trained separate, continent-specific models using current (1970 – 2000) climate layers and projected future layers for 2041 – 2060 under the SSP2-4.5 scenario. Finally, we converted MaxEnt's probabilistic output into projected changes in harvested area, production, and iron and zinc delivery.

Input Data

Occurrence data. We used the Spatially Explicit Agricultural Production (SPAM) dataset which provides global gridded estimates of crop production, downscaled at 5 arcmin (~9 km^2) resolution with multi-year averaging [43]. SPAM disaggregates national and subnational statistics using a cross-entropy approach to estimate four dimensions of crop presence: physical area (all pixels biophysically suitable), harvested area (land actually cultivated), yield (output per unit area), and total production. For our purposes, harvested area was chosen as the primary input because it serves as the most direct representation of realized land use on ground, that integrate both biophysical feasibility (soil, climate, water availability) and socioeconomic drivers (market access, input availability, farmer choices, infrastructure) that determine where farmers actually plant – and continue planting – soybeans in a given pixel [44,91,92]. By using harvested area rather than potential area or mere suitability indices, our model inherits a built-in filter that excludes marginal or unused lands, since pixels with zero harvested area might be constrained, even if they are physically suitable [43,44,92]. This means that starting from observed cropping patterns rather than theoretical maxima, our baseline is grounded in current reality, which, in turn, ensures that any future expansion projections remain conservative unless, perhaps, there is clear evidence of socio-economic or policy change.

For soybeans, we merged SPAM's 2010 and 2020 releases (combining irrigated and rainfed systems) to create a single, up-to-date occurrence layer. Because SPAM only reports pixels with recorded harvested area, the absence of a pixel indicates more than simple biophysical unsuitability; it reflects real-world barriers (e.g., crop rotation, low profitability, lack of infrastructure) that keep that cell uncultivated even though it might lie near the suitability margin [93]. Consequently, our model captures both the realized footprint of soybean cultivation and the approximate "maximum extent" of viable land under current management and socioeconomic conditions.

Environmental variables. To model the bioclimatic constraints on soybean cultivation, we used WorldClim version 2.1 data [90] at 30 arc-second resolution (~1 km²). We included both historical climate data (1970 – 2000 averages) and future projections (2041 – 2060) under the SSP2-4.5 scenario – a "middle-of-the-road" pathway representing moderate socioeconomic development and stabilized emissions [14]. This scenario anticipates approximately 2.4°C warming by 2100 and corresponds to a radiative forcing of 4.5 W/m². We selected bioclimatic variables relevant to soybean growth and stress response, including mean annual temperature, temperature seasonality, annual precipitation, and precipitation seasonality (see Table 1a for the full list of variables used).

Model Development

Modeling approach. We modelled soybean suitability using a species distribution modelling (SDM) approach with the Maximum Entropy (MaxEnt) algorithm [88,94]. MaxEnt models suitability by contrasting observed occurrence points with a background sample across the study area [89,95], and has demonstrated superior predictive performance over other machine learning methods such as Random Forest and generalized linear models for climate-driven crop mapping [88]. Occurrence points for our study were derived from SPAM's harvested-area layer, ensuring the model learns from realized soybean distribution patterns rather than potential or physical area, while background points were used to project suitability across the study domain.

Training data preparation. We generated training data by randomly sampling 100,000 points from regions with documented soybean presence in the SPAM dataset. Stratified sampling was conducted across six continents (Africa, Asia, Oceania, South America, Europe, and North America) to capture global variation in soybean distribution. By sampling exclusively from harvested-area pixels, we ensured that the MaxEnt model was calibrated using locations with realized, socioeconomic-filtered soybean production, rather than potentially suitable but unoccupied land. Each training point was then matched to values for 19 bioclimatic variables, forming the predictor matrix for model fitting.

Prediction data preparation. To extrapolate suitability beyond current cultivation zones, we used the Global Agro-Ecological Zones (GAEZ v4) dataset [44]. We selected the rainfed, high-input suitability and attainable yield layers for soybeans and generated prediction points for all global regions identified as potentially suitable by GAEZ. These GAEZ-based prediction points enabled the projection of suitability beyond SPAM's harvested-area footprint, that is, to identify pixels where cultivation could expand if all socioeconomic and management barriers were removed. Each prediction point was matched to the same set of 19 bioclimatic variables as the training point

Model calibration. MaxEnt models were fit independently for each continent to capture regional differences in climate–soybean relationships. To reduce spatial bias and overfitting due to dense clusters of occurrence points in major growing regions, we spatially thinned occurrence records at 5 km using 10 iterations, following established best practices [96]. The model included linear, quadratic, product, and hinge feature classes, with the number of knots set to 10 to balance flexibility and overfitting risk. Each model incorporated nineteen bioclimatic predictor variables from WorldClim v2 (1970–2000); for future projections, we used downscaled CMIP6 layers under the SSP2-4.5 scenario. Model complexity was controlled by including linear, quadratic, product, and hinge feature classes [88,89], with the number of knots set to 10. The presence-to-background weight was set to 75 to balance contrast and account for uncertain absences. After model fitting, continuous suitability outputs were rasterized at 5-arc-minute resolution and then binarized into presence or absence using a threshold of 0.5. Model performance was evaluated for each continent using the area under the curve (AUC), omission rate, sensitivity, and specificity.

Spatial aggregation of changes. Global country and subnational boundaries were obtained from the Global Administrative Areas (GADM) database (https://gadm.org). Our gridded outputs (e.g. maps of soybean climatic suitability, harvested area and projected country-level suitability changes) were overlaid on the GADM polygons. We then aggregated the raster-based changes up to each administrative unit. In practice, zonal-statistic calculations were performed for each GADM-defined country polygon: pixel-level changes in soybean suitability, harvested area and nutrient supply were summed (or averaged as appropriate) within each country boundary. This yielded country-level totals of change in suitability and production for soybeans. These country aggregates were used in subsequent analyses and summaries.

Model discrimination. We evaluated model discrimination using the area under the receiver-operating-characteristic curve (AUC–ROC), a threshold-independent metric. AUC ranges from 0.5 (random prediction) to 1.0 (perfect discrimination). In practice, AUC > 0.8 is commonly taken as indicating good discriminatory power (graphically, a highly discriminative model's ROC curve rises steeply toward the upper-left, yielding a large AUC.). We generated ROC curves from MaxEnt's continuous logistic suitability outputs. Consistent with other large-scale SDM studies [23,97], we anticipated that models spanning continental climate gradients would achieve AUC values well above 0.8, reflecting strong separation of known presences and absences.

Response curves and ecological plausibility. To interpret how environmental variables drove the model, we examined each predictor's marginal response curve (i.e. plotting predicted suitability vs. that predictor while holding all others at their mean) [98]. These response curves quantify each climatic variable's effect on soybean probability of occurrence. We identified key inflection points and suitability ranges from these curves, then compared them to published ecophysiological thresholds for soybean. For example, soybean germination and growth are known to be optimal around 15–25 °C [99] and to require roughly 500 mm of rainfall during the growing season [100]. Where our model's response curves showed peaks or plateaus near those values, we considered this concordance evidence of ecological realism. In short, agreement between the MaxEnt-derived tolerance ranges and literature values (e.g. optimum temperatures ≈15–25 °C [99], season precipitation ≈500 mm [100]) supported the plausibility of the modelled relationships.

Thresholding and accuracy metrics. Following convention, we converted MaxEnt's logistic output into a binary suitability map using a cut-off of 0.5 (scores ≥ 0.5 deemed "suitable," < 0.5 as "unsuitable"). Predictions were compared to observed presence/absence data to construct a confusion matrix [77,97], tallying true positives (TP), false positives (FP), false negatives (FN), and true negatives (TN). From these, we calculated a comprehensive set of classification metrics for each continent, including accuracy (the proportion of correct predictions across all sites, $(TP + TN) / (TP + FP + FN + TN)$), precision (the proportion of predicted presences that were truly present, $TP / (TP + FP)$), and negative predictive value (the proportion of predicted absences that were truly absent, $TN / (TN + FN)$). We also computed the F1 score, defined as the harmonic mean of precision and recall ($2 \times Precision \times Recall / (Precision + Recall)$), and the Matthew's correlation coefficient (MCC), which provides a balanced measure even in the presence of class imbalance i.e.,

$MCC = (TP \times TN - FP \times FN) / \sqrt{[(TP + FP)(TP + FN)(TN + FP)(TN + FN)]}$.

The false positive rate ($FP / (FP + TN)$) and false negative rate ($FN / (TP + FN)$) were used to quantify errors of commission and omission, respectively. Balanced accuracy was calculated as the mean of sensitivity ($TP / (TP + FN)$) and specificity ($TN / (TN + FP)$), providing a robust assessment when classes are imbalanced. Finally, we computed Youden's J statistic [101] ($sensitivity + specificity - 1$), equivalent to the true skill statistic (TSS), to identify the threshold that maximizes overall discrimination. This suite of metrics provides a robust, prevalence-independent evaluation of model performance and enables comparison across regions. Continent-specific results are provided in Supplementary Tables S1b and S1bi.

Estimating changes in area and production. We assumed that changes in climatic suitability would result in proportional changes in actual soybean cultivation area, in the absence of major socioeconomic constraints. Thus, if a country's suitable area increased by X%, we estimated its harvested area could similarly expand by X%; conversely, a loss of suitable climate space was assumed to yield an equivalent percentage decline in area under cultivation, reflecting the assumption that farmers would shift to newly suitable regions and withdraw from newly unsuitable ones. Using this rule, we calculated net changes in soybean harvested area (hectares) for each country by 2050. Corresponding changes in production were then estimated by multiplying the area change by each country's current average yield (mean yield from 2019–2023 [35], assumed constant for future projections). This approach yields potential production gains (tonnes/year) for countries gaining suitable area, and production shortfalls for those losing area.

Nutritional translation. To assess the nutritional impact, we converted changes in soybean production into changes in iron and zinc supply. We used nutrient composition data for soybeans (dry) from the USDA FoodData Central database (which reports iron and zinc content per 100 g edible portion). According to USDA, raw soybeans contain approximately 16 mg iron and 4.9 mg zinc per 100 g. Using these values, every tonne (1,000,000 g) of soybeans provides ~160,000 mg of iron (157 g) and 49,000 mg of zinc (49 g). We applied these conversion factors to the country-level production changes to compute the gain or loss of iron (g/year) and zinc (g/year) attributable to climate-driven shifts in soybean area.

Finally, we expressed these micronutrient changes in terms of the number of people's annual requirements. Women of reproductive age (WRA, 15–49 years) were chosen as the reference group, given their higher iron and zinc requirements and greater risk of deficiency, providing a conservative benchmark [102]. Based on published Harmonized Average Requirements (assuming low dietary bioavailability), we used 22.4 g per year as the iron requirement per

WRA and 10.2 g per year as the zinc requirement per WRA (assuming 5% iron absorption and diets high in phytate for zinc) [103]. Total iron or zinc change was divided by the per-woman annual requirement to estimate the number of annual requirements met or unmet as a result of the projected soybean changes. For simplicity, we report these as the "number of people" affected, using the WRA requirement as a proxy for one person, while acknowledging actual requirements vary by age and sex [103].

Validation and uncertainty. The suitability model accurately reproduced observed soybean distributions (Fig. 1a vs 1d), with high AUC and strong performance across all key classification metrics (accuracy, F1, MCC, TSS; Supplementary Tables S1b, S1bi, S1c). Model discrimination was highest in North America and Europe, where both sensitivity and specificity exceeded 0.75, and lower in Africa and Oceania, reflecting differences in environmental heterogeneity and data coverage. Inflection points in the response curves (optimal temperature ~25–35 °C, rainfall ~400–1500 mm) aligned with established agronomic thresholds (Supplementary Fig. S1 and Data S1), supporting ecological plausibility. Uncertainties arise from our use of a single climate scenario and idealized land-use assumptions (may not hold if farmer decision-making diverges); projections should therefore be interpreted as scenario-dependent trends rather than precise forecasts.

Resource availability

Correspondence and requests for materials should be addressed to the lead contact Ejovi Abafe (e.abafe@massey.ac.nz).

Materials availability

This study did not generate new physical materials.

Data availability

All data used in this study are publicly available from established sources. Global soybean suitability projections and harvested area data were obtained from the Global Agro-Ecological Zones (GAEZ) v4 database (https://gaez.fao.org/) and the Spatial Production Allocation Model (SPAM; https://www.mapspam.info/). Administrative boundaries for country-level and subnational analyses were taken from the Global Administrative Areas (GADM) v 4.1 database (https://gadm.org/). Crop nutrient composition data were sourced from USDA FoodData Central (https://fdc.nal.usda.gov/). Harmonized nutrient requirement values were taken from Allen et al. (2020; https://doi.org/10.1093/advances/nmz096). Climate projections (SSP2-4.5) were accessed from WorldClim v2 (https://www.worldclim.org/). All other data supporting the findings of this study, including supplementary tables and country-level projections, are available within the supplementary information files or from the corresponding author upon reasonable request.

Code availability

Species distribution modeling was performed using the MaxEnt tool in ArcGIS Pro (version 3.4.0, Esri), following established protocol as fully described by Fitzgibbon et al. (2022; https://doi.org/10.3390/land11091382). Data analysis and processing were conducted in Microsoft Excel 2024 and R (version 4.4.2; RStudio). Custom R scripts used for data visualization are available from the corresponding author upon reasonable request.

Author contribution

EAA, NWS, TMRM, and WCM conceptualized the study and developed its methodology. EAA calibrated the model, analyzed the data, compiled the outputs, and drafted the manuscript. NWS, TMRM, and WCM critically reviewed and revised the manuscript. All authors reviewed and approved the final version.

Competing interest declaration

The authors declare that no competing interests exist

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Table 1a | Bioclimatic variables used to model soybean suitability under current and future climates.

Bioclimatic variables were obtained from the WorldClim dataset (version 2.1) at 30 arc-seconds (~1 km²) resolution [90]. All temperature variables are in degrees Celsius (°C), and precipitation variables in millimetres (mm). Variables represent historical conditions (1970–2000) and projected climate (2041–2060) under SSP2-4.5.

Code	Variable name	Description	Units
BIO1	Annual Mean Temperature	Mean of monthly mean temperatures	°C
BIO2	Mean Diurnal Range	Mean of monthly (max temp − min temp)	°C
BIO3	Isothermality	(BIO2/BIO7) × 100	%
BIO4	Temperature Seasonality	Standard deviation of monthly temperature × 100	%
BIO5	Max Temperature of Warmest Month	Highest monthly maximum temperature	°C
BIO6	Min Temperature of Coldest Month	Lowest monthly minimum temperature	°C
BIO7	Temperature Annual Range	BIO5 − BIO6	°C
BIO8	Mean Temperature of Wettest Quarter	Mean temperature of the wettest three-month period	°C
BIO9	Mean Temperature of Driest Quarter	Mean temperature of the driest three-month period	°C
BIO10	Mean Temperature of Warmest Quarter	Mean temperature of the warmest three-month period	°C
BIO11	Mean Temperature of Coldest Quarter	Mean temperature of the coldest three-month period	°C
BIO12	Annual Precipitation	Total annual precipitation	mm
BIO13	Precipitation of Wettest Month	Total precipitation in the wettest month	mm
BIO14	Precipitation of Driest Month	Total precipitation in the driest month	mm
BIO15	Precipitation Seasonality	Coefficient of variation of monthly precipitation	%
BIO16	Precipitation of Wettest Quarter	Total precipitation in the wettest three-month period	mm
BIO17	Precipitation of Driest Quarter	Total precipitation in the driest three-month period	mm
BIO18	Precipitation of Warmest Quarter	Total precipitation in the warmest three-month period	mm
BIO19	Precipitation of Coldest Quarter	Total precipitation in the coldest three-month period	mm

Table 2 | Projected country-level changes in soybean iron and zinc yield, and corresponding impact on population requirements by 2050.

Projected changes in total iron and zinc yield (grams), and the number of people whose recommended annual requirements could be met by these changes, for major soybean-producing countries by region. Yield changes are based on projected soybean climatic suitability and harvested area in 2050 under the SSP2-4.5 climate scenario. The number of people whose requirements could be met per year is calculated using harmonized average requirements for women of reproductive age (WRA) by [103] and nutrient composition data from USDA FoodData Central [104]. Values: K = thousand, M = million, B = billion, T = trillion. See Data S2 – 7 for full results by country and Data S8 for subregional breakdown.

Region	Country	Iron yield change (grams)	Iron requirements met (people per year)	Zinc yield change (grams)	Zinc requirements met (people per year)
Africa	South Africa	-36.2B	-4.4M	-11.1B	-3.0M
	Zambia	-10.2B	-1.3M	-3.1B	-839K
	Zimbabwe	-2.6B	-321K	-803M	-216K
	Ethiopia	4.2B	515K	1.3B	346K
	Benin	6.2B	754K	1.9B	506K
	Nigeria	26.5B	3.2M	8.1B	2.2M
Oceania	Australia	-1.5B	-182K	-454M	-122K
Asia	Indonesia	-9.3B	-1.1M	-2.8B	-764K
	Cambodia	-5.8B	-715K	-1.8B	-480K
	Vietnam	-5.8B	-704K	-1.8B	-472K
	India	166.6B	20.4M	50.9B	13.7M
	China	569.7B	69.7M	174.1B	46.8M
	Russia	707.1B	86.5M	216.1B	58.0M
Europe	Ukraine	-43.0B	-5.3M	-13.2B	-3.5M
	Moldova	-4.0B	-488K	-1.2B	-328K
	Hungary	-6.2B	-753K	-1.9B	-505K
	France	17.6B	2.2M	5.4B	1.4M
	Italy	41.3B	5.0M	12.6B	3.4M
	Russia	308.3B	37.7M	94.2B	25.3M
North America	United States	3.9T	482M	1.2T	323M
	Canada	2.6T	316M	790.1B	212M
	Mexico	8.1B	989K	2.5B	664K
South America	Colombia	-3.6B	-440K	-1.1B	-295K
	Ecuador	-1.3B	-158K	-395M	-106K
	Venezuela	-712M	-87K	-218M	-58K
	Paraguay	171.7B	21.0M	52.5B	14.1M
	Argentina	287.4B	35.1M	87.8B	23.6M
	Brazil	2.9T	350M	875.3B	235M
	Brazil	2.86T	350M	875.29B	235M

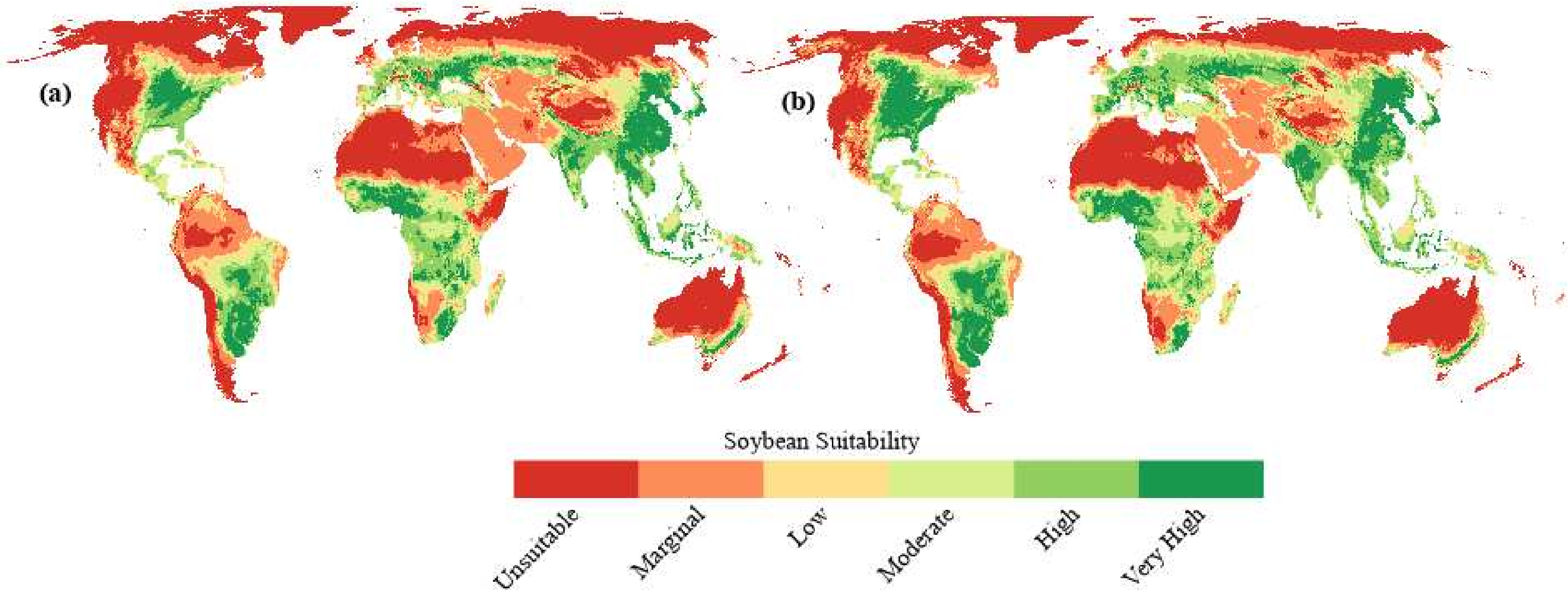

Fig. 1 | Global soybean suitability under historical and future climate scenarios. (a) Baseline suitability for soybean cultivation under historical climate conditions (WorldClim v2.1, 1970–2000); (b) projected suitability by 2050 under the SSP2-4.5 climate scenario. Suitability was modelled using MaxEnt, with occurrence data derived from the Spatial Production Allocation Model (SPAM) for the years 2010 and 2020 [43]. Models were trained with all 19 bioclimatic variables (BIO1–BIO19), representing temperature and precipitation. Future projections (b) used downscaled WorldClim v2.1 data for SSP2-4.5 (2050) [90]. Continuous suitability probabilities (0 – 1) were reclassified into six categories: Unsuitable (≤0.04), Marginal (<0.19), Low (<0.34), Moderate (<0.54), High (<0.74), and Very High (≤1.00). See Table S1d for full classification details.

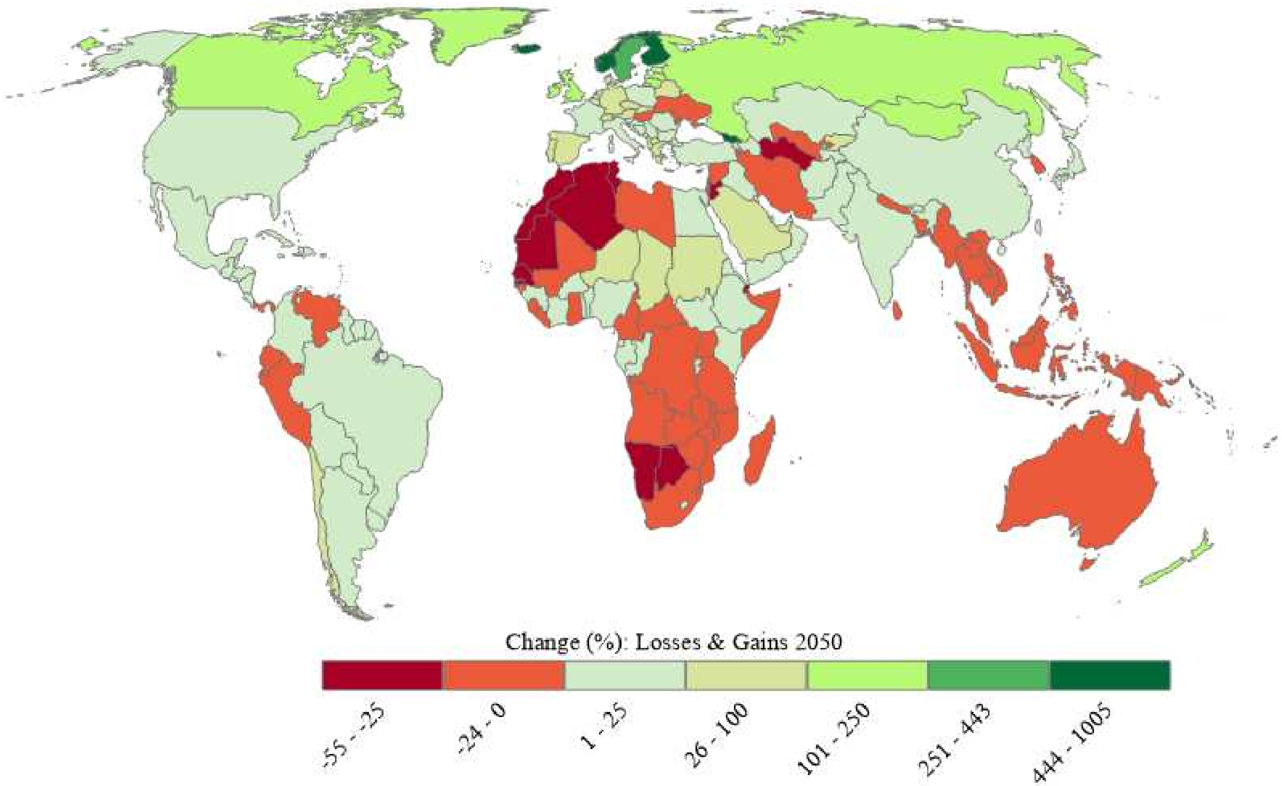

Fig. 1c | Projected country-level changes in soybean climatic suitability and harvested area by 2050 (SSP2-4.5). Projected gains and losses in soybean climatic suitability (% change) and harvested area (hectares) at the country level by 2050, based on MaxEnt model projections under the SSP2-4.5 climate scenario. Country boundaries were defined using the Global Administrative Areas (GADM) database (https://gadm.org). For transcontinental countries (e.g., Russia, Türkiye), reported values represent the mean of their separate continental components. Percentage changes are relative to baseline and may overstate impacts in countries with very small or no baseline soybean area, where large proportional changes reflect negligible absolute areas in the SPAM [43] dataset.

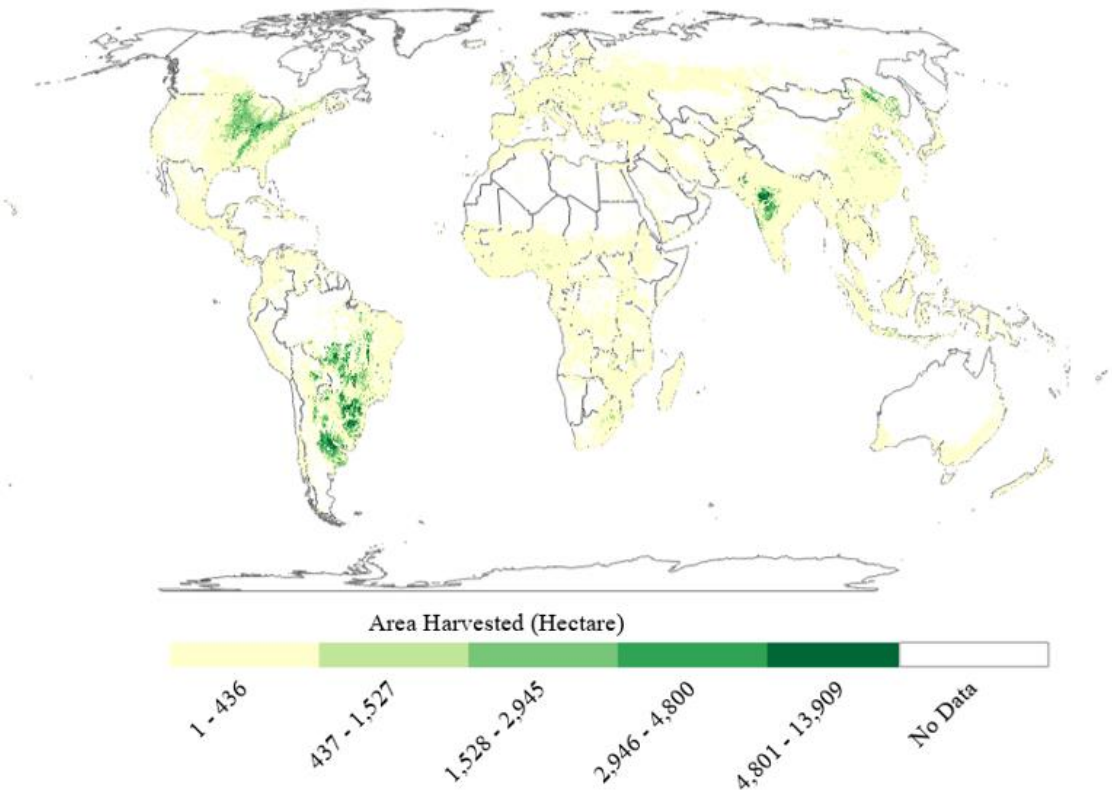

Fig. 1d | Global distribution of soybean harvested area, 2010–2020. Spatial distribution of global soybean harvested area based on SPAM data, pooling 2010 and 2020 to capture recent cultivation patterns and minimize temporal bias. Values indicate total harvested area per ~10 km grid cell (hectares); values may exceed the cell's physical area (10,000 ha) in regions with multiple cropping cycles. Country and subnational boundaries for mapping and summary statistics were defined using the Global Administrative Areas (GADM) database (https://gadm.org). SPAM integrates national and subnational statistics, remote sensing, and ancillary spatial data to generate spatially explicit crop distribution maps [43].

Figures

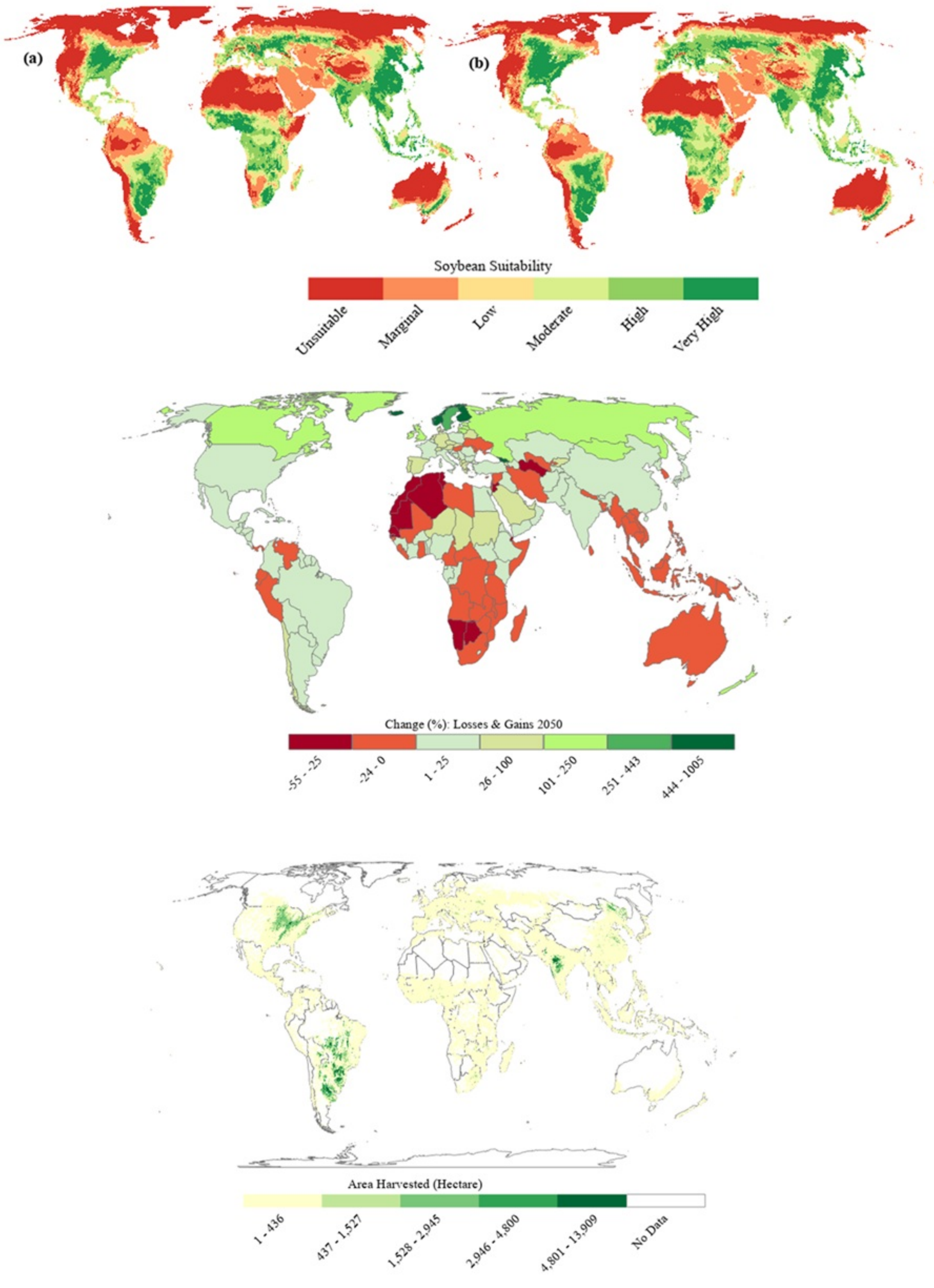

Figure 1

Global soybean suitability under historical and future climate scenarios. (a) Baseline suitability for soybean cultivation under historical climate conditions (WorldClim v2.1, 1970–2000); (b) projected suitability by 2050 under the SSP2-4.5 climate scenario. Suitability was modelled using MaxEnt, with occurrence data derived from the Spatial Production Allocation Model (SPAM) for the years 2010 and 2020 [43]. Models were trained with all 19 bioclimatic variables (BIO1–BIO19), representing temperature and precipitation. Future projections (b) used downscaled WorldClim v2.1 data for SSP2-4.5 (2050) [90]. Continuous suitability probabilities (0 – 1) were reclassified into six categories: Unsuitable (≤0.04), Marginal (<0.19), Low (<0.34), Moderate (<0.54), High (<0.74), and Very High (≤1.00). See Table S1d for full classification details.

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