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Improving maize self-sufficiency in Northern Latin America to reduce imports and land clearing

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Abstract

Maize has been the basis of diets in Northern Latin America since its domestication 9,000 years ago. However, the region has become a major maize importer over the past three decades, which poses a threat to national food security and natural ecosystems. Here, we investigate the potential to increase maize production in the region through yield intensification on existing cropland and assess scenarios of self-sufficiency, import requirements, and land-use change. Using crop modeling coupled with local climate, soil, and management data, we show that average farmer yield represents only 42% of the yield potential as determined by local climate and soils. Closing the exploitable yield gaps reduces but does not eliminate the maize deficit, especially in populous countries such as Mexico, Colombia, and Peru. On the other hand, failure to narrow down current yield gaps can double the regional maize deficit within the next 25 years. We conclude that the region must improve current yields to mitigate the negative economic and environmental outcomes associated with larger imports and land clearing for agriculture.

Introduction

The Northern Latin America (NLA) region includes Mexico, Venezuela, Colombia, Peru, Ecuador, and several countries in Central America and Caribbean. The region hosts 350 million hectares of forests and savannahs of high conservation value and a population of 340 million, of which *ca.* 23 million are chronically undernourished[1–3]. Since its domestication in Mexico *ca*. 9,000 years ago, maize has been a key component of NLA diets and culture[4,5]. For example, Mexico has the highest per-capita maize consumption in the world for direct human food, reaching 123 kg per person per year[6]. However, NLA has shifted from being nearly self-sufficient for maize in the past to heavily rely on imports since early 1990s **(**Fig. 1A**)**. At present, NLA imports half of the domestic maize that is being consumed in the region, mostly from the United States, Brazil, and Argentina [3]. This change has been driven by a threefold increase in maize demand, with a comparably smaller increase in domestic production due to modest yield gains and a slight reduction in maize area **(**Fig. 1B**)**. Moreover, average yields have remained stagnant in most of NLA rainfed maize areas, including Central America, Venezuela, and Mexico **(Extended Data** Fig. 1**)**[3,7]. In the current context of trade disruption and geopolitical conflicts, countries in the region seek to attain a reasonable level of self-sufficiency for key staple crops, especially maize[6,8,9].

At question is how to achieve the desired degree of maize self-sufficiency while minimizing the negative environmental impacts associated with land conversion for agriculture. Recent studies have shown that 130 million hectares of natural ecosystems in NLA are suitable for agriculture, including high conservation value areas in tropical highlands in Mexico and the Andes, rainforests in Central America and the Amazon Basin, and savannas in the Llanos of Colombia and Venezuela[10,11]. The NLA region hosts *ca.* 900 endemic species of birds and 1200 endemic amphibians[12], representing 10–15% of the global species in each class. Furthermore, the region can become a major CO_2 emitter if natural ecosystems are converted for production of annual crops. For example, Molotoks et al.[13] estimated that Mexico alone might release nearly one billion tons of C due to cropland expansion by 2050. Thus, without an explicit effort to increase maize production on existing cropland, it would be difficult for the region to reduce import requirements while avoiding land clearing for agriculture, a trend that is evident in other regions of the world[14–16].

The potential to increase maize production in NLA without massive land clearing depends on the capacity to increase yield on existing cropland, which needs to be complemented with policy and regulation to ensure that yield gains lead to land sparing for nature[17,18]. Unfortunately, there has been no effort to quantify the potential maize production of the region and how yield intensification may contribute to achieving a more desirable level of self-sufficiency while alleviating pressure on land clearing. Such effort requires estimating the current yield potential, as determined by local weather and soils, and current yield gaps, that is, the difference between farmer yield and yield potential[19–21]. Estimating the yield potential for the NLA region is challenging. First, climate within the region ranges from temperate to tropical and from arid to humid. Second, complex topography leads to sharp gradients in climate over short distances. Third, there is wide range of cropping systems, from irrigated to rainfed crops and from single to double maize systems, that may co-exist in many countries. Finally, maize is grown by a highly heterogeneous mix of farmers, ranging from traditional smallholders to large commercial farmers. Hence, to be relevant and effective to orient national research programs and inform policy, a detailed approach that accounts for the spatial variation in climate, cropping systems, water regimes, and types of maize growers is needed to quantify current yield potential and identify areas with largest room to increase on-farm yields through better agronomic management.

The NLA region is approaching a crossroads in which reaching a more desirable level of maize self-sufficiency will conflict with conservation of natural ecosystems and their rich biodiversity[10]. Here, we investigated to what extent maize yield intensification on existing cropland in NLA can reduce reliance on imports while alleviating pressure on conversion of natural ecosystems for maize cultivation. We followed an approach that combines crop modeling with spatially explicit local data on climate, cropping systems, soils and water regimes to identify areas with largest room for yield intensification. Our assessment focused on the largest eight producing countries in the NLA region – Mexico, Guatemala, Honduras, El Salvador, Venezuela, Colombia, Ecuador, and Peru – which collectively account for 93% and 97% of regional maize harvested area and production, respectively **(Extended Data** Fig. 2**)**. Finally, we investigated future scenarios of maize self-sufficiency for different scenarios of yield intensification. We then discuss implications of these findings for agricultural research and extension programs and policy aiming to improve food security and protect national ecosystems.

Results

Yield potential and stability as determined by local climate and soils

The area-weighted average yield potential in the NLA region was 12.6 t ha^{-1} $crop^{-1}$ (Fig. 2A). Among countries, water regimes, and cropping seasons, national average yield potential was lowest for rainfed maize in Ecuador, Peru, and Colombia, ranging from 8.5 to 9.6 t ha^{-1} $crop^{-1}$. However, the lower average yield potential in these countries was compensated by higher crop intensity as farmers can grow two maize crops per year in most of their producing regions, yet with lower and less stable yields in the second crop (**Extended Data** Fig. 3). Conversely, irrigated maize in Mexico and rainfed maize in El Salvador and Honduras showed higher national average yield potential (13.9–16.8 t ha^{-1} $crop^{-1}$) but with only one crop harvest per year as irrigated and rainfed maize are only grown during the dry and wet seasons, respectively. Irrigated maize in Peru combines the highest yield potential (18.2 t ha^{-1} $crop^{-1}$) with two crop harvests per year, resulting in the highest annual yield potential in the region, although limited to a small area (0.1 M ha). On the other hand, Mexico, Guatemala, and Venezuela, which are the three countries with largest maize area, accounting for 76% of regional maize area, showed intermediate average yield potential for rainfed maize (11.4–12 t ha^{-1} $crop^{-1}$).

Spatial variation in yield potential was not only apparent in countries with irrigated and rainfed crops (Mexico and Peru) but also within the same water regime and country. For example, rainfed maize yield potential in Mexico ranged from 5.1 t ha^{-1} $crop^{-1}$ to 17.4 t ha^{-1} $crop^{-1}$ across sites due to sharp differences in precipitation and elevation (Fig. 2B). On the other hand, production risk, as quantified using the inter-annual coefficient of variation of yield potential, was relatively low in both irrigated and rainfed maize (area-weighted average CV = 12% and 21%, respectively) (Fig. 2C). Most rainfed maize is grown during the wet season, when ample water supply from precipitation reduces the probability of water stress, leading to relatively high and stable yield potential. Variation in yield potential was large (CV from 35 to 70%) only for rainfed crops grown at high-elevation (e.g., central highlands of Mexico), water-limited environments (e.g., southern Ecuador), and for second-maize crops exposed to terminal drought (*e.g.*, Orinoquia basin in Colombia). Environments where water limitation was large (*i.e.*, difference between water-limited yield potential and yield potential > 20%) represented less than 10% of the harvested maize area in the region (Fig. 2E).

Gaps between average on-farm yield and yield potential

Across sites, water regimes, and environments, the average area-weighted farmer yield was 5.3 t ha^{-1}, which represents only 42% of the yield potential (Fig. 2A). Achieving yield potential is unfeasible because it requires high levels of inputs and perfection in crop and soil management, including weed, pest, and disease control[22–24]. A more realistic target is to reach 80% of yield potential, which is considered a reasonable field target for farmers who have adequate access to technology, inputs, markets, and agronomic knowledge[20,21]. Using this 'attainable yield' as a reference to evaluate the available room for yield improvement, our study identified regions with largest room for yield improvement at national and subnational levels. For example, Honduras, Guatemala, and El Salvador showed largest yield gaps, with average farmer yields representing just 13–20% of the yield potential (Fig. 2A). By contrast, yield gaps were relatively small in Ecuador and for irrigated maize in Mexico, where average farmer yields reached 60–62% of the yield potential. Irrigated fields in Peru had intermediate gaps (ca. 50% of the yield potential). Rainfed maize systems in Mexico, Peru, Colombia, and Venezuela showed larger yield gaps, with average farmer yields ranging from 30 to 44% of the potential (Fig. 2A). However, these countries showed large differences at subnational level. For example, in Colombia, farmers in Valle del Cauca were close to the attainable yield, reaching 72% of the potential, whereas farmers in the northern Caribbean region showed wider gaps, with average yields as low as 16% of the potential (Fig. 2F). Likewise, in Mexico, yield gaps were larger in the southern tropical region and central highlands, intermediate in the mid-altitude central region, and smaller in the northwest Pacific coast (Fig. 2F).

Maize self-sufficiency in different scenarios of yield gap closure

None of the eight countries included in our analysis produce enough maize to meet their domestic demand, with maize deficits ranging from about 16.9 Mt in Mexico to 0.1 Mt in Ecuador, summing up a total of 31.2 Mt of maize that needs to be imported from other regions (Fig. 3A). Inclusion of other countries in the NLA region that produce little maize but still demand large quantities increase the deficit to 35.4 Mt (Fig. 3A, **inset)**. The population of NLA is projected to grow from 339 million in 2020 to 404 million by 2050, which together with a 26% increase in maize consumption per capita during the same period, will increase maize demand by 50%, reaching 111 Mt per year in 2050 (**Supplementary Table 1)**. Considering current average yields and harvested area, such increase in maize demand could raise the annual maize deficit of the region to a total of 73 Mt, which is equivalent to *ca*. US$14.5 billion at current commodity prices (Fig. 3C). The largest absolute increase in maize demand and potential deficit is expected in Mexico (+ 16.1 Mt), while the largest relative increases are expected in Peru (+ 131%) driven mainly by rising feed demand from increasing meat consumption.

We explored how closing the exploitable yield gap on existing cropland can contribute to reducing import requirements and land requirements by 2050 (Fig. 3B). For this scenario, we assumed no change in maize area, number of crops per year, and irrigated fraction across the region. Likewise, we assumed no change in area share of native varieties in Mexico, a country with protective policies on maize genetic diversity and cultural heritage[25–28]. Additionally, we assumed that average relative yield gain in countries not included in our yield gap assessment and that of native varieties in Mexico will equal the average relative yield gain in the rest of the region under each scenario **(Methods; Supplementary Table 2).** Our results indicate that if farmers reach 80% of the yield potential by 2050 across NLA, they can offset the projected increase in maize demand, reducing the need for imports from the current 35 Mt to 28 Mt and substantially more when compared with the maize deficit projected for the scenario without yield increase (73 Mt). This reduction would save US$1.5 billion relative to current annual maize import expenditures and US$9 billion when compared with the scenario without yield increase. However, reaching 80% of the yield potential by 2050 would require unprecedented rates of yield gain of up to 270 kg ha^{-1} $year^{-1}$, which sharply contrasts with their recent yield trends of little to no yield gains (**Extended Data** Fig. 1**)**. They are also much higher than historical rates of yield gain in major maize producing countries, including United States, Argentina, Brazil, and China[29].

Therefore, we also explored an intermediate and more plausible scenario where farmers close half of the exploitable yield gap (Fig. 3, **Supplementary Table 2 & Supplementary Table 3**). In this scenario, all countries but one will still not be self-sufficient for maize. Thus, while yield intensification can help mitigate the impact of growing maize consumption in NLA, it will not be sufficient by itself to eliminate the large deficit, especially in Mexico, Peru, Colombia, and Venezuela (Fig. 3A). For example, maize imports will more than double in Peru compared to current levels under all scenarios. Still, domestic yield improvement is essential to make countries less reliant on maize imports, especially in the current context of geopolitical conflicts among countries. For example, the maize deficit in Mexico in the scenario without yield increase (33 Mt) is equivalent to US$6.6 billion and *ca.* 3 million hectares of maize in the United States, which is the main source of imported maize. Likewise, failure to increase average yields will add pressure on cropland expansion. For example, the maize deficit projected for Colombia, Guatemala, and Peru, three countries with large tracks of forest and savannah that could potentially be cleared for agricultural production, would be equivalent to 2.2, 2.4, and 5 million hectares of new cropland in the scenario without yield intensification (Fig. 3B; **Supplementary Table 4**). On the other hand, the area requirement would decrease to 1.3, 0.2, and 2 million hectares if farmers close half of the exploitable yield gap. At the end, yield intensification could help ameliorate, but does not eliminate, the need for imports and/or cropland expansion to offset the large maize deficit in the region. This result highlights the need for careful land-use planning to minimize the negative environmental impact associated with cropland expansion and ensure the economic resources and infrastructure needed to store and transport maize imports.

Discussion

Despite being the center of origin and diversity of maize, our results show that half of the maize consumed in NLA is produced outside the region. In the context of grain price volatility, trade disruptions, and geopolitical conflicts, it would be prudent for countries of the region to reach a more reasonable level of self-sufficiency for maize and other crops as has been highlighted in previous reports[6,9,30]. Our study shows that, without yield improvement, meeting future maize demand will require larger imports and/or cropland expansion (Fig. 3). Offsetting the maize deficit would require an annual import amount of nearly 73 Mt, with an associated value of US$14.5 billion. On the other hand, the extra land requirement to avoid imports sums up to 22.6 million ha, increasing the risk of converting carbon-rich ecosystems and negative impacts on biodiversity and climate warming. Either way, failure to improve current self-sufficiency through yield intensification will have profound economic and environmental consequences in the region.

The yield potential estimated for the region in our study is comparable to those reported for other maize producing regions with similar biophysical conditions. For example, the yield potential of irrigated maize in Mexico and Peru (16.8–18.2 t ha^{-1}) is comparable to that reported for irrigated maize in arid climates[31,32]. Likewise, the relatively high and stable yield potential reported for rainfed maize is consistent with previous studies in favorable rainfed environments in Sub-Saharan Africa and South-east Asia[33,34]. Moreover, the yield potential is relatively high and stable across the region, due to the small degree of water limitation. On the other hand, the average yield gap in the NLA region is among the largest worldwide, except for those in Sub-Saharan Africa and Southern Asia[33,36,37]. Our results suggest that agronomic management is the main factor explaining the low maize yields across the NLA region, together with the yield penalty associated with use of native varieties. Not surprisingly, yield gaps are relatively small for irrigated maize in Peru and Mexico, and rainfed maize in Ecuador, where national programs have provided support for technology adoption[38,39]. Previous studies have shown that farmer yields in the region could increase substantially with better nutrient management, including balanced nitrogen, phosphorous, and potassium fertilization and better timing and placement[40,41], adoption of soil management practices to improve soil cover and organic matter while reducing soil erosion, compaction, and acidity[42–45], and improved plant stands through better sowing practices and weed, disease, and pest control[41,46]. At present, maize management is highly heterogeneous across NLA, with some farmers applying high inputs with low efficiency, while others relying in traditional practices and no modern technologies, reflecting uneven access to information, credit, and technical support[38,39]. For example, in Colombia and Mexico, about half of the maize area is cultivated by smallholders using native varieties and traditional practices, reaching yields of only 2 t ha^{-1} [9]. Consequently, achieving higher yields with high input-use efficiency and cost-effectiveness will require targeted investments in agricultural research and development, extension services, and policies that improve farmers' agronomic management, access to inputs, markets and information.

Full closure of the exploitable yield gaps (*i.e.*, increasing average farmer yield up to 80% of the yield potential) could greatly buffer against the large maize demand projected for the next 25 years and even allow a few countries (Guatemala, El Salvador, Ecuador, and Honduras) to reach self-sufficiency and generate a small surplus available for export to neighboring countries (Fig. 3; **Supplementary Table 4**). Likewise, intensification could mitigate conversion of natural ecosystems for agriculture, although land-use policy and enforcement must be in place to ensure that yield gains lead to land sparing for nature. However, complete yield gap closure would require drastic changes in crop management and technology adoption, which are unlikely to occur fast enough considering the historical yield trends in the region[47,48]. Closing half of the exploitable yield gap, which is a more feasible target, would still contribute to reducing the maize deficit but falls short to ensure a reasonable level of self-sufficiency in populous countries of the region, including Mexico, Peru, Colombia, and Venezuela. Thus, other alternatives might be explored in addition to yield intensification to further improve maize self-sufficiency and reduce import reliance, including expansion of maize area. However, this option is subject to several constraints and potential negative outcomes (**Supplementary Table 4**). For example, avoiding the maize deficit of Colombia, Venezuela, Ecuador, and Peru through rainfed maize area expansion would require 8.2 million hectares of land clearing at current yield levels. If cropland expansion occurs at expense of rainforest, 4,453 $MtCO_2e$ would be released from associated land clearing, which has a social cost of US$846 billion[10,13,14,49]. In contrast, the environmental impact would decrease substantially by combining yield intensification with strategic conversion of grasslands, pastures, and other low-C ecosystems for maize cultivation (e.g., the Orinoquia region in Colombia and Venezuela)[50]. For instance, the extra maize area requirement of those four countries (i.e., Colombia, Venezuela, Ecuador, and Peru) could be reduced from 8.2 M ha to 3.8 M ha by closing half of the exploitable yield gap (Fig. 3), while the greenhouse gas emissions could be reduced from 4,453 $MtCO_2e$ to 232 $MtCO_2e$ if this is further combined with strategic conversion of grasslands and pastures instead

of rainforest. However, we note that long-standing fragile land-tenure, social conflicts, and wealth inequality across the region constrain the feasibility of a targeted cropland expansion into low-C areas[51,52]. On the other hand, low maize-self-sufficient and larger maize imports from other countries such as Brazil, Argentina, and the United States could lead to externalities in other countries, including land clearing for maize cultivation and/or larger use of agricultural inputs to foster further yield gains. Thus, improving regional maize production could have positive environmental impacts from local to regional levels.

Irrigation expansion and/or higher maize cropping intensity (*i.e.*, number of crops per year) could be another strategy to boost maize production **(Supplementary Table 4)**. However, we are not aware of changes in irrigation fraction or cropping intensity in the region over the past 25 years and there are several factors limiting adoptions and/or impact. For example, some studies suggest plenty of room for irrigation expansion in southern Mexico[25], and there have been recent announcements of billionaire investments to expand irrigation in Peru[53]. Yet, irrigation resources will most likely be used to grow high-value cash crops with higher profit than maize[54,55]. Furthermore, freshwater availability for irrigation is becoming increasingly limiting in some regions, including the Pacific region in Peru and Mexico[54–57]. On the other hand, growing a second maize crop may be possible in some regions where double cropping is not currently practiced[58]. However, yields of the second crop are usually lower and less stable compared with the main crop due to water limitation, reducing their adoption and potential impact[58]. Finally, there has been debate about the role of native maize in Mexico, which accounts for 60% of the national rainfed maize harvested area[7] (3.2 M ha). While increased adoption of hybrid seed would certainly raise average yields, the exact impact on national maize production is uncertain as native varieties are often grown in less favorable environments with lower yield potential, degraded soils, and by smallholders with limited access to inputs[25]. Moreover, there is a strong desire by local governments and NGOs to conserve the maize genetic diversity and increase their productivity as reflected in the current research programs, policies, and public debate[6,26–28,59,60], [27,28]. For our scenario assessment, we assumed that the yield of native varieties will increase at the same relative rate as for hybrid maize, rising from 1.2 t ha^{-1} to 1.9 t ha^{-1} (+ 60%) under the scenario of half closure of exploitable yield gaps and up to 2.6 t ha^{-1} with full closure. Associated maize production would be different if the future area and/or yield of native maize differ substantially from those assumed in our assessment.

Our analysis is subject to several sources of uncertainty. Estimates of yield potential and yield gaps depend on the quality and representativeness of weather, soil, management and yield data used for model calibration and upscaling[61]. To minimize these uncertainties, we prioritized high-quality measured data and used models that have been calibrated for locally adapted hybrids grown in experimental sites across the regions **(Extended Data Fig. 5)**. Our study does not explicitly account for the potential impacts of climate change on future maize yield in the region. Although climate change is expected to negatively affect maize production in parts of NLA, particularly in Central America[62,63], the relatively modest changes projected for the first half of this century, together with ongoing adaptation through improved genetics and management, suggests that our conclusions for 2050 are robust. Moreover, the magnitude of the yield gap is large **(**Fig. 2**)**, which means that the room for yield improvement will still be high regardless of changes in the yield potential as driven by climate change. Finally, we explored other possible strategies (cropland expansion, irrigation, cropping intensity, and changes in area of native maize varieties) to increase maize production in NLA and estimated their potential impact **(Supplementary Table 4)**. We are aware that our semi-quantitative analysis was based on coarse statistics, fragmented data from previous studies, and broad assumptions **(see Methods)**. Still, our assessment clearly shows that other options to increase maize production in the region are limited by multiple biophysical and social factors, highlighting the role of yield intensification on existing cropland as a pathway to achieve a more reasonable level of maize self-sufficiency in the region while also protecting natural ecosystems.

Methods

Study area

We assessed eight main producing countries in the NLA region: Mexico, Guatemala, Peru, Venezuela, Honduras, Colombia, Ecuador, and El Salvador. Collectively, these countries include 10 million hectares planted with maize, accounting for 93% and 97% of maize harvested area and production in the NLA region[3]. We considered both rainfed and irrigated crops in Mexico and Peru, where irrigated maize accounts for 22 to 25% of total maize harvested area[7,64]. For other countries, we only considered rainfed crops as irrigated area is relatively small (< 5%)[65]. Thus, we evaluated a total of 10 country-water regime combinations.

For each country and water regime, we selected several representative sites. The goal was to cover a large fraction of the national maize area while portraying the range of biophysical environments where maize is grown. To that end, we followed the site selection protocols of the Global Yield Gap Atlas (GYGA, www.yieldgap.org)[66,67], which considers availability of weather stations with long-term records, maize harvested area distribution, and a climate-zone (CZ) spatial framework. The latter delineates regions based on three parameters influencing crop yield: (i) annual growing-degree days, which provides an indication of the length of the growing season, (ii) aridity index, which indicates the degree of water limitation, and (iii) temperature seasonality, which describes the annual oscillation in temperature[68]. As a first step, we selected CZs that account for > 5% of national maize area for each country-water regime combination. Within these CZ, we delineated 100-km radius buffer zones around available weather stations to calculate the maize harvested area covered by each weather station, clipping their borders to ensure that they do not extend beyond the CZ where each station was located. Subsequently, we identified weather stations with > 1% of national maize area coverage and selected a number of them until reaching a coverage of *ca.* 50% of national maize area with selected stations for each country-water regime. To do so, we first selected the station with largest maize harvested area in each CZ. Then, we discarded those closer than 180 km to the selected stations and repeated the process until reaching the desired coverage. In those

places where weather stations where not available for important maize producing regions, “hypothetical” stations were created to ensure proper cover of these areas.

Given the strong interest on preserving the genetic diversity of maize native varieties, particularly in Mexico[25,26], we only focused on maize areas planted with hybrid seed – including yellow maize for animal feeding and white maize for milling. Unfortunately, there are no maps of hybrid maize area across NLA. Thus, we first applied this site selection protocol by considering all rainfed or irrigated maize harvested area as reported in SPAM v2010[69,70]. Then, we refined our selection using local information on hybrid maize area[6,64,71] and expert knowledge of agronomists and researchers from private and public sectors, removing sites where there is little or no hybrid maize area and adding sites where hybrid maize area is not well represented in SPAM. In total, we selected 65 buffers that included 26% of the total regional maize harvested area (including native varieties), and between 18–83% of the total national harvested area **(Extended Data** Fig. 2**)**. In turn, the CZs where buffers were located included 46% of the total regional maize harvested area, and between 34–83% of the total national harvested area. In Mexico, the only country with available data on hybrid maize area[6], the selected buffer zones covered 30% of the national hybrid maize area, while the CZs covered 50%. Achieving higher maize coverage with a reasonable number of sites was not possible due to the sparse distribution of maize across NLA and the region complex topography that leads to small climate and buffer zones. Nevertheless, collectively, the selected buffers covered well the range of biophysical environments where maize is grown in the NLA region **(Extended Data Fig. 4)**.

Weather data for simulation of yield potential

We compiled, quality-checked, and harmonized long-term (2000–2021) daily data on incident solar radiation, maximum and minimum temperature, and precipitation **(Supplementary Table 6)**. Prior research has shown that 10 to 15 years of daily weather data is needed for a robust estimation of average yield potential and its inter-annual variability for rainfed crops[61]. Following recommendation from previous studies[67,72,73], we gave priority to measured data on temperature and precipitation. Unfortunately, long-term daily records on temperature and precipitation were not available for Honduras, Venezuela, and Ecuador. For 11 sites in these countries, we used measured daily data collected over short periods (< 3 years) or measured monthly averages to calibrate long-term NASA-POWER data on temperature and precipitation following the propagation methods developed by van Wart et al. (2015)[72]. A total of 5 sites did not have any weather record available, and we thus used the NASA-POWER temperature and precipitation data directly. At the end, we used measured, propagated, and uncorrected NASA-POWER temperature and precipitation data for 75%, 17%, and 8% of the 65 sites, respectively. Finally, we used incident solar radiation data from NASA-POWER for all sites as previous studies have shown that they can reliably be used for crop modeling[61].

Temperature outliers were corrected using 30-day moving-window temporal correlations with two nearby stations within a 50 km radius[74] when available. These same correlations were used to fill short periods of missing temperature data (< 10 consecutive days), while longer data gaps were filled with biased-corrected NASA-POWER estimates[72]. Precipitation data were visually inspected and, when necessary, corrected or gap-filled using data from nearby stations within 20 km in the same CZ, or from NASA-POWER when no nearby weather station was available[61]. Following this approach, about 2% of the total daily weather data was filled or replaced using correlations from nearby stations or with NASA-POWER data. Finally, we used the Priestley-Taylor method to calculate the reference crop evapotranspiration (ET_0)[75].

Soil properties for simulation of rainfed crops

We used local soil maps and soil profile data to identify the dominant soils and associated properties at each site. For Mexico, Colombia, and Ecuador, national soil maps were available[71,76–78] and it was possible to estimate the fraction of maize area accounted by each soil type in each buffer zone. In those cases, we selected the 2 or 3 most representative soils in each buffer and retrieved associated soil properties from the SISLAC soil profiles database, including soil texture, organic carbon, and bulk density[79]. For other countries (Guatemala, El Salvador, Honduras, Venezuela, and Peru), we selected up to three soils profiles per site directly from SISLAC[79] based on their geolocation and agricultural suitability. We selected soil profiles that were located in (or close to) maize fields according to WorldCereal[65]. Selected soils were validated with local agronomists and researchers from private and public sectors. Based on reported soil texture, we estimated the volumetric soil water content at field capacity and wilting point for each soil layer using pedo-transference functions from the literature for tropical soils[80–82]. An exception was central and north Mexico for which pedo-transference functions for temperate soils were used[83,84]. Information on rootable soil depth was scarce and fragmented. Based on our review of the literature, we set a maximum soil depth of 1.5 and 0.85 meters for temperate and tropical soils, respectively, to account for differences in soil pH between tropical and temperate soils[85,86]. Given the uncertainty in maximum rooting depth of maize in tropical environments, we conducted a sensitivity analysis to assess its influence on rainfed yield potential. Across sites, yield changed by 50–150 kg ha^{-1} for every 10 cm difference in soil depth, with a negligible (< 3%) effect on yield potential in 75% of the cases **(Supplementary Fig. 1)**. Low sensitivity of model outputs to choice of soil depth is attributable to the relatively minor water limitation in the environments where maize is grown across the region **(**Fig. 2**)**.

Simulation of yield potential for irrigated and rainfed crops

We used the CERES-Maize model embedded in DSSAT v4.8[87] to simulate maize yield potential. Simulations assumed no nutrient limitation and no yield reduction due to biotic factors such as weeds, pathogens, and insect pests. In the case of irrigated crops, simulations assumed no water limitations whereas simulations for rainfed crops considered the impact of water stress on grain yield. For the latter, to account for the benefits of conservation

tillage on soil water balances and rainfed yields[42], we simulated long-term crop rotations (including fallow periods) assuming that crop residues were left on the field through no-till or minimum soil disturbance tillage, using the Century model to simulate residue cover dynamics[88,89] and the Suleiman-Ritchie method to estimate soil potential evaporation[90,91]. Yield potential was simulated for each site based on site-specific weather and soil, dominant cultivar, and local crop calendars and dominant crop rotations, as determined based on consultation with local agronomists and researchers **(Extended Data** Fig. 3**)**. In those cropping systems with two maize crops per year (*e.g.*, Peru), both crop cycles yields were averaged to estimate site-specific yield potential on a per crop basis. To determine the optimal plant density, we followed the approach developed by Guilpart et al.[85] based on the seasonal crop water balance (ET_0 – rainfall). Plant densities ranged from 4 to 8.2 plants m^{-2} for rainfed maize, with an average of 7.6 plants m^{-2}, and was set to 8.5 plants m^{-2} for irrigated maize. The choice of optimal planting density was validated with local agronomists and researchers. In all cases, grain yields were adjusted to the standard 15% grain moisture content for commercialization.

Model genetic coefficients were calibrated and validated to represent the most dominant hybrid in each region. First, we calibrated phenological coefficients using data from an irrigated experiment planted on November 26th, 2021, at the CIMMYT research station in Obregon, Sinaloa, Mexico. The experiment was managed to avoid water and nutrient limitations and yield reductions due to biotic stresses. It included four widely used hybrids and three replicates. All phenological phases were carefully recorded, including emergence, anthesis, and physiological maturity. High-quality weather records were available from an on-site weather station. Second, we used data on sowing and silking dates from a vast network of maize trials conducted by a seed company across NLA region to validate phenological coefficients and calibrate hybrids not evaluated at the research station by comparing them with calibrated hybrids. We selected trials located close to weather stations (≤ 50 km distance and ≤ 100 m elevation difference) for which measured weather data were available. To further reduce the influence of measurement errors on phenological coefficients, we grouped observations by hybrid, country, and altitude range (200-meter intervals) and kept groups with at least three field trials. The final dataset included 285 phenological observations distributed across 45 groups. We also used the experimental data to adjust model parameters related with photoperiod sensitivity[92] and the cardinal temperatures associated to cultivars adapted to tropical highland environments[92]. After the calibration, comparison of the average duration of phenological phases showed good agreement between simulated and observed values **(Extended Data Fig. 5)**. Default values for maize were used for growth-related coefficients (*e.g.*, respiration, photosynthesis, water-use efficiency, etc.), but potential grain number and grain filling rate coefficients were calibrated using measured data from the CIMMYT experiment. Following this approach, we calibrated the genetic coefficients of eight cultivars that were highly representative of the maize genotypes adapted and widely grown in the NLA maize producing regions.

To validate model capacity to predict yield potential under irrigated and rainfed conditions, we compared simulated yield potential against the 95th percentile of hybrid trial yields (Y95) for each hybrid by country by water regime combination. The Y95 has been used in previous studies as an empirical proxy of yield potential derived from measured yields in cultivar trials[20,93,94]. For the validation, we selected trials located near a weather station (≤ 100 km distance and ≤ 150 m elevation difference) with data for the corresponding cropping season. To avoid trials with sub-optimal stands and/or severe nutrient deficiencies, we only considered plots with a plant population density at harvest between 6 to 9 plants m^{-2} and a nitrogen fertilizer rate ≥ 200 kg ha^{-1}. We simulated the yield potential of each of the selected 127 maize hybrid trials based on the weather data from nearby stations, and trial-specific cultivar and planting date and density, and, in the case of rainfed crops, soil properties derived FAO Harmonized World Soil Database for each trial site[95]. Comparison of Y95 *versus* simulated yields for those same trials showed reasonable agreement, indicating that the model is capable to simulate maize yield potential across the range of environmental, cultivars, and water regimes in the NLA region **(Extended Data Fig. 5)**.

Estimation of average farmer yield and yield gaps

Average farmer yield for each site was retrieved from sub-national official statistics **(Supplementary Table 7)**. To calculate the average yield for a given site, we used the average yield data reported for the administrative units that overlapped with the selected buffers. In those cases in which more than one administrative unit was located within the buffer, we calculated a weighted average based on fraction of harvested area of each of them relative to the area in the buffer as reported by SPAM[69]. Since our goal was to get a representative estimate of average current farmer yield while avoiding the impact of climate in specific years, we used available yield data from at least 5 years during the 2010–2023 period, giving preference to recent years. Unfortunately, no subnational official statistics were available for Venezuela. The maize hybrid trial network used for model validation also included data on average farmer yield (outside the experimental area). Hence, we used these data to estimate average yields in Venezuela. However, farmers conducting field experiments tend to follow better management, leading to higher yields compared with the rest of farmers in a given region. To avoid this bias, we re-scaled these yields so that their national weighted average matched the national average yield reported by FAOSTAT[3,66]. In the case of Guatemala, subnational yield data were only available for one year (2020). Hence, we adjusted the site-specific average farmer yield values reported in 2020 to ensure that their weighted average at the national level (1.8 t ha^{-1}) matches the one reported by FAOSTAT between 2010 and 2023 (2.1 t ha^{-1}) by increasing all of them proportionally (17%). Given the large area share of native varieties in some regions of Mexico, we calculated average hybrid maize yields by adjusting average farmer yields reported through official statistic by area share and yield of native varieties at the municipality level based on site-specific data reported by CIMMYT[6] as follows:

$$Ya_h = \frac{Ya - Ya_n \times A_n}{A_h} \quad \text{(Eq. 1)}$$

where Ya_h is the average farmer hybrid maize yield, Ya_n is the average farmer native variety yield, and A_h and A_n are the area fraction of maize hybrids and native varieties, respectively. We did not adjust average farmer yields in other countries besides Mexico given the large share of modern hybrids and/or lack of data to differentiate hybrid and native variety yields. Thus, any negative impact on yield associated with use of native varieties in other countries will be included in the yield gap.

For a given buffer, the yield gap was estimated as the difference between the average yield potential considering all simulated years (2000–2021) and average farmer yield[67]. We reported yield gaps as percentage of yield potential. Farmer yields were also reported as percentage of yield potential to indicate the level of 'yield gap closure'. In the case of rainfed maize, each simulated soil was weighted by their relative contribution to the harvested area within the 100-km buffer of each site to retrieve an average rainfed yield potential for each buffer[66]. In those countries where no soil type maps were available, all soils were given the same weight. For buffers with rainfed maize, we also computed a water limitation index (WLI, %) as:

$$WLI\ (\%) = 100 \times (1 - Yw/Yp) \quad \text{(Eq. 2)}$$

where Yw is the water-limited yield potential and Yp is the yield potential without water limitations to get an estimation of the yield limitation due to water supply[96]. Area-weighted yield potential and average farmer yields were also calculated at climate zone, national, and regional levels[66]. To do so, the buffer-level average farmer yield and yield potential were upscaled to CZ level based on the relative contribution of each buffer to total CZ harvested area. Subsequently, CZ yields were upscaled to national levels based on the relative contribution of each CZ to the national maize harvested area. The upscaling was performed separately for irrigated and rainfed maize for Mexico and Peru. Additionally, the maize harvested area distribution reported for Mexico[70] was adjusted based on data on area of native varieties from CIMMYT[6] so that our national and regional estimates for Mexico only considered hybrid maize. Finally, average yield potential and average farmer yield in the NLA region were estimated based on the national-level estimates and fraction of each water regime. Yield gaps at national and regional levels were estimated as the difference between the area-weighted yield potential and average yields.

Scenario assessment

We evaluated different scenarios of maize production and import and land requirements by 2050. We selected 2050 as the target year because it gives enough time for long-term planning and adoption of new technologies, while still being short enough to avoid the projected long-term detrimental impact of climate change on maize yields[97]. In addition, 2050 coincides with the time in which the NLA region will reach 99% of the peak population in this century[98]. Therefore, although maize demand might continue increasing after 2050 due to higher per-capita demand, the rate of increase will slow down considerably during the second half of the century.

We considered three scenarios of yield intensification: baseline (no yield gain) and half and full closure of the exploitable yield gap. The baseline scenario assumes that average farmer yields remain the same as around 2020 (2018–2022 average)[3]. The scenario of full yield gap closure assumes that farmer yields reach, on average, 80% of the yield potential. The latter is commonly referred to as the 'attainable yield', and considered reasonable a target as evidenced by the yield reached in world regions with good access to markets, technology, and extension services[21]. This scenario is useful to understand the overall production potential of the region. However, because closing the yield gap in 25 years requires rates of yield gain that may be difficult to achieve, we also explored a more realistic scenario in which half of the current exploitable yield gap is closed within the next 25 years, which would be more realistic under a scenario of high investment on agricultural research and development programs. For those countries in the NLA region that were not included in our assessment (*i.e.*, Nicaragua, Costa Rica, Panama, Cuba, Dominican Republic, and Haiti), which together represent 3% of total maize production in NLA, we assumed the same average relative yield increase as in the rest of the region. We made the same assumption for maize native varieties in Mexico. For all scenarios, we assumed no changes in harvested area, cropping intensity, and fractions of irrigated area and native maize.

We estimated the annual maize deficit for each country and for the region by comparing the estimated production in each scenario with the project maize demand in 2050. The maize demand was calculated based on the current demand (2020) and the projected relative change in maize demand per capita and population increase between 2020 and 2050. Current total national maize demand was assumed equal to the national domestic maize supply (2018–2022 average) reported in FAOSTAT[3]. Current maize demand per capita was calculated as the ratio between total maize demand and the 2020 country population from UN Population Division[98]. These values served as the baseline to project future maize demand per capita by 2050, which was derived from the relative change in average per capita maize demand between this baseline period (2020) and 2050, using projections from the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) database SSP2 scenario[99]. The IMPACT model projects maize demand per capita by linking population and income with commodity-specific demand functions that account for price, income elasticities, and dietary patterns, which are fed into a global partial-equilibrium framework for simulation of future consumption levels. Then, future maize demand by 2050 was calculated by multiplying the estimated per capita maize demand with each country's expected population, based on the medium fertility variant of the UN population projections[98]. Lastly, we calculated maize deficits and net import requirements as the difference between projected production and demand. We calculated the cost of import requirements considering an average maize price of US$ 200 per metric ton (2017–2024 average from the World Bank)[100]. For each scenario, the area required to cover maize deficits was calculated as the ratio between maize deficits and the average yield of hybrid maize under rainfed conditions. Thus, the area requirement assumes that all maize area expansion is planted with hybrid maize in rainfed conditions, without changes in irrigation and native varieties area. Likewise, the area requirement calculation assumes that the new hybrid maize area reaches the same average yield as the area already under cultivation at the corresponding yield intensification level.

Finally, we assessed production, environmental, and socio-economic outcomes associated with other pathways to increase maize production in the region based on a combination of our results and data from the literature and investigated potential factors limiting their adoption **(Supplementary Table 4)**. These pathways included irrigation expansion, increase in cropping intensity, changes in the fraction of native maize varieties and hybrid maize, and cropland expansion. For the latter, we estimated greenhouse gas emissions (GHG) associated with land conversion by calculating GHG associated with changes in C stocks from aboveground and belowground biomass when land is converted for maize production (GHG_{BIO}), and GHG emissions derived from changes in soil organic C (GHG_{SOC})[14]. For each land use type (Amazonian rainforest and tropical grasslands), GHG_{BIO} was estimated based

on the change in C stocks between the land use type that was converted for production and the average C stocks of maize. C stocks from total biomass were assumed equal to 151.04 t C ha^{-1} for the Amazonian rainforest, 20.48 t C ha^{-1} for tropical grasslands, and 5 t C ha^{-1} for maize[101]. GHG_{SOC} was estimated by assuming that 4% of soil organic carbon (SOC) stocks are lost due to land conversion, following IPCC 2019 guidelines for natural vegetation converted to no-till annual crop production[102]. SOC stocks were assumed equal to 48.8 t C ha^{-1} for Amazonian rainforest and 28.95 t C ha^{-1} for tropical grassland. We expressed GHG_{BIO} and GHG_{SOC} derived from land conversion as CO_2 equivalents by multiplying changes in C stocks by 3.67.

Software

Crop model simulation of yield potential was done with DSSAT (v4.8) [87]. All data analysis, including spatial analysis, was conducted in R (v4.4.2)[103] with the packages terra[104], geodata[105], data.table[106], nasapower[107], DSSAT[108], ggspatial[109], and ggplot2[110].

Data availability

All maize yield potential data generated for this paper are available at the Yield Potential and Yield Gap Atlas (www.yieldgap.org). National level data on maize yield, harvested area, production, export, and import are available at www.fao.org/faostat. Gridded data on maize distribution by water regime is available at www.mapspam.info. Sources of subnational level data on maize yield and area are listed in Supplementary Table 7. Sources of weather station data from national weather services are listed in Supplementary Table 6. Gridded weather data from NASAPOWER are available at https://power.larc.nasa.gov/. National soil type maps are available at https://geoportal.igac.gov.co/contenido/datos-abiertos-agrologia (Colombia), http://geoportal.agricultura.gob.ec/ (Ecuador), and https://www.inegi.org.mx/temas/edafologia/#Descargas (Mexico). Soil profiles data from SISLAC are available at http://54.229.242.119/sislac/es. Data on the current and future population size are available at https://population.un.org/wpp/. Source data are provided with this paper.

Declarations

Competing interests

The authors declare no competing interests.

Authors contribution

F.A.M., J.M.F, and P.G. conceived the research. E.H., J.M.F., C.O., E.T.R., T.V, LB, AR, and FL provided data for model calibration, management practices, and/or validated results. F.A.M., G.R., P.G., and E.H. performed data acquisition, data processing, modeling, and analysis. F.A.M. and P.G. wrote the manuscript with feedback from all authors.

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Footnotes

1. Including Guatemala, Honduras, El Salvador, Nicaragua, Panama, Dominican Republican, Haiti, and Cuba.
2. Yield potential is determined by solar radiation, temperature, and crop traits that determine length of growing period, light interception by the canopy, its conversion to biomass and partitioning of biomass to grains[13]. In the case of rainfed crops, water-limited yield potential is also determined by precipitation patterns and soil properties influencing the crop water balance[14].
3. Costa Rica, Cuba, Dominican Republic, Haiti, Nicaragua, and Panama.

Figures

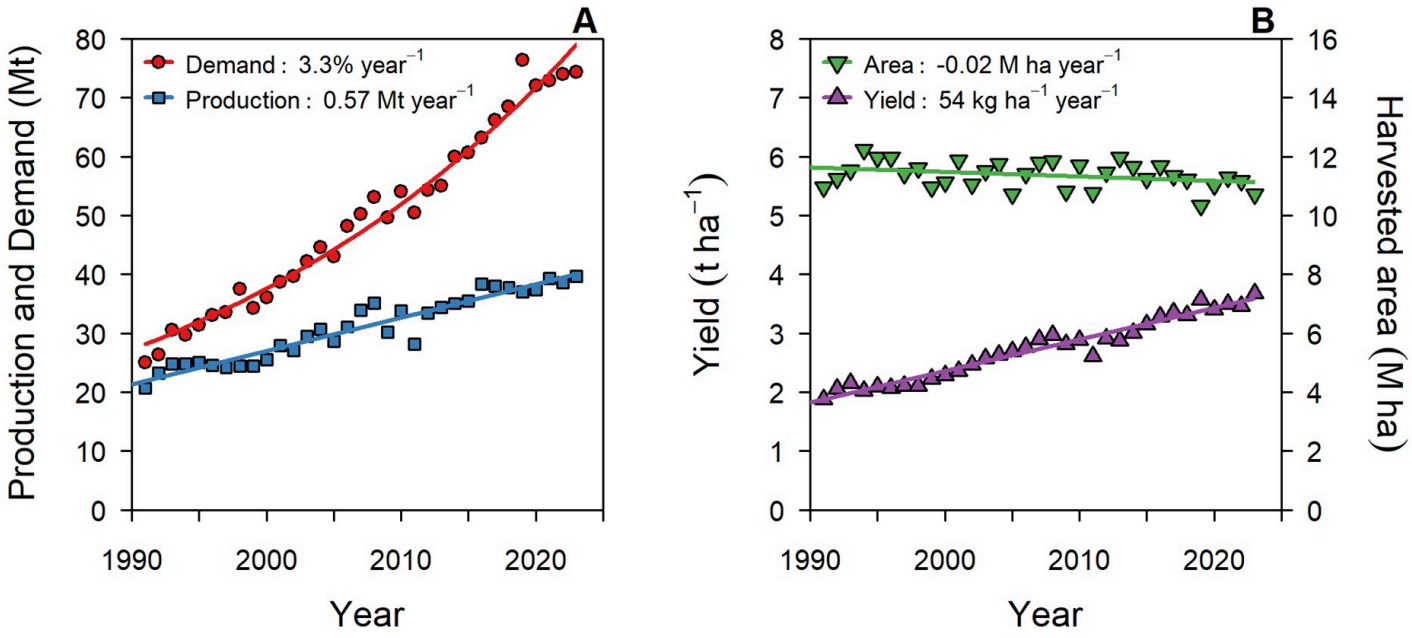


Figure 1

Recent changes in maize production and demand in Northern Latin America. Trends in (A) maize production and demand, and (B) harvested area and yield in Northern Latin America between 1991 and 2023. Data from FAOSTAT[3]. Values in each panel show the rate of change of a variable per year: Production (Mt) = -1103 + 0.57 × year (r^2 = 0.92, P < 0.001). Demand (Mt) = 27 × (1 + 0.033) $^{(year - 1990)}$ (r^2 = 0.98, P < 0.001). Harvested area (M ha) = 41.8 – 0.015 × year (r^2 = 0.11, P = 0.06). Yield (t ha^{-1}) = -105 + 0.54 × year (r^2 = 0.95, P < 0.001). Trends by country are shown in Extended Data Fig. 1. Source data are provided as a Source Data file.

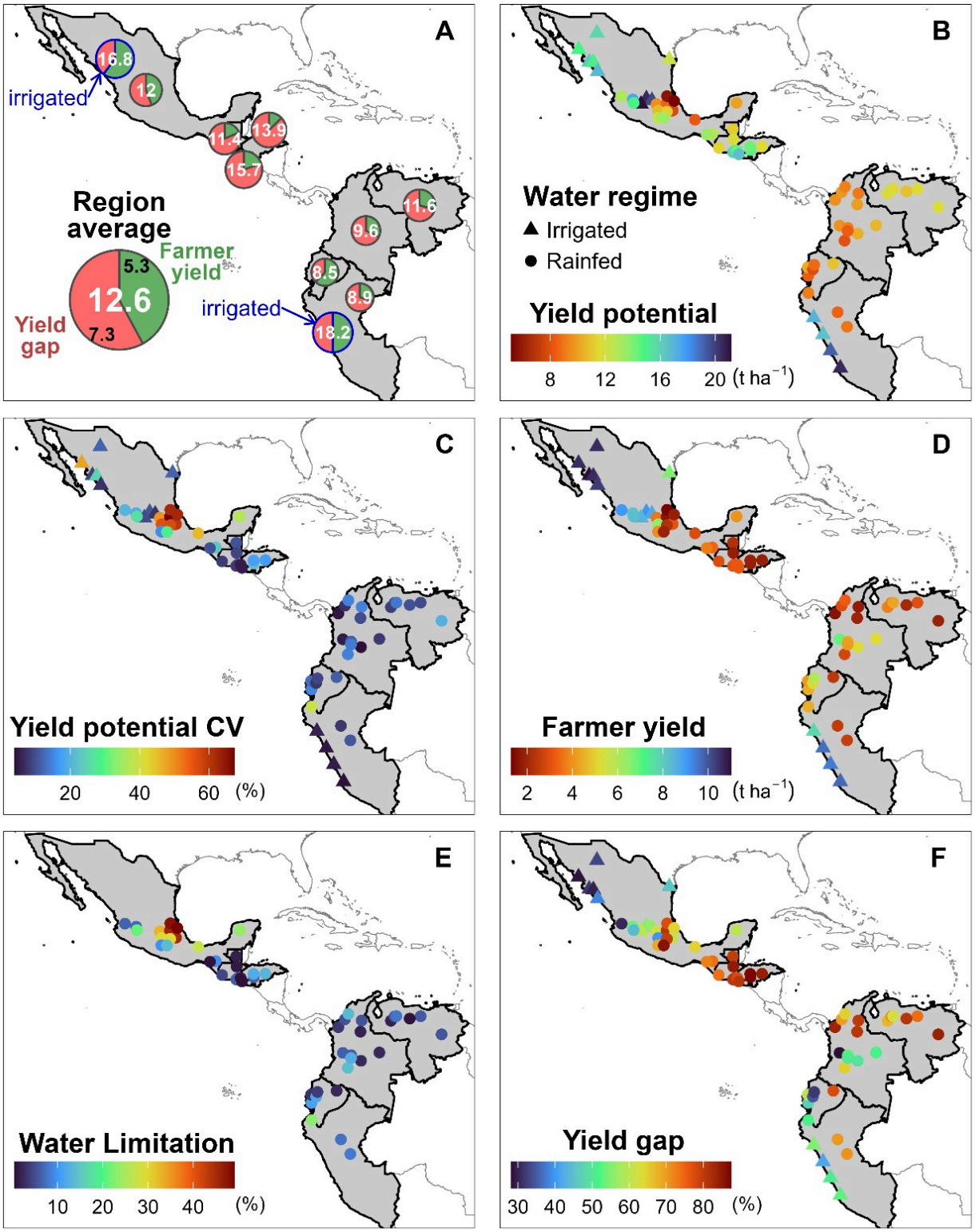


Figure 2

Maize yield potential and gaps in Northern Latin America. (a) Average yield potential (t ha^{-1} crop^{-1}) and fraction of farmer yield and yield gap relative to the yield potential for the whole region and for each country, with size of pie charts proportional to the yield potential. Separate values are shown for irrigated and rainfed crops in those countries with both water regimes. (b) Yield potential, (c) associated year-to-year coefficient of variation (CV), and (d) average farmer yield for representative maize producing sites in the region. Also shown is the (e) water limitation and (f) yield gap (see Methods for their calculation). Base map was extracted from GADM (https://gadm.org/). Source data are provided as a Source Data file.

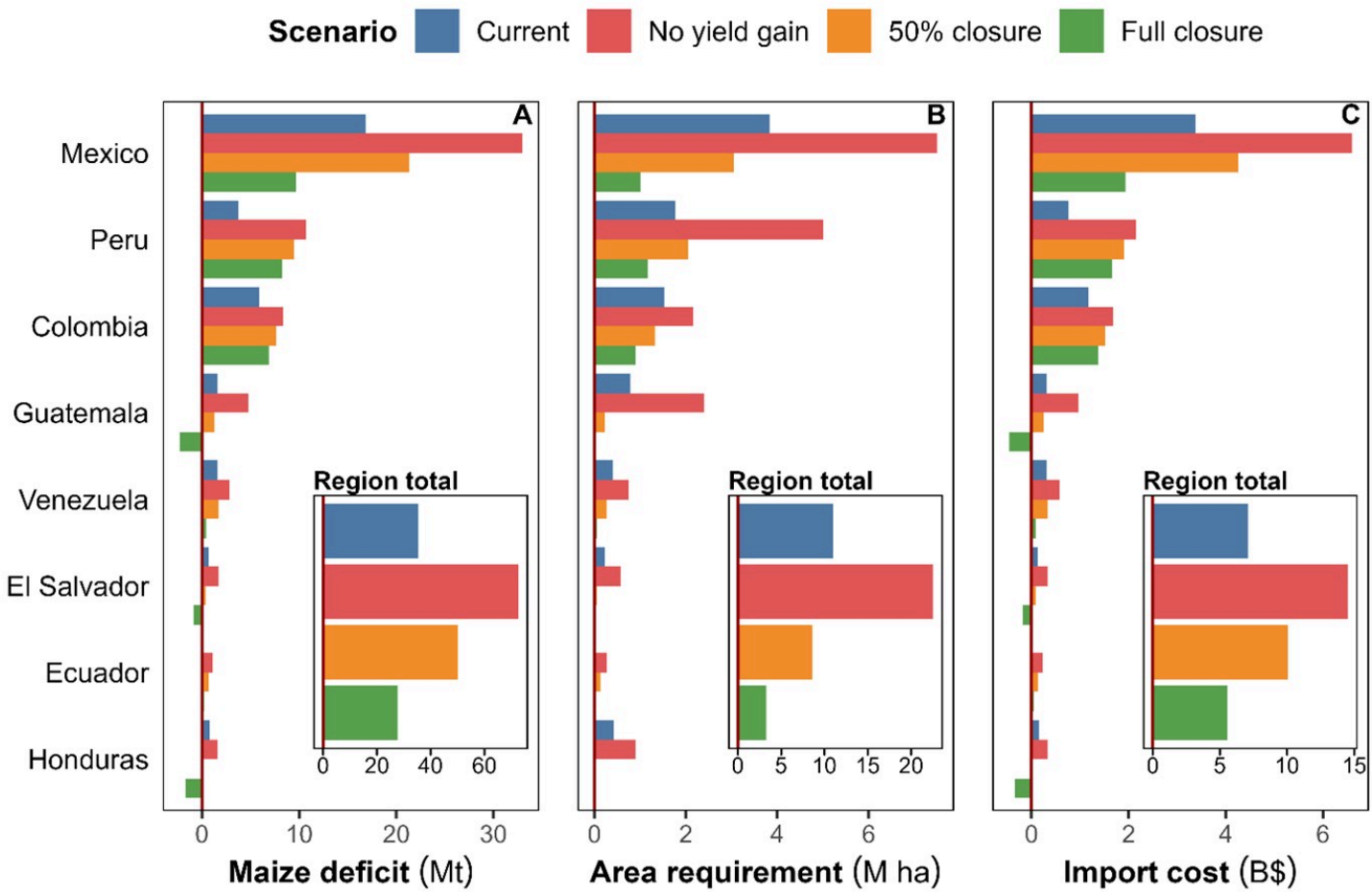


Figure 3

Current and future maize deficits under three scenarios of yield gain. (A) National maize deficit (demand minus production) in eight countries in Northern Latin America in 2020 (current) and for three scenarios of yield intensification by 2050: (i) no yield gain, (ii) 50% closure of the exploitable yield gap, and (iii) full closure of the exploitable gap. The exploitable yield gap was calculated as the difference between average yields and 80% of the yield potential (see Methods). Also shown are the (b) cropland requirements or (c) monetary value associated with maize imports needed to fulfill the maize deficiency. Insets inside each panel show the aggregated values for the entire Northern Latin America region, including other minor maize producing countries. See Methods for assumptions on fraction of area under irrigation and planted with native maize.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- AramburuMerlosetalSupplementaryInformation.docx