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Six decades of global crop yield increase and cropland expansion from 1960 to 2020

Karina Winkler[1,2], **Richard Fuchs**[1], **Mark Rounsevell**[1,3,4] **and Martin Herold**[2,5]

1 Land Use Change & Climate Research Group, IMK-IFU, Karlsruhe Institute of Technology (KIT), Germany
2 Laboratory of Geoinformation and Remote Sensing, Wageningen University & Research (WUR), The Netherlands
3 Institute of Geography & Geo-ecology (IFGG), Karlsruhe Institute of Technology (KIT), Germany
4 School of GeoSciences, University of Edinburgh, United Kingdom
5 Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Germany

E-mail: karina.winkler@kit.edu

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Abstract

Population growth, changing consumption preferences, technological advances, globalised trade and environmental influences have all shaped global agriculture. An increasing demand for agricultural commodities has led to greater production through land area expansion and/or intensification (represented here as increasing yields). Yet, the interlinkages between global agricultural expansion and intensification, remain unclear. Here we (1) analyse the spatiotemporal patterns of global cropland changes and crop yield changes at a spatial resolution of 1 km during six decades (1960–2020) and (2) explore the relationship between yield increases and cropland expansion across agroecological country zones by applying a temporal cross-correlation and a Granger causality test. We find that high-income countries have followed a trajectory of yield increase and land contraction on croplands, in accordance with the concept of land sparing and mediated by policy. Conversely, low-income countries have increased yields less but substantially expanded cropland area over time. However, emerging countries in tropical regions (e.g. Brazil, Indonesia, Thailand, Colombia, and Malaysia), had both the highest crop yield increases and cropland expansion rates. By analysing the relationship of annual crop yield and cropland area changes, we see potential rebound effects of yield increases in tropical lowlands of low- to middle-income countries. Our results suggest that high-profit crops such as soybean, oil palm and sugar cane have triggered further agricultural expansion into natural ecosystems. Increasing tree crops is the underlying cause of more than half of the global deforestation for cropland expansion. Overall, the relationship between yield increases and expansion on cropland differs by region and is likely affected to varying degrees by political intervention, global trade, technology transfer and climate change.

1. Introduction

Agriculture covers over one third of the global land surface [1]. With a rising world population, technological advances, changing consumption patterns and globalised trade, cropland and pasture areas have undergone significant expansion and intensification in recent decades. The 'Green Revolution' marked a pivotal phase of technology-driven productivity increases in agriculture, introducing high-yielding crop varieties alongside fertilisers, irrigation, pesticides, and mechanisation to boost crop yields [2, 3]. Although agriculture produces more than enough food for all people, its global distribution is unequal and almost one billion people suffer from insecure food supply [4, 5]. Rising affluence has further shifted diets towards resource-intensive foods like meat and refined sugars, exacerbating pressures on agriculture to meet future demands, [6]. To sustain projected needs by 2050, agricultural production would have to roughly double [7, 8], but this comes at a significant environmental cost - agricultural expansion and accompanying intensive management are major drivers of climate change, biodiversity loss, land and freshwater degradation [7, 9–13]. Overall, agricultural land use has steadily become an arena of conflicting interests, as the demand for food, fodder and energy is balanced against climate change mitigation and biodiversity conservation [14, 15].

There are two main strategies to increase agricultural production: (1) expanding the area of croplands and pastures, concurrent with the loss of natural ecosystems, or (2) agricultural intensification targeted at increasing the productivity (per unit area) of existing agricultural land [16, 17]. Agricultural intensification denotes an increase in agricultural land use intensity, which is multidimensional. It refers to the input intensity, including land, capital (e.g. technology, mechanisation, agrochemicals applied) and labour, and targets the output intensity, referring to the output per unit land, *viz.* yields [18, 19].

In addition to cropland changes such as cropland expansion and contraction, this study focuses on land use intensity from an output perspective. We use increasing crop yields as an indicator of output intensification. While previous work has mainly focussed on crop type-specific analyses [20], we use an aggregated yield across crop types as an indicator of the overall productivity of cropland. Aggregating yield changes across crop types (average yield weighted by cultivation area) provides a comprehensive measure of overall agricultural productivity, capturing shifts in output intensity while accounting for regional crop diversity.

Increasing crop yields on existing agricultural land is often regarded as a sustainable solution, since it is assumed to reduce pressure on land that can be returned to nature (land sparing) [16, 21]. However, increasing agricultural productivity can also cause pollution through increasing use of inputs and lead to a knock-on (or rebound) effect, where the adoption of intensification stimulates land use expansion by increasing the profitability of agriculture [21].

While extensive research has focused on spatial patterns of agricultural expansion and contraction—particularly in the context of tropical deforestation [22, 23]—the spatiotemporal patterns of the interplay between cropland intensification (as e.g. measured via productivity or yield increases) and area dynamics remains poorly understood at a global scale. Existing studies often treat these dimensions in isolation: analyses of land-use extent emphasise geographic shifts in cultivation [24–26], while assessments of agricultural intensification typically focus on crop-specific management factors or productivity trends [27–29]. This disconnect stems partly from data limitations, as global-scale, long-term and spatially explicit datasets simultaneously tracking cropland extent and management practices remain scarce [19].

Theoretical frameworks posit a land-sparing effect, where yield gains reduce pressure for agricultural expansion [20, 30]. Indeed, global crop production growth has been driven predominantly by yield improvements, with estimates indicating that 89% of production increases stem from intensification, while only 11% result from cropland expansion [31]. In many cases, yield gains have offset population-driven demand, lowering per capita cropland requirements for staple crops [32–34]. However, empirical outcomes vary significantly across regions. In post-1990s Europe and North America, for example, agricultural intensification coincided with cropland stabilization or contraction, supported by policy incentives and market-driven set-aside programs [30, 35, 36]. In contrast, sub-Saharan Africa and parts of Asia continue to experience agricultural expansion despite low baseline yields—a trend tied to population growth, limited technological adoption, and weak market access [20, 37]. Globally, the relationship between cropland area and production remains uneven: temperate regions show strong intensification-driven land sparing, while, in many tropical regions, a rebound effect of increasing productivity, mediated through market factors such as price elasticity, may lead to agricultural expansion [38, 39]. These disparities cannot be accurately localised, highlighting the need for simultaneous, integrated spatial and temporal analyses of both cropland extent and yield intensity to pinpoint opportunities for sustainable land-use transitions.

While recognising that the causal links between agricultural productivity and area change have already been addressed in a substantial and expanding body of literature, a notable methodological mismatch persists between spatial depth and statistical significance. On the one hand, global-scale studies primarily focus on cross-country comparisons [20, 32, 33, 36] or decomposition analyses [31, 34] based on the Food and Agriculture Organization (FAO) panel data, which has often been regarded the only consistent database for assessing yield-area relationships. While these studies employ robust statistical methods (e.g. regression models, cointegration or decomposition analysis) or stylised model experiments, they often rely on a-priori assumptions derived from theoretical concepts and overlook within-country heterogeneity, masking localised dynamics. On the other hand, research that uses spatially explicit data offers granular insights but often remains confined to particular management contexts, specific crop types or individual countries [40–43], which limits its generalisability.

By using a spatially explicit data-driven approach of mapping 1960–2020 cropland use and productivity changes simultaneously at the global scale, this study addresses two gaps: (1) quantifying the spatiotemporal patterns of global changes in cropland systems, particularly gross area expansion and contraction, yield increases and decreases on croplands during the last six decades (1960–2020) and (2) examining country- and regional-scale relationships between cropland productivity and expansion.

By focusing on these integrated dimensions—rather than applying country-scale or context-specific approaches—the study contributes novel insights into the complex interplay between intensification and land use transitions with a high resolution at the global scale. It builds upon existing frameworks and harmonises available data while offering more spatial depth and data proximity than prior studies. This works illuminates previously overlooked intra-country and cross-border dynamics that contribute to understanding the relationship between intensification and land use expansion.

2. Method

2.1. Mapping cropland area changes

We derived changes in agricultural areas from the land use/cover maps of the Historic Land Dynamics Assessment+ (HILDA+) database, a data-driven reconstruction of global land use change from 1960 to 2020 at 1 km spatial resolution [26]. We used an updated version (version 2.0) of HILDA+ (https://doi.pangaea.de/10.1594/PANGAEA.974335) [44], which contains more detailed subcategories of the cropland class. The additional cropland-related land use categories tree crops, agroforestry and annual crops (definitions are provided in Supplementary table S1) were derived from a combination of remote sensing-based spatial datasets (see Supplementary table S2) and crop production statistics from the FAO [45]. Fractional coverage (area fractions) of the new land use categories from spatial data was used for a potential reclassification of HILDA+ version 1.0 land use categories cropland, pasture/rangeland, grass/shrubland or forests (not matching ESA CCI forest categories). First, this involved a reclassification of the original spatial datasets (see Supplementary table S2) into binary maps for each of the new land use categories and subsequent resampling/reprojection to area fractions on a 1 km-resolution target grid in Eckert IV projection. Second, the reclassification was carried out using a likelihood map: For tree crops, the year-specific national-scale share of tree crop production on total crop production from FAO [45] was multiplied with the area fraction of tree crops from the spatial datasets (the closest reference year was used), resulting in a harmonised likelihood map of tree crop occurrence. Grid cells with likelihood values of at least 0.5 (50% likelihood) were reclassified to tree crops. For agroforestry, only the area fractions from the spatial datasets (Lesiv *et al* and Zomer *et al* agroforestry maps; see Supplementary table S2) were used as likelihood maps, since there are no FAO production statistics available, applying the same procedure as for tree crops, using a threshold of 0.5 for reclassification. All remaining former HILDA+ cropland areas that have not been reclassified to either tree crops or agroforestry are classified as annual cropland.

The areas of cropland as well as the areas of cropland expansion and contraction were mapped globally for the period of 1960–2020 at decadal time steps. For croplands, the HILDA+ land use categories annual crops, tree crops and agroforestry were merged. From these data, we calculated the global and per-country net area changes in croplands.

2.2. Mapping crop yield changes

For mapping and analysing changes in cropland productivity, we used the average crop yield (tonnes per ha) as an indicator of output intensity. With a data-driven approach, we generated a time series of global maps of mean crop yield at 1 × 1 km spatial resolution from 1960 to 2020. The crop yield maps were developed from a base map drawing on five spatial datasets, national crop yield statistics from the FAO and the annual trends in crop yields derived from four spatial datasets.

2.3. Base map of crop yields 2000

We first generated a harmonised base map of mean crop yield in the reference year 2000 based on five global datasets containing yield as a variable (Earthstat M, Earthstat-R, GAEZ, GDHY, SPAM; see table 1).

To derive this base map, we calculated the weighted-average crop yield of all available crop types in the respective datasets at the pixel level, using the formula:

$$\bar{y}_w = \frac{\sum_{i=1}^{n} y_i{*}a_i}{\sum_{i=1}^{n} a_i}$$

with $\bar{y}_w$ as the weighted average crop yield, y_i as the yield and a_i as the harvested area for one crop type at a specific location (pixel). This method accounts for the proportion of harvested area per crop type within each pixel.

For datasets lacking harvested area data, an unweighted average yield was used. The resulting maps were resampled and reprojected to a 1 × 1 km grid in Eckert IV equal-area projection and a pixelwise average was calculated, with non-cropland pixels masked out (according to HILDA+). The harmonised map was calibrated

Table 1. Spatial datasets used for crop yield mapping.

Dataset	Variable	Crop types	Spatial resolution	Temporal resolution	References
Earthstat-M	• Harvested area • Yield	175 crops	5 arc min (~10 km)	2000	[46]
Earthstat-R	• Harvested area • Yield	4 crops: maize, soybean, rice, wheat	5 arc min (~10 km)	1995, 2000, 2005	[47] based on [46]
Earthstat-R-trend	• Rate of yield change	4 crops: maize, soybean, rice, wheat	5 arc min (~10 km)	1961–2006	[48]
GAEZ	• Harvested area • Yield • Production	26 crops	5 arc min (~10 km)	2000, 2010 (v4); 2015 (v5)	[49, 50]
GDHY	• Yield	4 crops: maize, soybean, rice, wheat	0.5 deg	annual 1981–2016	[28]
SPAM	• Harvested area • Physical area • Yield • Production	42 crops (20 crops in 2000)	5 arc min (~10 km)	2000, 2005, 2010	[51]

to FAO national crop yield statistics (FAO, 2022) by adjusting pixel yields to match national weighted-average yields, ensuring consistency. We excluded all crop types within a country that were not covered as complete time series in the FAO statistics in order to avoid sharp yield fluctuations due to data gaps, abandoning or introducing certain crop types. The final FAO-calibrated map provides global mean crop yields at a 1 km resolution for 2000. For a detailed description of the methodological steps, please refer to the Supplementary Information S1.

2.4. Data-derived reconstruction of crop yields 1960–2020

We reconstructed global crop yields from 1960 to 2020 using FAO data (FAO, 2022) and various spatial datasets (see table 1). Country-specific yield values were adjusted for changes in country boundaries using trends from predecessor countries. We extended FAO data (covering 1961–2020) back to 1960 via linear extrapolation. Trend maps from the Earthstat-R, GAEZ, GDHY and SPAM datasets were used to derive relative yield changes. Starting from a base map in 2000, we iteratively mapped yields at five-year intervals, calibrating changes to national FAO trends. This process was applied to the HILDA+ cropland areas, resulting in global yield maps at a 1 km spatial resolution. For detailed methods, see Supplementary Information S2.

2.5. Analysis of relation between crop yield and area changes

The relation between crop yield changes and crop area changes was analysed by country and agroecological zone.

For a country-by-country comparison, we used a commonly used classification of countries adopted by the FAO and based on the World Bank income group. It categorises countries by their gross national income (GNI) per capita into four different groups (low-income, lower-middle-income, upper-middle-income, high-income). For this analysis, the country grouping from the year 2023 was used [52]. Preceding changes in the income group of the countries were neglected.

To account for spatial heterogeneities within countries, we analysed crop yield and crop area changes for each country and agroecological zone. For this, the GAEZ v4, a simplified classification of 33 agroecological zones was used [49, 53]. Its underlying climate information is based on historical data for the time period 1981–2010. The agroecological zones were combined with the country areas to combined agroecological country zones for further regional time series analyses.

To analyse the relationship between crop yield and area changes, we first conducted a cross-correlation analysis. This method allows for the examination of the temporal relationship between two time series, accounting for potential time lags. We applied this analysis to the combined agroecological country zones from 1961 to 2020, using crop yield changes (t/ha) and cropland area net changes (km^2) as variables. The cross-correlation function was computed for lags up to 5 years to capture both immediate and delayed effects. Key metrics derived from this analysis include:

- Correlation coefficient: Indicates the strength and direction of the relationship between yield and area changes.

- P-value: Represents the statistical significance of the correlation.
- Optimal time lag: Identifies the time delay at which the correlation is strongest.

We categorized the relationships based on the direction (positive or negative) and significance ($p < 0.05$) of the correlations. This initial analysis provided insights into the overall patterns of association between yield increases and cropland expansion across different regions.

Building upon these findings, we employed the Granger causality test to further investigate potential causal relationships between crop yield increases and cropland expansion. This statistical approach allows for the examination of whether changes in one variable (e.g., crop yield change) can predict future changes in another variable (e.g., cropland area change). The test was applied to the same dataset used in the cross-correlation analysis. We utilized a maximum lag of 5 years to account for potential delayed effects. The analysis yielded several key metrics:

- F-statistics: These values indicate the strength of the causal relationship, with higher values suggesting stronger causality.
- P-values: These represent the statistical significance of the causal relationship, with values below 0.05 considered significant.
- Optimal lag times: These indicate the time delay (in years) at which the causal relationship is strongest.
- Covariance coefficients: These determine the direction (positive or negative) of the relationships.

Based on these metrics, we categorised the causality types as bidirectional (significant in both directions), unidirectional (yield to area or area to yield) with positive or negative relationships, or no causality. This approach provided insights into land sparing dynamics and potential rebound effects across different regions. For instance, a significant unidirectional causality from yield to area with a negative coefficient might suggest land sparing, while a positive coefficient could indicate a rebound effect.

The combination of cross-correlation and Granger causality analyses allowed for a comprehensive examination of the complex relationships between cropland intensification and land use change over six decades.

3. Results

3.1. Cropland area changes

By aggregating all areas of cropland expansion (with cropland comprising annual crops, tree crops and agroforestry) during the last six decades, we find that global cropland has expanded by a total of 4.09 million km^2 (ca. +27%), an area that is more than twice the size of Mexico.

Of this gross expansion area, about 30% (1.25 million km^2) is the result of deforestation. Another 30% (1.22 million km^2) was at the expense of other natural vegetation areas. Globally, the largest areas of cropland expansion can be found in tropical regions, particularly in West Africa, the Amazon basin and Indonesia (see figures 1(a)–(c), (e)). Cropland classes with the strongest expansion extent were annual crops (2.91 million km^2; 71% of the expansion area), followed by tree crops (1.04 million km^2; 25% of the expansion area). The expansion of agroforestry at 0.14 million km^2 was comparatively small (only 3% of the expansion area). It is striking that around 63% of the increasing tree crop areas have expanded into natural forests (0.66 million km^2). This implies that more than half of the global deforestation for cropland (52%) was due to the expansion of tree crops (e.g. oil palm, cocoa, or rubber). Hence, this suggests that tree crops have been the largest driver of global deforestation for cropland in the last 60 years.

However, croplands have also contracted in some regions, particularly in Europe (see figures 1(a),d). Globally, 2.55 million km^2 (ca. 17%) of cropland areas were abandoned from 1960 to 2020. Of this gross cropland contraction area, around 29% (0.75 million km^2) transitioned into forests, and another 29% (0.74 million km^2) transitioned into other natural vegetation.

Considering both gross expansion and contraction areas, we find that the global cropland change was a net expansion of 1.53 million km^2 (+10%).

Countries with the largest gross cropland expansion are Indonesia (ca. 420,000 km^2), India (257,000 km^2), Brazil (228,000 km^2), China (223,000 km^2) and the U.S. (215,000 km^2). It is mainly tropical regions that have the largest deforested areas for crop production. Indonesia has the largest such change, with a deforestation area for cropland of ca. 327,000 km^2. Indonesia is followed by Brazil (~90,000 km^2), China (~70,000 km^2), Nigeria (~60,000 km^2) and Malaysia (~50,000 km^2). In all of these countries except Brazil, tree crops are by far the most

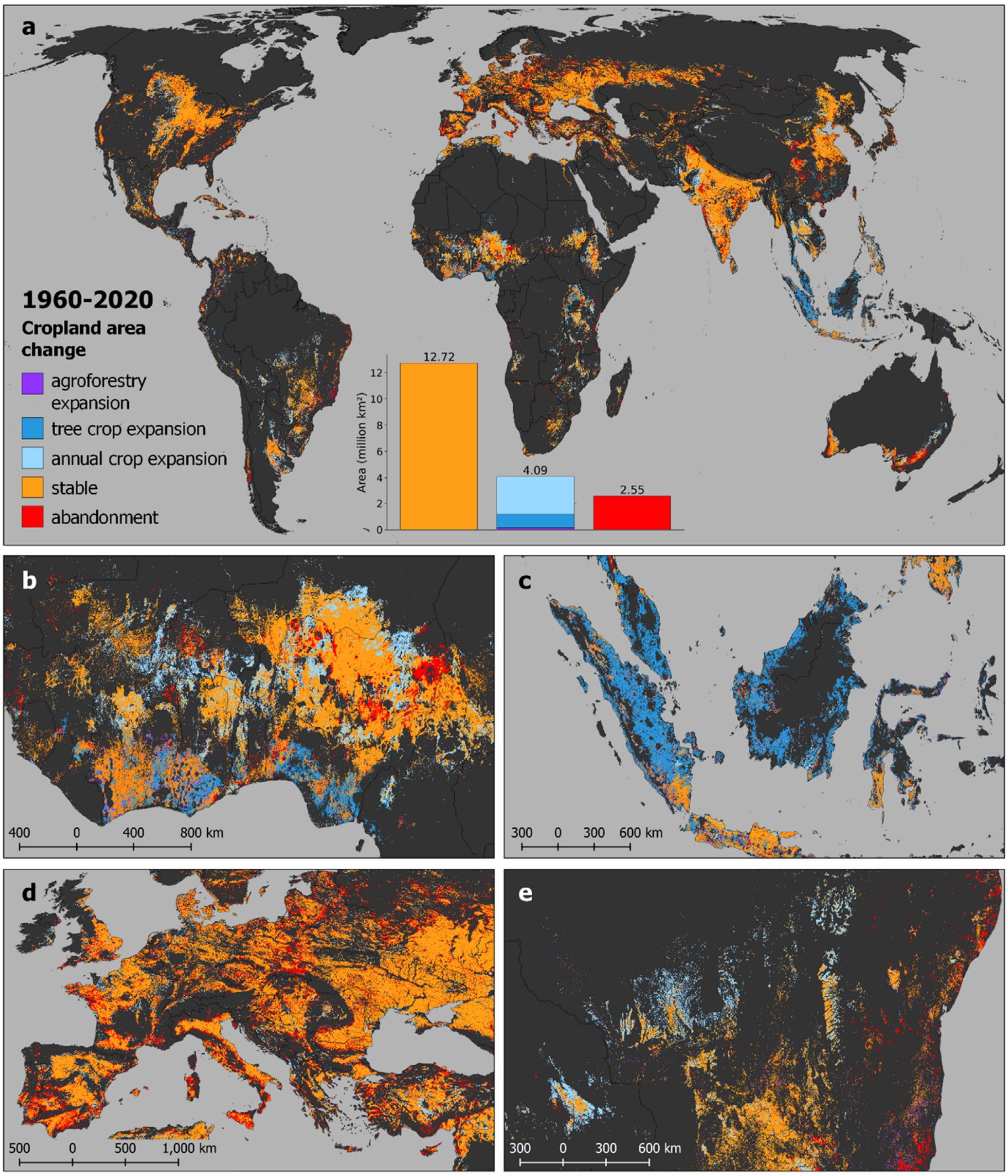

Figure 1. Map of cropland area change from 1960 to 2020 including areas of stable cropland, expansion, and abandonment. Expansion areas are further subdivided into the expansion of agroforestry, tree crops and annual crops. The maps have global (a) and regional (b): West Africa, (c): Indonesia (d): Europe, (e): Brazil) extent. The bar chart shows the global areas under the different cropland change categories. This figure was adapted from [54].

important cause of deforestation. In Indonesia, tree crops account for 89% of the total deforestation for cropland, in China for 76%, in Nigeria for 89% and in Malaysia as much as 97% (see figure 1).

In contrast, the largest cropland contraction can be found in the E.U. (ca. 430,000 km^2), the U.S. (270,000 km^2), India (250,000 km^2), Russia (220,000 km^2) and China (140,000 km^2). Apart from India, these are high-income or upper middle-income countries located in the Global North.

In terms of the overall net change in cropland area from 1960 to 2020, the highest cropland increases are found in emerging countries of the Global South, particularly in tropical regions (see Supplementary figure S1). Again, Indonesia has the largest increase with a net cropland increase of around 410,000 km^2, followed by Brazil (150,000 km^2), Thailand and Argentina (130,000 km^2 each) as well as Malaysia (100,000 km^2). We find that the share of tree crops on deforestation areas is remarkably high in countries of Southeast Asia (e.g. Indonesia 89%, Thailand 99%, Malaysia 97%) and Sub-Saharan Africa (e.g. Nigeria 91%, Côte d'Ivoire 53%, Uganda 73%), but comparably low in Latin America (e.g. Brazil 0%, Argentina 0%, Colombia 20%). The largest net cropland decreases are mainly found for annual crops in the E.U. (ca. 320,000 km^2) - particularly in Poland (60,000 km^2), Italy (50,000 km^2) and Spain (40,000 km^2) - in Russia (160,000 km^2), the U.S. (60,000 km^2) as well as in Australia (40,000 km^2). It is striking that countries of the Global North, mostly high-income countries, are exclusively among the top net cropland contracting countries (see Supplementary figure S1).

3.2. Crop yield changes

By reconstructing the changes in mean crop yield for the last six decades (1960–2020) as an output-based measure of cropland intensity, we find that global crop yields have increased by around 3.74 t/ha to a total average of 6.27 t/ha, which is an increase of around +2.5% per year.

Regions with the highest absolute increases in mean crop yield from 1960 to 2020 are located in the Arab region (Kuwait +64 t/ha, Jordan +11 t/ha), in Central America (Costa Rica +23 t/ha, Guatemala +16 t/ha, Puerto Rico +12 t/ha), the Netherlands (+24 t/ha), Belgium (+16 t/ha) as well as Swaziland (+39 t/ha; see Supplementary figure S2). Apart from the Arabian Peninsula and Central America, we also find high relative yield improvements in Northern Africa. In contrast, the greatest declines in crop yield from 1960 to 2020 can be found in countries located at the Caribbean Sea, e.g. Barbados (−39 t/ha) or Guyana (−14 t/ha). Also, some countries in sub-Saharan Africa—Sudan (−0.9 t/ha) and Namibia (−0.8 t/ha)—show yield declines. In Europe, overall crop yield decreases can only be observed in Norway (−1.1 t/ha) and Moldova (−0.7 t/ha; see Supplementary figure S4).

Focussing on the countries with the largest crop production, we identify high crop yield increases in countries of Southeast Asia, such as Malaysia (+10.5 t/ha or +610%), Thailand (+5.7 t/ha or +255%), and Indonesia (+6.0 t/ha or +200%), but also in China (+8.2 t/ha or +412%) and Pakistan (+5.7 t/ha or +304%; see maps in figure 2 for relative and Supplementary figure S4 for absolute changes).

Eastern Europe as well as countries in the Sahel Zone show comparably lower yield increases than other countries with large cropland areas (see figures 2(a), (b), d). This is due to large fluctuations in crop yields over time (see Supplementary figure S5).

3.3. Yield increase versus cropland expansion

By comparing the crop yield increases with cropland expansion during the period 1960–2020, we find that high-income countries, mostly in temperate zones of Northern America, Eastern Asia and Europe, have tended to increase their yields while reducing their cropland areas, whereas low-income countries in tropical zones of Africa, Latin America and South-eastern Asia have improved yields less but substantially increased cropland area. (See figure 3 and figure 4 for a regional-scale and Supplementary figure S6 for a country-scale comparison of changes in yields and area). It is striking that middle-income countries belonging to the group of emerging markets, which are characterised by high rates of economic growth and mainly located in the tropics (e.g. Brazil, Indonesia, Thailand, Colombia, and Malaysia), show both high crop yield increases and cropland expansion rates from 1960 to 2020.

However, the relationship between yield increase and cropland expansion has not always been the same everywhere over time. Supplementary figures S7 and S8 show the pathways of decadal cropland yield and area change for different countries during 1960–2020. Croplands in Indonesia, for example, went through a period of yield increase without major expansion during 1960–1990, which was followed by a 10-year expansion phase and, finally from 2000 onwards, by both massive crop yield increases and expansion. Brazil experienced sharp crop yield increases with high but declining cropland expansion rates since the 1980s. However, a decline in yields and cropland area is noticeable during the last decade (2010–2020). Nigeria has a highly dynamic trajectory, with 30 years of yield increase and net cropland contraction followed by an enormous cropland expansion with low rates of yield increase and even decrease during 2010–2020. China underwent a phase of cropland abandonment during 1960–1980, followed by high yield increases with cropland expansion. Interestingly, the U.S. shows a shift from 30 years of cropland expansion to 30 years of contraction, particularly during 1990–2010, while crop yield increases have been consistently high. The trajectories of yield increase and cropland expansion in Russia, Ukraine and Kazakhstan during 1960–2020 are characterised by large fluctuations in crop yield changes and large-scale cropland contraction. We find that the E.U. has followed a long- time trajectory of large net cropland contraction with constant yield increases, interrupted by a phase of stagnating yields during 1990–2010.

Cross-correlating the annual crop yield change and gross cropland expansion at the regional level (agroecological country zones) resulted in weak to moderate positive and negative correlations (see figure 5) with average values of significant positive correlation coefficients of ca. 0.34 (min: 0.25, max: 0.67) and significant negative correlation coefficients of ca. −0.33. (min: −0.61, max: −0.26). We identified areas of significant moderate positive correlations (correlation coefficients between 0.5 and 0.7) on irrigated croplands, such as in northern Chile and Tunisia, in the tropical highlands of Tanzania, Colombia and Ecuador. The tropical lowlands of Western Africa (Guinea, Mali, Sierra Leone, Togo), South-eastern Africa (Zimbabwe, Zambia and

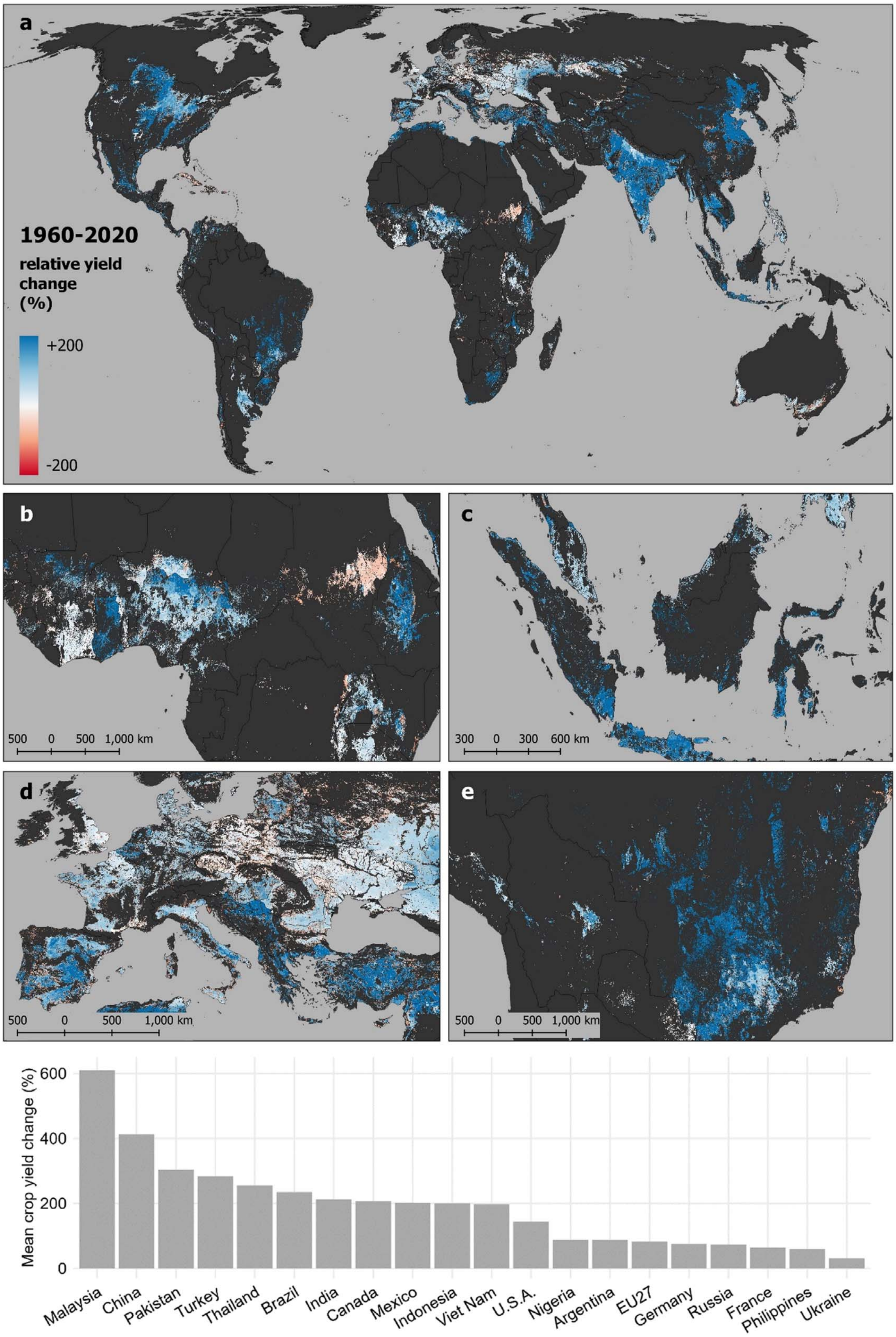

Figure 2. Relative crop yield change (in %) on croplands from 1960 to 2020: Global (a) and regional maps (b)–(e), bar chart (bottom) displaying the averages for the top 20 crop producing countries (incl. EU27 as country group). This figure was adapted from [54].

Malawi) and South-eastern Asia (Indonesia and Vietnam) also show significant positive but slightly lower correlations (correlation coefficients between 0.3 and 0.5). In contrast, significant moderate negative correlations between crop yield and cropland area changes (correlation coefficients between −0.5 and −0.7) can be found in the tropical lowlands of Eastern Africa (Tanzania and Burundi) and the Caribbean (Nicaragua, Haiti,

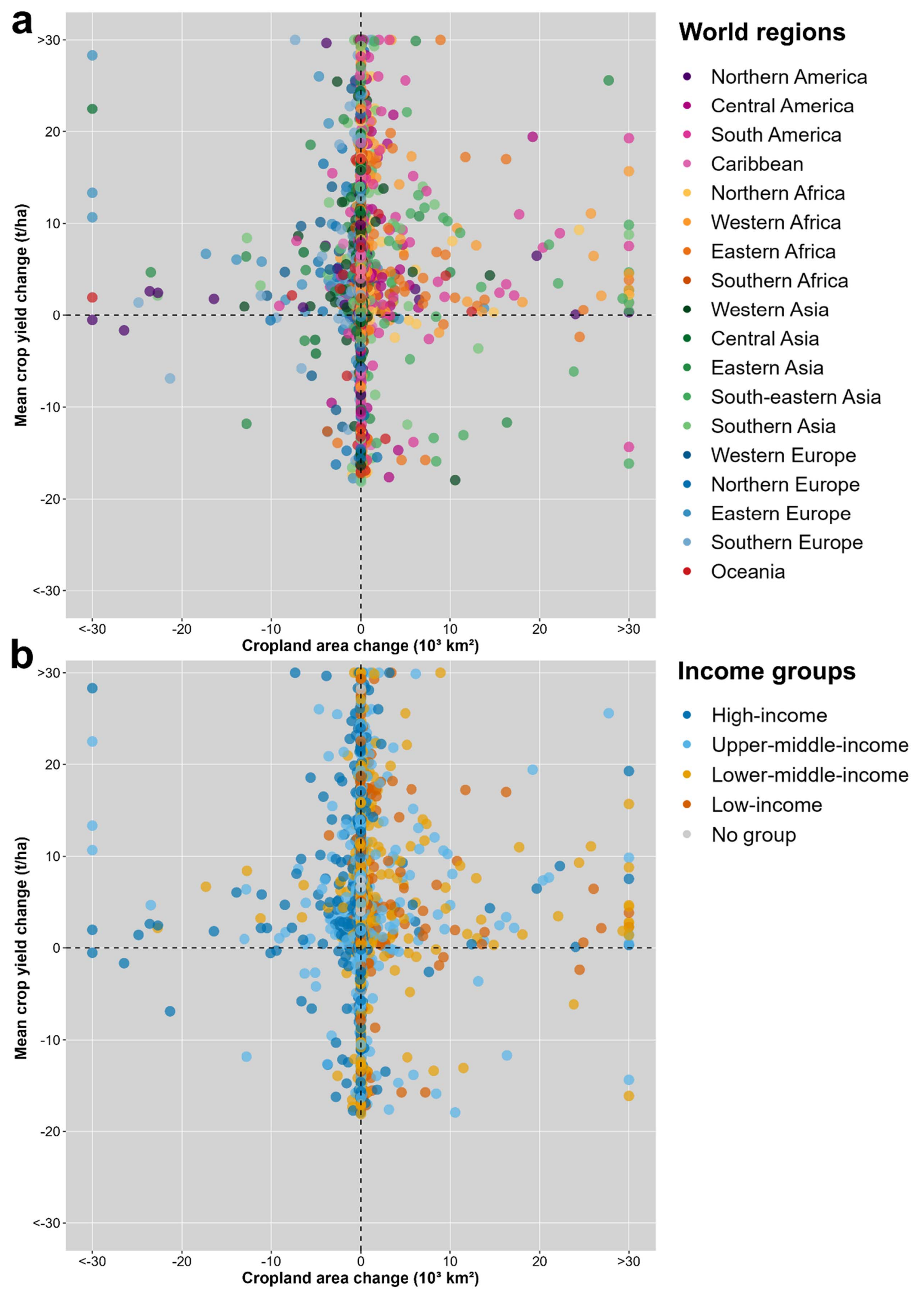

Figure 3. Relation of mean crop yield change (in t/ha) and cropland net area change (in 10^3 km^2) for all global agroecological zones and countries during 1960–2020. Dots are coloured based on (a) different world regions based on FAO and (b) country-specific income groups based on FAO.

Venezuela). Lower negative correlations (correlation coefficients between −0.3 and −0.5) are also evident around irrigated cropland areas, such as in Sri Lanka, the sub-tropical Mediterranean (Italy, southern France) and South-eastern Europe (Romania, Ukraine), as well as in temperate cool regions of Central Europe (Czechia, Germany) and the tropical lowlands of Central America (Mexico, El Salvador, Costa Rica).

By applying a Granger causality test to explore whether changes in crop yield can predict changes in cropland area or vice versa, we find significant causal relationships between annual crop yield and area change on only 32% of the agroecological country zones (n = 1464). Those regions show average F-statistics of ca. 5.6 (min: 2.4, max: 27.9), indicating moderate to strong predictive causal relationships between annual crop yield and area changes in the significant agroecological country zones, with varying strengths across different regions. In 68% of the regions, no causal relationship is recognised. We identify different Granger causality types for the relationship of crop yield and area changes: unidirectional causality from yield to area on 14%, unidirectional causality from area to yield on 13% and bidirectional causality between both yield and area on 6% of the analysed agroecological country zones.

Ca. 7% of the agroecological country zones showed a unidirectional causality from yield to area with negative covariance coefficients. This significant 'yield → area' causality with a negative relationship of yield and area changes indicates that yield increases lead to reduced cropland area, supporting the land sparing hypothesis. Strikingly, the agroecological zone most associated with such a land sparing causality type is characterised by extensive irrigation (14% of cases), followed by land with terrain limitations (10%), dominantly built up land (7%), dominantly hydromorphic soils (7%) and water (7%). Land sparing can be attributed to larger regions in Europe, Western Africa, Argentina, Central America, Western and South-eastern Asia (see blue areas in figure 6). We find the highest 'land sparing' causality in humid warm (mean F-statistics of 12.8) and sub-humid, moderately cool subtropics (F-statistics of 9.1), zones with steep terrain (F-statistics of 12.5) and sub-humid tropical high- and lowlands (F-statistics of 7.5, 6.3). World regions in which the land sparing causality is strongest are South-eastern Asia (F-statistics of 7.2), South America (F-statistics of 7.0), and Western Africa (F-statistics of 6.0).

We find a significant unidirectional Granger causality from crop yield to area with positive covariance coefficients on another ca. 7% of the agroecological country zones. Significant 'yield → area' causalities with a positive relationship of yield and area changes suggest that yield increases lead to increased cropland expansion, indicating a rebound effect where efficiency gains paradoxically increase land as a resource use. Again, land with terrain limitations (15% of the cases), dominantly hydromorphic soils (9%) and ample irrigation (9%) are the agroecological zones in which most 'rebound effect' causality types are present. We find the strongest Granger-causalities for the rebound effect in semi-arid, sub-humid and humid lowlands of the tropics (mean F-statistics of 12.5, 10.2, 7.7), most notably in Eastern (Tanzania, Malawi Zambia), Southern (Botswana) and Western Africa (Ghana, Côte d'Ivoire, Guinea), Eastern and South-eastern Asia (China, Vietnam; see red areas in figure 6).

Further, unidirectional Granger causalities from cropland area to yield changes with positive correlation coefficients are evident in Southern Europe, Indonesia, Colombia and Western Africa. (see green areas in figure 6). This suggests that increases in cropland area are driving or coinciding with subsequent increases in crop yields. Strongest Granger-causalities for this area-induced intensification can be found in cold, wet agroecological zones as well as wet and dry, cool temperate regions (mean F-statistics of 15.2, 8.1, 7.8). Once again, land scarcity, in the form of terrain limitations and dominantly steep terrain, plays an important role. They represent 27% of the agroecological country zones with a causality type of area-induced intensification.

The relationship between crop yield and cropland changes demonstrates not only temporal differences but also substantial spatial variations. Different agroecological zones within the same country have diverging yield and cropland change relations. Opposing trends in neighbouring regions can be seen in Argentina, with indications for land sparing in the Pampas and a rebound effect in the Espinal (see figure 6(a)). Regional disparities on sub-national level can also be observed in subtropical southern China and in Vietnam (see figure 6(c)), in Colombia and Venezuela (see figure 6(e)), southern and eastern Europe (see figure 6(d)).

While tropical agroecological zones experienced an increase in yields and an expansion of cropland between 1960 and 2020, temperate regions tended to increase their yields and decrease their cropland area over the same period. In subtropical zones, deserts and regions with terrain limitations, yields tended to increase less and sometimes even decrease, while cropland often contracted between 1960 and 2020 (see figure 4).

4. Discussion

4.1. Regional heterogeneity across the globe

An added value of this study is the integration of both global coverage and high spatial resolution. As land use and yield dynamics are simultaneously mapped in a spatially explicit way at a 1 km^2 resolution, the presented database allows for analysing spatiotemporal patterns from local to regional as well as from country to global scales. The analysis at the agroecological country level (as demonstrated here) serves as a sample of such a global assessment at the sub-national level.

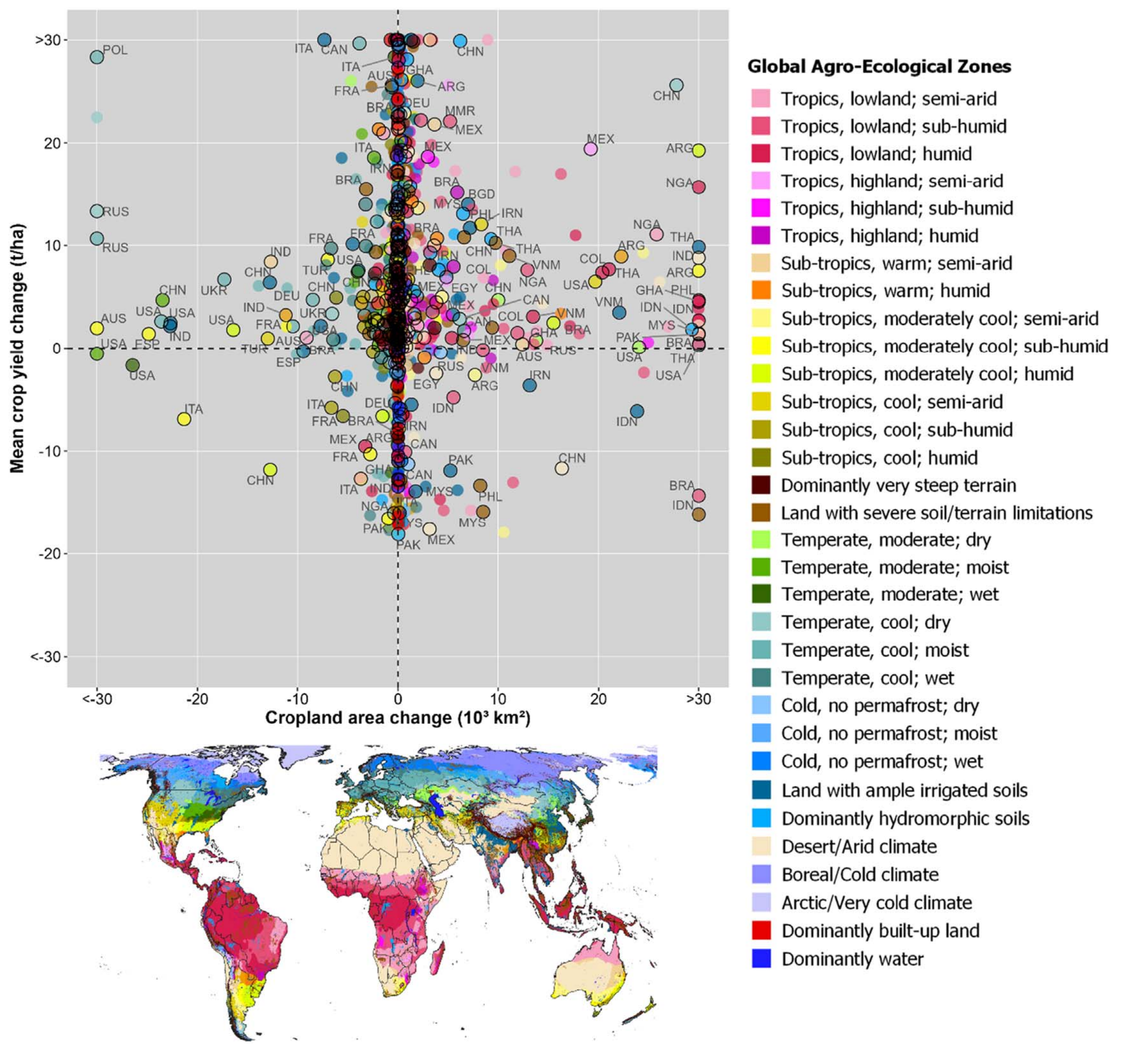

Figure 4. Relation of crop yield and cropland area changes across agroecological zones (a) Relation of mean crop yield change (in t/ha) and cropland net area change (in 10^3 km^2) for all global agroecological zones and countries during 1960–2020. Dots are coloured based global agroecological zones (GAEZv4). The top 30 crop producing countries (2020) were outlined in black and labelled according to their ISO3 codes: CHN: China; IND: India; BRA: Brazil; USA: United States of America; IDN: Indonesia; RUS: Russia; NGA: Nigeria; THA: Thailand; ARG: Argentina; PAK: Pakistan; MEX: Mexico; TUR: Turkey; UKR: Ukraine; FRA: France; CAN: Canada; VNM: Vietnam; MYS: Malaysia; PHL: Philippines; DEU: Germany; BGD: Bangladesh, EGY: Egypt; ESP: Spain; POL: Poland; AUS: Australia; COL: Colombia; IRN: Iran; COD: DR Congo; MMR: Myanmar; ITA: Italy; GHA: Ghana. Note that not all labels are displayed due to overlapping content.

The spatial heterogeneity identified in crop yield-area dynamics provides critical nuance to existing frameworks by revealing how subnational agroecological conditions mediate intensification outcomes. While García *et al* (2020) [33] and Goulart *et al* (2023) [39] emphasise regional-scale land-sparing or rebound effects, this study demonstrates that opposing trends (e.g., Argentina's Pampas vs. Espinal) can coexist even within single countries, highlighting the importance of localised drivers. By contrasting tropical cropland expansion with temperate land sparing and subtropical cropland contraction, the findings advance beyond Rudel *et al* (2009) [55] and Villoria (2019) [33], which primarily attribute global patterns to broad economic forces, by illustrating divergent pathways likely shaped by terrain, climate, and institutional factors at subnational scales. This granular spatial perspective offers a more actionable framework for tailoring interventions, such as prioritizing yield gains in ecologically sensitive zones while managing rebound risks in high-demand regions.

Our approach extends the existing body of scientific research in this field, which predominantly relies on FAO data alone, thereby neglecting cross-border and sub-national variations. Our spatially explicit analysis reveals a gross cropland expansion of approximately 4 million km^2 globally, nearly double the FAO's reported net expansion of 2.3 million km^2 between 1960 and 2020 [56]. This significant disparity underscores the limitations of relying solely on net changes, which mask substantial underlying gross dynamics occurring within national boundaries. Specifically, FAO statistics reflect aggregate outcomes where concurrent cropland expansion and contraction offset each other, obscuring the true scale of land conversion processes. By capturing these detailed spatial patterns, our approach highlights the essential value of high-resolution methodologies in understanding the full magnitude of land system transitions that remain invisible to conventional national-scale accounting frameworks.

4.2. Drivers of crop yield and area changes

This study employs the average yield across all crop types as a measure of cropland intensity from an output perspective. Although this method does not directly link yield changes to specific drivers such as management practices from an input perspective (e.g., fertilizers, pesticides, irrigation, mechanization, crop varieties) or natural influences (e.g., climate effects, CO_2 fertilization), analysing spatiotemporal patterns of global cropland and yield change offers insights about the relation of crop yield and area changes, which can be discussed in context of underlying factors and their socioeconomic background.

The impact of spatial shifts in crop cultivation on yield fluctuations was addressed by implementing a spatially explicit weighting of crop-specific yields according to their respective cultivated areas. This implies that switching from one crop to another on the same area has no effect on the average yield change analysed in this study.

We find that the countries with the highest absolute or relative yield increases mostly have small areas of cropland and specialise in high-yielding crops that often involve heavy use of technology. For example, Kuwait has increased its tomato yields by more than ten-fold, Saudi Arabia has improved its maize yield by almost nine-fold, while Nicaragua has seen substantial increases in cassava, potato, and cocoa yields [45, 57]. These yield increases can be attributed to shifts towards higher-yielding crop varieties, the adoption of irrigation and indoor farming techniques. In addition, results from analysing the relation of crop yield and area changes across different agroecological zones revealed a strong positive predictive causality between yield and area changes on irrigated lands, indicating a land-sparing effect of technology-driven intensification.

Furthermore, our findings illustrate the impact of political circumstances and interventions on agricultural management, affecting yield and cropland changes. The collapse of the Soviet Union led to reduced fertilizer use and widespread cropland abandonment from 1990 to 2000, with Russian agricultural investments dropping by 95% [58]. The removal of fertilizer subsidies decreased soil fertility and yields [59]. This disruption caused a shift from former intensification to abrupt yield declines alongside massive cropland abandonment. Since the early 2000s, increasing yields and cropland expansion in Russia, Ukraine and Kazakhstan, as observed in this study, have likely resulted from investments and government support for recultivation [60]. In the Western Siberian grain belt, recultivation, rising fertilizer inputs, and narrowing crop rotations have reversed the trend of cropland contraction [29]. In the E.U., continuous yield increases with simultaneous cropland reduction are likely due to subsidy-driven intensification on productive land and abandonment of marginal land, influenced by the post-Soviet regime change [61]. This represents a redistribution rather than a real increase in yields, as abandoning less productive land boosts overall yields due to the higher productivity of the remaining land. The Granger causality test failed to detect significant predictive causality in more than two thirds of the agroecological country zones, suggesting non-direct relationships between yield and area changes. In many regions, subsidies or other political and socioeconomic influences may be indirect drivers of yield and area changes. This is consistent with the conclusions of Ewers *et al* (2009), who suggested that the land sparing patterns of yield increases in developed countries are superseded by high agricultural subsidies [32].

Moreover, it is important to note that not all yield increases are due to intensification alone, nor are yield reductions solely influenced by management factors; climatic changes also play a significant role and may be another factor that shapes the crop yield-area relationship. The African Sahel has experienced severe droughts in recent decades. In Sudan, where we found a trend of decreasing crop yields, sorghum and millet yields declined due to drought in at least 15 years between 1970 and 2006 [62]. Gibon *et al* (2018) linked crop yields in the Sahel (Niger, Mali, Senegal, Burkina Faso) to climate variability, with soil moisture explaining 81% of millet yield variability from 1998 to 2014 [63]. In Ethiopia, where we observed periods of declining yields, climate variability has led to yield decreases on productive croplands over 35 years [64]. In Ukraine, climate variations, particularly in 2003, caused substantial losses in winter and summer crops [65].

This underscores the complex interplay between political, technological, and climatic factors in shaping agricultural outcomes.

4.3. Crop production shifts in emerging countries

The remarkable rates of cropland expansion (mainly for tree crops) and yield boosts in emerging countries are linked to major shifts in crop types. In 2020, Brazil's crop production was dominated by sugar cane (69% of production, 12% of area) and soybeans (11% of production, 44% of area), compared to 1961 when soybeans were negligible (0.2% of production, 0.1% of area; FAO, 2022). In China, production shifted from sweet potatoes (22% of production, 8% of area) and rice (17% of production, 20% of area) in 1961 to maize (13% of production, 23% of area) in 2020. Indonesia replaced rice (19% of production, 40% of area in 1961) with oil

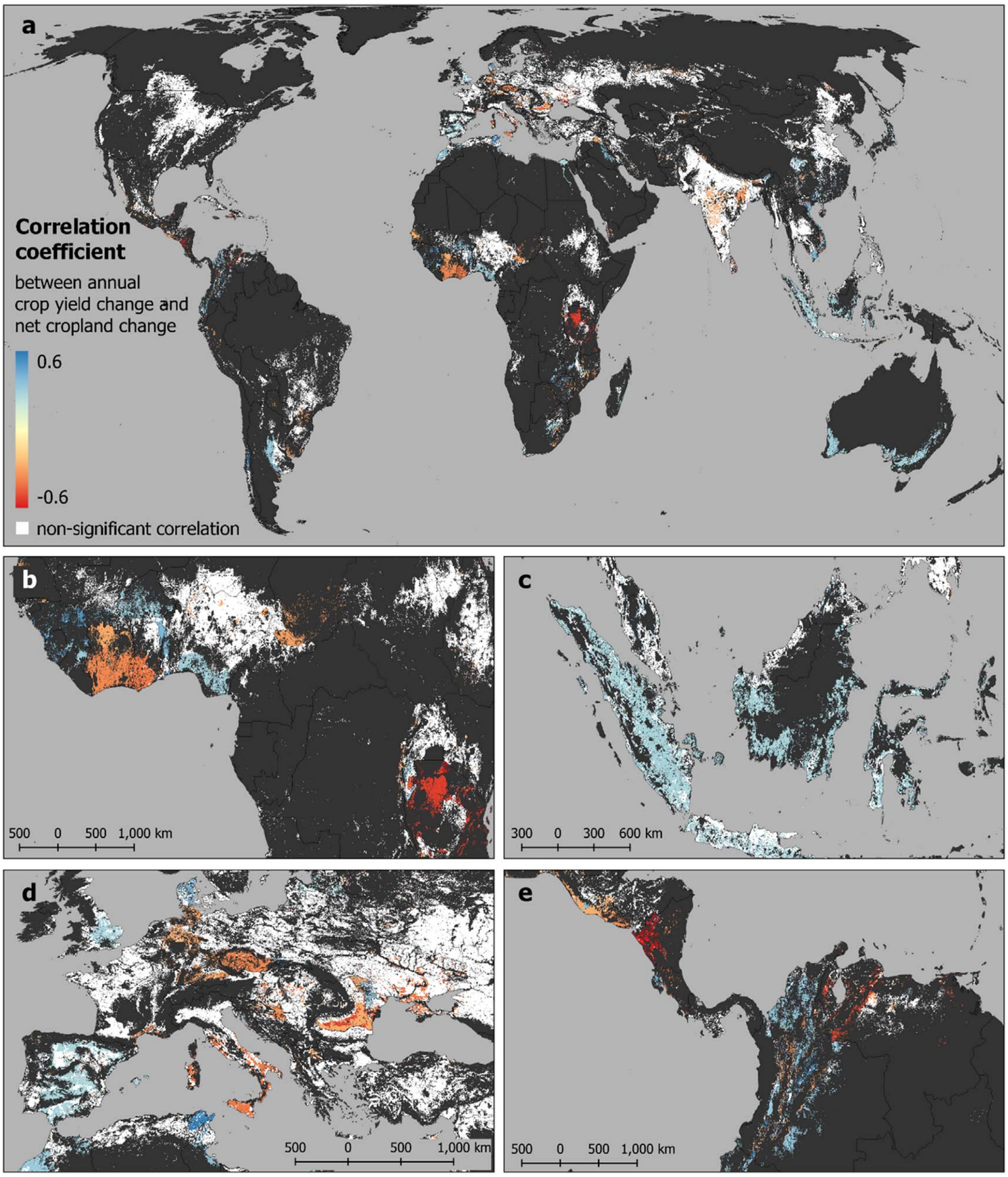

Figure 5. Correlation coefficients from temporal cross-correlation of annual crop yield changes and net cropland changes from 1960 to 2020 across agroecological country zones. Only areas with significant correlations are displayed (significance level of 95%). Global (a) and regional maps: western Sub-Saharan Africa (b), Indonesia (c), Central and Southern Europe (d), Central and northern South America (e).

palm, which accounted for 53% of production and 33% of harvested area in 2020. Thailand saw a shift from rice (37% of production, 74% of area in 1961) to sugar cane (38% of production, 9% of area in 2020).

Historically, these countries focused on staple crops for domestic supply. Today, they grow large quantities of crops for the global market, often for animal feed. Crop supply and utilization statistics from the FAO (2022a) show that while the proportion of crops produced for food has decreased, the share for animal feed and exports has risen dramatically. In Indonesia and Brazil, the share of food crops halved from 1961 to 2019 (from 60% to 30% in Indonesia, from 29% to 14% in Brazil), while the proportion of exports more than doubled in Indonesia and increased seven-fold in Brazil [66]. In China, where the population has more than doubled since 1960, the share of food crops decreased from 75% to 68%, while fodder crops increased from 10% to 16% and exports from 0.8% to 2.3%. In Thailand, food production dropped from 57% to 16%, with feed tripling from 3% to 9% and exports slightly increasing from 20% to 21%. In Mexico, the share of food crops increased from 38% to 47%, while feed and exports roughly quadrupled (from 4% to 15% and 3% to 13%, respectively; FAO 2022a).

4.4. Linking cropland intensification and expansion

Our findings about crop yield and cropland changes align with theoretical concepts of the relationship between intensification and expansion such as the land sparing or the knock-on (rebound) effect of intensification, each in different world regions. Growing international trade has led to tele-coupled effects between agricultural land use change in different parts of the world. The distinctive role of emerging markets, characterised by notable growth in crop yields and expansion of agricultural land, has been largely shaped by international trade. This is particularly true for large-scale oil palm and timber plantations at the expense of forests in Indonesia [37, 67, 68]. In addition, deregulation and expansionist policies, as pursued by the Indonesian government since the 1980s, paved the way for a market-driven palm oil expansion. The palm oil boom is an example of the knock-on effect of intensification causing further expansion [69]. Thailand shows a similar cropland trajectory, where large expansion started after the onset of continuously high yield increases.

Brazil ranks among the top countries for cropland intensification and expansion [70]. Consistent with our findings, Dias *et al* (2016) found that cropland expansion in Brazil has slowed, followed by significant intensification, particularly in soybean and coffee regions [71]. Soybean and maize are often cultivated in double cropping systems, enhancing land rents and promoting further expansion [72]. This suggests a rebound effect where intensification of high-profit crops such as soybeans drives additional expansion, even though the Granger causality test in this study failed to identify a direct predictive causality between crop yield and area changes across agroecological zones in Brazil.

In China, strong crop yield increases aligns with Hu *et al* (2020) who attribute crop productivity increases to improved management practices (crop mix, cropping frequency, fertiliser, irrigation, and paddy rice water management) [70]. However, the rising efficiency in crop production only partially compensated for the environmental pressures [73]. Our findings from the Granger causality test suggest a rebound effect from cropland intensification over large parts of southern China (see figure 6(c)), which may have exacerbated agriculture-driven pressures to the environment.

While the land-sparing theory may apply to high-income countries, where it is often regulated by agricultural policies (e.g. as seen for the E.U.), our findings suggest a knock-on (or rebound) effect in emerging economies of the tropics, such as Tanzania, Ghana, China or Vietnam. In these regions, intensification of high-profit crops triggers further expansion, supporting the hypothesis of a knock-on effect. Our findings also align with the theory of induced intensification suggesting that growing demand and land scarcity drive intensification, moderated by technology and institutional constraints [33]. When land becomes scarce and prices rise, intensification is more likely, especially for staple crops with low price elasticity. Conversely, available land and low land prices encourage expansion [33, 74]. This particularly applies to internationally heavily traded (cash) crops with high price-elasticity of demand such as sugarcane, oil palm and soybean, which corresponds with the findings of García *et al* (2020) [33] and Villoria (2019) [36].

The observed unidirectional Granger causalities from cropland area to yield changes with positive correlation coefficients, e.g. in Indonesia and Colombia, may align with this concept of induced intensification. Resulting patterns, in particular the existence of such unidirectional Granger causalities in areas with terrain limitations, suggests that in these regions, changes in cropland area are driving subsequent increases in crop yields, as land becomes scarce. However, the possibility that these correlations may be spurious cannot be discounted. The observed area-yield relationship may also be driven by other underlying factors, such as the increasing use of technology leading to efficiency gains in agriculture, or the implementation of land reforms including land consolidation.

4.5. Limitations, potential and future research

While our study offers valuable insights into global cropland and yield changes, it has several limitations. The use of a weighted average yield across all crop types may obscure crop-specific trends and responses to various drivers from the input side (e.g. fertilisation, irrigation, cropping frequency). By using the average yield as a mass- rather than energy-related measure, distortions in yield changes may occur due to the varying water contents of different crop types. Consequently, caution should be exercised when undertaking regional comparisons of absolute yield figures. Moreover, our analysis does not directly account for the impact of technological advancements, policy changes, or market forces on yield and area changes. The exclusive emphasis on yield increases as a metric for evaluating output intensification and subsequent productivity gains could be regarded as a one-dimensional perspective on agronomic management, given its reliance on both management and environmental factors. The study design precludes any definitive conclusions regarding the specific influences of these factors on productivity. Nevertheless, given that the enhancement of productivity is the ultimate objective of all intensification measures, this study offers a comprehensive perspective on the implementation of intensification from an output perspective.

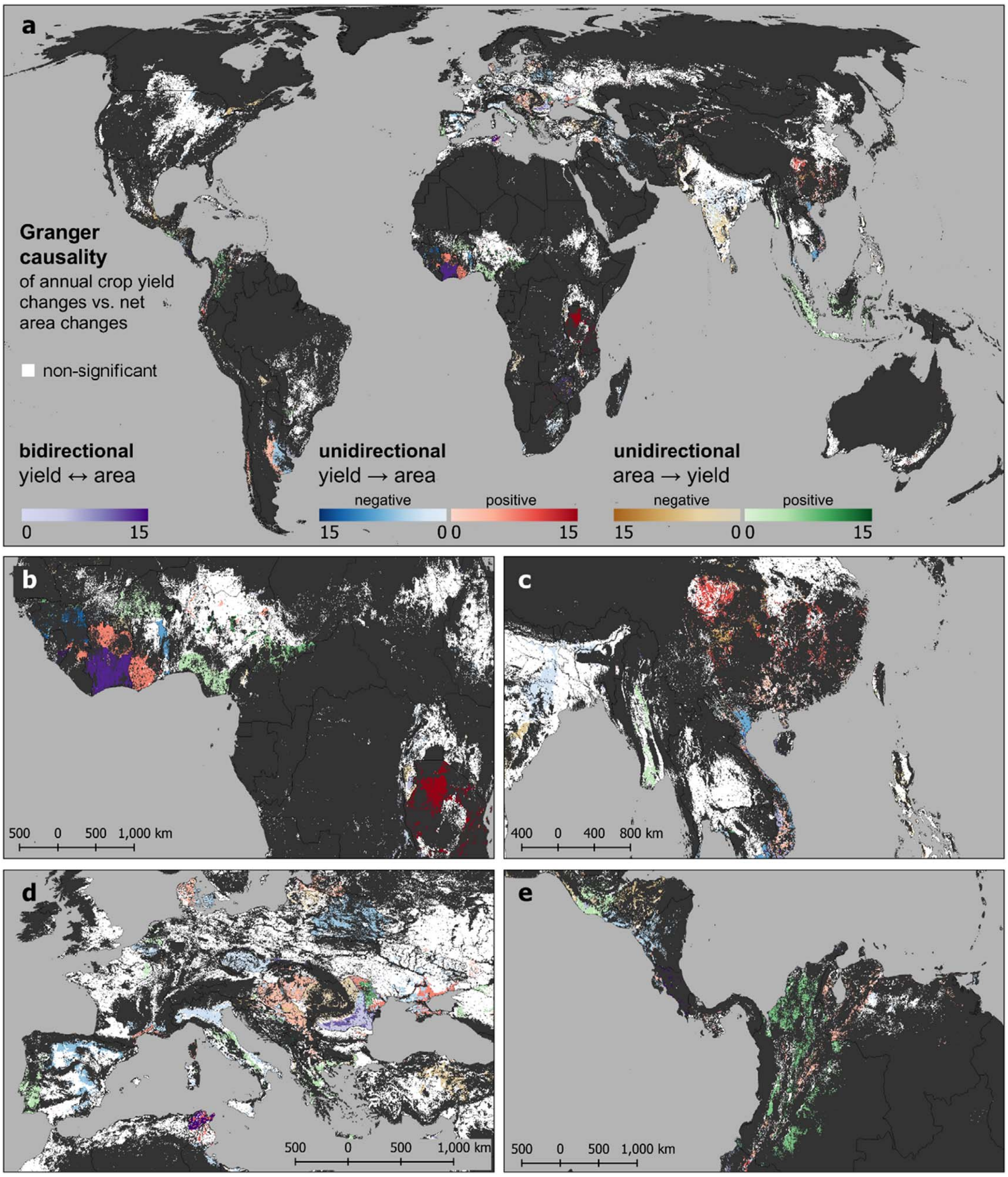

Figure 6. F-statistic from granger causality test for predictive causality between annual crop yield changes and net cropland changes from 1960 to 2020 across agroecological country zones. Only areas with significant predictive causality are displayed (significance level of 95%). The direction of the relationship, whether past values of one indicator provide statistically significant information for predicting the other, is displayed in different colour ranges: unidirectional Granger-causality for *yield → area* in blue (negative correlation) and red (positive correlation), unidirectional Granger-causality for *area → yield* in gold (negative correlation) and green (positive correlation), bidirectional Granger-causality for *yield ←→ area* in purple (both positive and negative correlations). Global (a) and regional maps: western Sub-Saharan Africa (b), South-eastern Asia (c), Central and Southern Europe (d), Central and northern South America (e).

Although deriving direct causal relationships was not the aim of this study, another significant limitation lies in the use of cross-correlation and Granger causality tests. While these methods provide valuable insights into relationships between variables and are thus justified for a first exploration of the spatiotemporal links, they have inherent limitations in establishing true causality. These tests primarily detect temporal precedence and predictive power rather than direct causal mechanisms. To address these shortcomings in future studies that explicitly deal with causality, statistical approaches should be complemented with experimental designs, instrumental variable techniques, or structural equation modelling. Counterfactual modelling of land change would be required for causal inference, disentangling complex causal pathways in land systems to assess the impact of specific management interventions and/or historical events [75].

Despite the extensive body of literature addressing the relationship between intensification and agricultural land change on global to regional scales, this study represents a novel integration of multiple datasets harmonising both global coverage and spatial depth. Further, the data harmonisation approach applied in this study, in compiling both the spatiotemporally dynamic land use and crop yield maps, attenuates potential data artefacts and outliers, which are often associated with reliance on single data streams. By combining the spatial distribution from gridded input data with a calibration to nationally aggregated indicators from the FAO (as the sum of cropland areas or the weighted average yield across crop types), we have developed a novel, internally consistent dataset of changes in land use and crop yield that is based less on assumptions than on quality-assured and freely available scientific data. Notably, it provides a means of identifying spatiotemporal patterns and statistical relationships at different scales, of which agroecological country zones (as used here) are just one example.

Nevertheless, further refinement of the analytical method is required to incorporate additional factors influencing the yield-area relationship, thereby enabling more nuanced conclusions to be drawn. Future research could benefit from integrating spatially explicit data on crop types and management practices as well as applying novel methods for establishing causal links, such as counterfactual modelling, to elucidate their specific impacts on yield and area changes. These avenues of research could provide a more comprehensive understanding of global agricultural dynamics and inform sustainable land use policies in the face of growing food demand and environmental challenges.

5. Conclusion

This study reveals significant global patterns in cropland expansion and yield increases over the past six decades (1960–2020). By a spatially explicit mapping of both area and productivity changes, it gives new insights into the spatiotemporal heterogeneity of gross cropland expansion and yield increases at a high spatial resolution beyond the country-scale.

High-income countries have generally increased yields through intensification while reducing cropland areas, in accordance with the concept of land sparing. In contrast, emerging economies have experienced both massive yield increases and cropland expansion, driven by international trade and a knock-on effect of intensification, particularly for high-profit crops such as sugarcane, oil palm, and soybeans. Notably, tree crops have been a major driver of global deforestation, especially in tropical regions.

Our findings underscore the complex interplay between socioeconomic, political, and climatic factors in shaping agricultural management and land use change. To gain a comprehensive understanding of global cropland intensification, particularly climate and management effects on crop yields, further research and the integration of spatiotemporally dynamic data on climatic and management factors are essential, e.g. analysing drought impacts or crop type-specific fertilizer and water use efficiency.

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The authors declare no competing interests.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: HILDA+ version 2.0, Global Land Use Change between 1960 and 2020: https://doi.pangaea.de/10.1594/PANGAEA.974335. Global crop yield data 1960-2020 and codes on correlation and Granger causality analysis: https://doi.org/10.5281/zenodo.13768506.

ORCID iDs

Karina Winkler https://orcid.org/0000-0002-2591-0620
Richard Fuchs https://orcid.org/0000-0003-3830-1274

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