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Measuring exposure of agriculture to observed temperature change

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Short Summary. We use FAO agricultural and temperature change data to derive indicators of exposure to warming since 1961. Indicators reveal how much key agricultural dimension such as rural population, cropland, major crops, and livestock, are located in countries where annual temperature rise exceeded 1.5 °C and 2 °C compared to the 1951–1980 baseline period. Results reveal growth in exposure worldwide and highlight which regions and agricultural dimensions may be most in need of adaptation.

Abstract. We used available FAO statistics as input metrics to compute simple indicators of exposure of agriculture at regional and global levels to temperature change thresholds, $\Delta T > 1.5$ °C and $\Delta T > 2.0$ °C, relative the 1951–1980 climatology. Since 1995 and with respect to $\Delta T > 1.5$ °C, results show that exposure of rural populations increased globally 14 times (from 64 to 920 million people); exposed agricultural land area grew five-fold (from 350 to 2000 million hectare, Mha). The exposed harvested area of soybean increased globally 90 times (0.5 to 45 Mha); rice 78 times (0.5 to 39 Mha); maize 38 times (2 to 76 Mha) and wheat 5 times (22 to 110 Mha). Finally, exposure of livestock grew six-fold for dairy cows and 20-fold for chicken broilers. Among regions, Europe had the largest exposure to $\Delta T > 1.5$ °C, with more than 80% of its rural population, cropland area, dairy cattle, maize and wheat harvested areas exposed in 2024. Exposure indicators for Central Asia, Western Asia and Northern Africa were above 65% for cropland area and wheat harvested area. The computed exposure indicators were found to increase nearly exponentially over the period 1961–2024 across all regions, highlighting the urgency of implementing appropriate agricultural adaptation strategies to avert possible negative impacts in coming decades. The data is available at https://doi.org/10.5281/zenodo.12665841 (Tubiello, 2025).

Keywords. Climate change; temperature change; agriculture; exposure; statistics; adaptation; Land use; Crops; Livestock

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1 Introduction

In a world where emissions of greenhouse gases keep increasing despite international agreements and overwhelming scientific advice to the contrary, climate change is expected to accelerate faster than previously expected (Hansen et al., 2023), threatening food security, nutrition and livelihoods in many regions (Cardona et al., 2012; Rosenzweig et al., 2008; King et al., 2018; IPCC, 2019). Impacts are expected to disproportionally affect vulnerable small-scale food producers, especially in sub-Saharan Africa, Southern Asia, Central and South America and Small Island States (Barker et al., 2021). Monitoring agricultural production may help relevant stakeholders in both public and private sectors to identify early threats and put in place effective adaptations where most needed. While current developments in machine learning, remote sensing and crop modeling promise to make implementation of real-time global agricultural monitoring a real possibility in the near term, the world is not yet there. Tubiello and Rosenzweig (2008) had proposed the development of simple climate change agricultural impact metrics to fill the current information gap, enabling the regular production of simple risk assessments, while more sophisticated solutions came to market. To date, simple indicators of agricultural exposure[1] to climate change are still lacking. We use readily available country-level agricultural data from FAO and temperature change data from NASA-GISS to compute exposure indicators, expressed as the proportion of total values (population, area, animal numbers) in countries in a given region where agriculture has become exposed to temperature changes above 1.5 °C and 2 °C, over the region total. While any threshold can be set within the methods developed herein, the two used herein were heuristically chosen as they represent important physical and psychological thresholds set by the Paris Agreement of the United Nations Convention on Climate Change (UNFCCC, 2015). The exposure indicators presented herein are meant to facilitate the identification of regions where agriculture is already at potential risk from observed climate change, making the need for appropriate adaptation planning urgent.

2 Methods

2.1 Country level statistics

We used a set of agricultural and temperature change statistics as input metrics into the computation of the proposed exposure indicators. The statistics are available through FAOSTAT for nearly 240 countries and territories for the period 1961–2024 (Tab. 1). Exposure indicators were computed for ten agricultural variables: 1) rural population; 2) agricultural land and cropland area; 3) harvested area of wheat, maize, rice and soybean; 4) animal stocks of dairy cows and chicken broilers; and 5) value of agricultural production.

[1]Exposure: The presence of people; livelihoods; environmental services and resources; infrastructure; or economic, social, or cultural assets in places that could be adversely affected (Cardona et al., 2012).

https://doi.org/10.5194/essd-2025-681
Preprint. Discussion started: 27 January 2026

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Discussions

Table 1: FAOSTAT Statistics used as input into the exposure indicators.

Domain	Data Item	Unit	Time series	Note
Temperature change on land (FAO, 2024d)	Meteorological year	°C	1961–2024	Compared to baseline 1951–1980 Produced jointly by FAO and NASA-GISS
Human population (FAO, 2024e)	Total population - both sexes	1000 No	1961–2024	Include estimates and projections after 2023
	Rural population			
Crops and livestock production (FAO, 2024a)	Harvested area- wheat	Ha	1961–2023[a]	Include multi-cropping areas
	Harvested area - maize			
	Harvested area - rice			
	Harvested area- soy			
	Dairy cows	animals	1961–2022[b]	FAOSTAT agrifood systems emissions categories
	Chicken broilers			
Land use (FAO, 2024c)	Agricultural land	1000 ha	1961–2022[b]	Cropland and permanent meadows and pastures
	Cropland area			Arable land and permanent crops
Economic value (FAO, 2024b)	Value of production	1000 Int$	1961–2023[a]	Crop and livestock gross production value

[a]2024 values were projected by carry-forward of 2023.
[b]2024 and 2023 values were projected by carry-forward of 2022.
[*]International dollars.

2.2 Exposure Indicators

Exposure of agricultural variable i in region R to temperature change threshold ΔT_a and year y, was computed as a regional share, and defined as:

$$e_{i,R}(\Delta T_a, y) = \frac{\sum_{c \in R; \Delta T_a} V_i(c,y)}{\sum_{c \in R} V_i(c,y)} \quad (1)$$

where:

$V_i(c, y)$ is the value of variable i in country c and year y;

$\sum_{c \in R} V_i(c, y)$ is the regional aggregate of variable V_i over all countries c in region R in year y;

$\sum_{c \in R; \Delta T_a} V_i(c, y)$ is the regional aggregate of variable V_i, limited to countries c in region R with temperature change $\Delta T > \Delta T_a$ in year y.

The FAOSTAT regions considered were twenty-three: Eastern Africa, Middle Africa, Northern Africa, Southern Africa, Western Africa, Central America, Northern America, South America, the Caribbean, Central Asia, Eastern Asia, South-Eastern Asia, Southern Asia, Western Asia, Eastern Europe, Northern Europe, Southern Europe, Western Europe, Australia and

https://doi.org/10.5194/essd-2025-681
Preprint. Discussion started: 27 January 2026

New Zealand, Melanesia, Micronesia, and Polynesia; plus their higher-level aggregates: Africa, Americas, Asia, Europe, Oceania, and World.

Temperature change is computed with respect to the 1951–1980 climatology. The difference between using this baseline as opposed to the IPCC pre-industrial baseline is about 0.2 °C (FAO, 2025). For each threshold ΔT_a and FAOSTAT sub-region R, equation (1) yields ten exposure indicators. The results presented herein refer to threshold $\Delta T_{1.5}$ = 1.5 °C and ΔT_2 = 2.0 °C.

2.3 Limitations and uncertainty

There are advantages and disadvantages to the use of the indicators developed herein. Advantages include their clear definition, ease of computation, public availability, and regular updates of the underlying agricultural statistics. Any user can access FAOSTAT and freely download the data needed as input to compute these exposure indicators, with minimal computational resources. The availability, simplicity and robustness of available national statistics underpin similar efforts developed by the UN system. For instance, under the United Nations Convention to Combat Desertification (UNFCCC, 2015), strategic objective aiming to 'mitigate, adapt to, and manage the effects of drought to enhance resilience of vulnerable populations and ecosystems', countries currently use similar indicators: a) trends in the proportion of land under drought over the total land area; and b) trends in the proportion of the total population exposed to drought (Barker et al., 2021).

At the same time, several limitations apply. First, sub-national exposure to temperature change is not captured, nor are the underlying statistics analyzed geospatially. This implies that the regional values of the exposure indicators considered herein should be regarded as upper limits, because each country exposed to a given temperature change threshold contributes fully to the computations. In reality, and especially so for countries with large area, the distribution of temperature change and agricultural variables may be misaligned sub-nationally, resulting in less area (or number of animals) being exposed to a given threshold than implied by using the corresponding national value. Such misalignment, which can be addressed in principle by using geospatial information, will nonetheless be less and less relevant as the recorded annual temperature changes increase over time above well above the ΔT > 1.5 °C or ΔT > 2.0 °C threshold, as it is being observed in recent years, increasing the probability that most or all of the country area (or animal numbers) will be exposed. Hence, the rate of increase in exposure indicators values reported herein for the period 1995–2024 can be regarded as conservative. Second, the indicators proposed do not consider additional agro-meteorological variables, such as precipitation, intensity and frequency of extreme events. The inclusion of these variables may likely increase the exposure indicators well beyond those obtained using only temperature change thresholds. Future work could therefore include analyses of monthly and/or seasonal temperature change signals, which may better capture exposure dynamics through negative effects in critical crop development stages. At the same time, data on the distribution of livestock and breeds, including beef cattle, across countries and regions would provide a better understanding of the exposure of livestock to changing climate conditions.

In terms of uncertainty, we treated the exposure indicators proposed—obtained by temperature change data and agricultural variables—as a product of independent statistical variables. Hence, the overall uncertainty was estimated as the sum of component relative uncertainties. The uncertainty of the FAOSTAT temperature change data was taken to be 10 % for regional

https://doi.org/10.5194/essd-2025-681
Preprint. Discussion started: 27 January 2026

and global aggregates (typically 0.1–0.2 °C), understanding that values can be lower in Europe and North America (5%) and much higher in African countries, up to 40% (Porter et al., 2014; IPCC, 2022a; IPCC, 2022b). The uncertainty of FAOSTAT agricultural statistics was taken to be 20% across the board (Toreti et al., 2020; Tubiello et al., 2023a; Tubiello and Rosenzweig, 2008). We thus estimated an overall uncertainty in the estimated exposure of about 30% globally, ranging from about 10% in Europe and North America to about 60% in Africa.

3 Results

We report values of regional exposure indicators for the year 2024 as well as their decadal trends since the year 1995, using averages for 1995–2004, 2005–2014 and 2015–2024. We focus on 6 of the total 10 indicators developed for brevity, noting that the full set of results across variables and years (1961–2024) are available as open access data at: https://doi.org/10.5281/zenodo.12665841 (Tubiello, 2025).

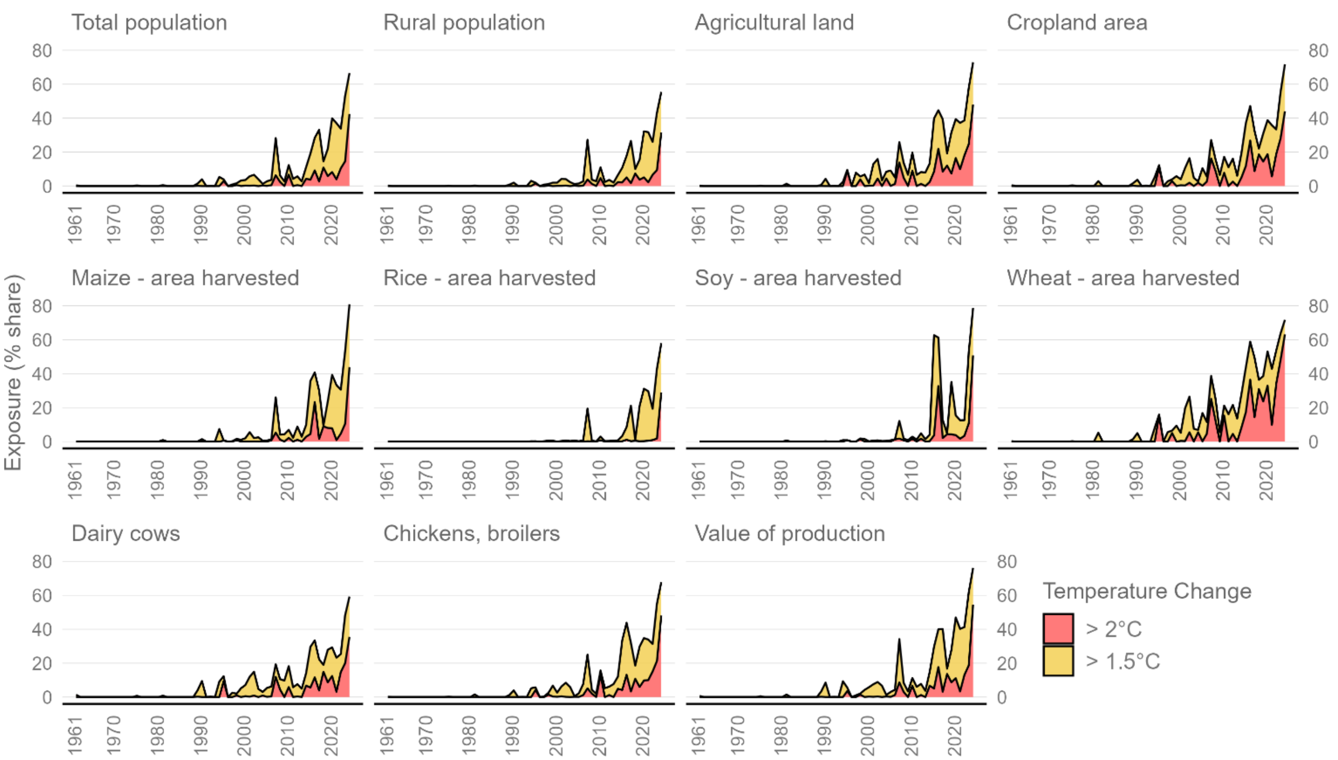

Figure 1: Exposure indicators of global agriculture to 1.5 °C and 2 °C temperature change, global trends 1961–2024.

https://doi.org/10.5194/essd-2025-681
Preprint. Discussion started: 27 January 2026

3.1 Key Findings for 2024

In 2024, the mean annual temperature change was greater than 1.5 °C in 163 countries or territories and greater than 2 °C in 88 countries or territories. National temperature records were broken in 129 countries or territories, about three times as much as in previous years. In correspondence to these observed temperature trends (FAO, 2024d), 1.9 billion people in 2024 lived in rural areas in countries with $\Delta T > \Delta T_{1.5}$ (and 1.1 billion for $\Delta T > \Delta T_2$) (Tab. 2, Fig. 1). Also in 2024, nearly 3.5 billion hectares of agricultural land were exposed to $\Delta T > \Delta T_{1.5}$, representing about three quarters of the world total agricultural land area (and 2.3 billion ha were exposed to $\Delta T > \Delta T_2$). On this agricultural land, nearly 160 Mha of wheat area (about 70% of the word total) were exposed to $\Delta T > \Delta T_{1.5}$, of which 140 Mha were already exposed to $\Delta T > \Delta T_2$. Furthermore, 110 Mha of harvested soybean area, 170 Mha of corn and nearly 100 Mha of rice were located in countries with $\Delta T > \Delta T_{1.5}$, representing 80% of world total harvested area in 2024 (60% for rice). In terms of livestock exposure, 165 million milking cows and over 12 billion chicken broilers were reared in countries with $\Delta T > \Delta T_{1.5}$ (about 60% of the world total). Economically, this resulted in 3.3 trillion US $ of the total value of agricultural production being generated in countries with $\Delta T > \Delta T_{1.5}$, an exposure of nearly 80% globally (2.3 trillion US dollars exposed to $\Delta T > \Delta T_2$).

Table 2: Overview of exposure indicators for year 2024. Values for Oceania were small and are not shown.

	Africa		Americas		Asia		Europe		World	
	> 1.5 °C	> 2 °C	> 1.5 °C	> 2 °C	> 1.5 °C	> 2 °C	> 1.5 °C	> 2 °C	> 1.5 °C	> 2 °C
Rural population										
Million people	530	100	180	60	1,020	750	170	160	**1,890**	**1,070**
Percent (%)	65.6	12.7	95.7	30.3	45.7	33.8	93.2	90.8	**55.5**	**31.4**
Production value										
Billion Int. $	317	81	880	385	1,538	1,352	519	509	**3,254**	**2,327**
Percent (%)	76.7	19.6	90.8	39.7	67.9	59.7	93.5	91.8	**76.1**	**54.4**
Agricultural land										
Million ha	722	190	966	384	1,361	1,290	436	431	**3,486**	**2,295**
Percent (%)	61.6	16.2	86.8	34.5	82.0	77.7	95	93.9	**72.9**	**48.0**
Maize (corn)										
Millon ha	28.8	1.2	70.7	26	52.7	47.9	16.5	16.4	**169**	**91**
Percent (%)	65.4	2.7	89.4	32.9	76.8	69.8	100	99.5	**81.0**	**43.9**
Rice										
Million ha	11.4	0.7	5.2	3.1	80.4	44.3	0.5	0.5	**98**	**49**
Percent (%)	62.0	4.0	90.8	53.8	56.0	30.9	100	94.8	**58.0**	**28.9**

https://doi.org/10.5194/essd-2025-681
Preprint. Discussion started: 27 January 2026

Soybean										
Million ha	4.5	0.0	85.7	52.2	10.9	10.7	6.6	6.6	**108**	**69**
Percent (%)	90.1	0.4	84.8	51.7	44.9	44.0	100	100	**78.7**	**50.8**
Wheat										
Million ha	8.7	6.1	30.4	14.7	59.2	58.8	59.7	59.6	**158**	**139**
Percent (%)	95.0	66.1	83.6	40.3	59.0	58.6	97.1	97.0	**71.7**	**63.1**
Dairy cows										
Heads (million)	41.1	6.4	41.3	21.5	52.3	41.4	29.6	29.1	**164**	**98**
Percent (%)	60.8	9.5	92.4	48.1	41.5	32.9	89.7	88.4	**59.2**	**35.5**
Chickens broilers										
Birds (million)	1,561	701	4,100	2,072	5,464	4,701	1,567	1,522	**12,693**	**8,996**
Percent (%)	86.7	38.9	92.8	46.9	51.1	44.0	92.2	89.5	**67.8**	**48.0**

3.2 Global and regional trends

We report herein exposure indicators results for six variables: agricultural land; harvested area of wheat, maize rice and soybean; stocks of dairy cows and chicken broilers. Full results are available in Tab. 3.

3.2.1 Agricultural land

Exposure of agricultural land to temperature change above 1.5 °C grew globally from 350 Mha on average for the decade 1995–2004, to over 2000 Mha in 2015–2024, a more than five-fold increase. Over the same period, world total agricultural area had decreased slightly, from about 4830 to 4780 Mha, whereas cropland area increased 6%, from about 1499 to 1580 Mha. As a percentage of total area, exposure of both agricultural land and cropland area to exposed to $\Delta T > \Delta T_{1.5}$ grew from 7% to 40% during 1995–2024. Europe and its subregions had the largest exposure of agricultural land to $\Delta T > \Delta T_{1.5}$ in the most recent decade (nearly 90%), up from only 20% in 1995–2004. The second most exposed regions in the most recent decade were Asia (about 60%), the Americas and Africa (about 30%) (Fig. 2; Tab.3).

Among subregions, exposure of agricultural land in Western Asia had a nearly 40-fold increase since 1995, to reach 80% in the most recent decade. Eastern Asia had a more than five-fold increase, to 65% currently. Central Asia (73%) and Northern Africa (44%) also had high exposure values. With respect to exposure to $\Delta T > \Delta T_2$, the indicators computed indicated more than 10-fold increases for agricultural area in Eastern Europe and Western Europe.

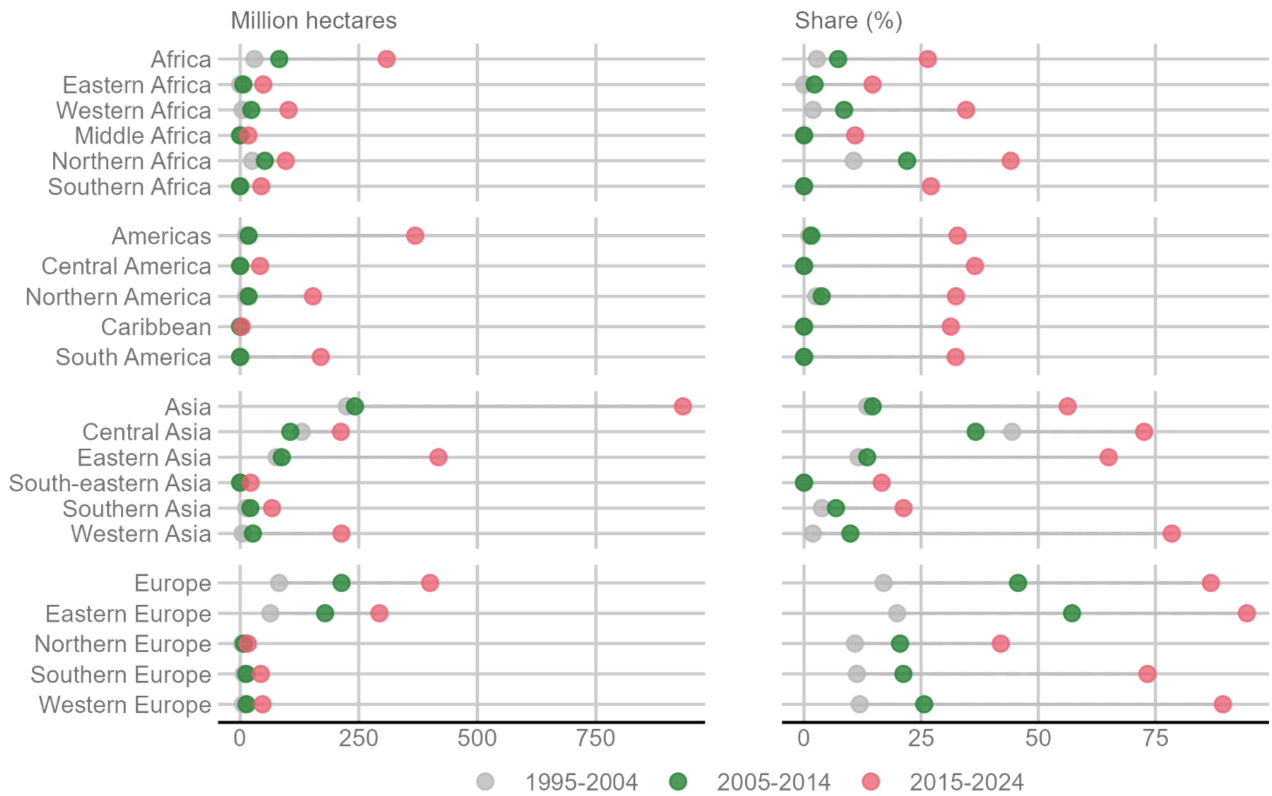

Figure 2: Exposure indicators of agricultural land to temperature change above 1.5 °C, by region and subregion, in absolute values and shares.

3.2.2 Harvested area of major world crops

The exposure indicators show that the global harvested area of rice and soybean exposed to $\Delta T > \Delta T_{1.5}$ increased 80-fold since 1995, from about 0.5 to 40 Mha. It increased 35-fold for maize harvested area, from 2 to 75 Mha and five-fold for wheat, from 20 to 110 Mha. In the most recent decade 2015–2024, exposure to $\Delta T > \Delta T_{1.5}$ affected about half of the global harvested area of wheat and maize, one-third of soybean and less than one-quarter of rice. At the same time, world total harvested area of wheat and rice increased only slightly since 1995 (2%–10%) and more strongly for maize and soybean (50–100%), though still much less than the reported increases in exposure indicators.

In the most recent decade and with respect to wheat, Europe had the largest exposure to $\Delta T > \Delta T_{1.5}$ (55 Mha of the 110 Mha global exposure and 90% regional share). All its subregions were among the most exposed in the world, reaching 90% of wheat harvested area in Eastern Europe and Western Europe. Additionally, 50% of wheat harvested area was exposed to $\Delta T > \Delta T_{1.5}$ in Africa, 40% in Asia and 33% in the Americas. The most exposed areas of maize were also found in Europe (85%

https://doi.org/10.5194/essd-2025-681
Preprint. Discussion started: 27 January 2026

overall and nearly 100% in Northern Europe), followed by Western Asia (70%), Central Asia (65%), and Eastern Asia (60%). More than half of the harvested area of rice was exposed to $\Delta T > \Delta T_{1.5}$ in Eastern Asia.

Soybean exposure to $\Delta T > \Delta T_{1.5}$ was largely located in South America (20 Mha) and North America (10 Mha), representing about a third of total soybean harvested area. Over 90% of soybean harvested aera in Eastern Europe and Eastern Asia were exposed, exhibiting nearly 5-fold increases since 1995 (Tab. 3, Fig. 3).

Table 3: Exposure indicators of harvested areas to temperature change above 1.5 °C of major crops, subregional results, averaged 1995-2004 and 2015-2024. Values for Oceania and its subregions were small and are not shown.

	Wheat		Maize		Rice		Soybean	
	1995–2004	2015–2024	1995–2004	2015–2024	1995–2004	2015–2024	1995–2004	2015–2024
	Thousand hectares							
Western Africa	0	12	12	3,954	13	3,111	0	545
Southern Africa	0	163	0	809	0	0	0	238
Middle Africa	0	2	0	972	0	305	0	20
Northern Africa	1,650	4,471	81	447	2	218	0	8
Eastern Africa	0	214	0	1,091	0	28	0	111
Africa	**1,650**	**4,862**	**93**	**7,272**	**15**	**3,663**	**0**	**923**
South America	0	1,697	0	10,353	16	1,775	0	21,195
Northern America	2,106	10,041	227	11,011	0	345	198	11,171
Central America and the Caribbean	0	235	0	3,337	0	96	0	71
Americas	**2,106**	**11,973**	**227**	**24,701**	**16**	**2,216**	**198**	**32,437**
Western Asia	1,056	8,004	61	752	19	133	2	27
South-Eastern Asia	0	29	0	1,448	0	10,384	0	91
Southern Asia	1,098	6,549	40	269	120	3,139	13	77
Central Asia	6,420	10,672	70	221	88	142	6	84
Eastern Asia	160	14,616	112	26,269	116	19,000	60	5,859
Asia	**8,734**	**39,869**	**284**	**28,958**	**343**	**32,798**	**81**	**6,138**
Western Europe	946	7,988	258	1,976	2	13	11	235
Southern Europe	815	4,205	432	2,296	61	306	48	591
Northern Europe	441	2,838	2	22	0	0	0	2
Eastern Europe	7,416	40,153	920	10,752	32	211	111	4,484
Europe	**9,619**	**55,184**	**1,612**	**15,045**	**94**	**530**	**170**	**5,311**
World	**22,108**	**111,888**	**2,215**	**75,977**	**468**	**39,207**	**451**	**44,809**

https://doi.org/10.5194/essd-2025-681
Preprint. Discussion started: 27 January 2026

180

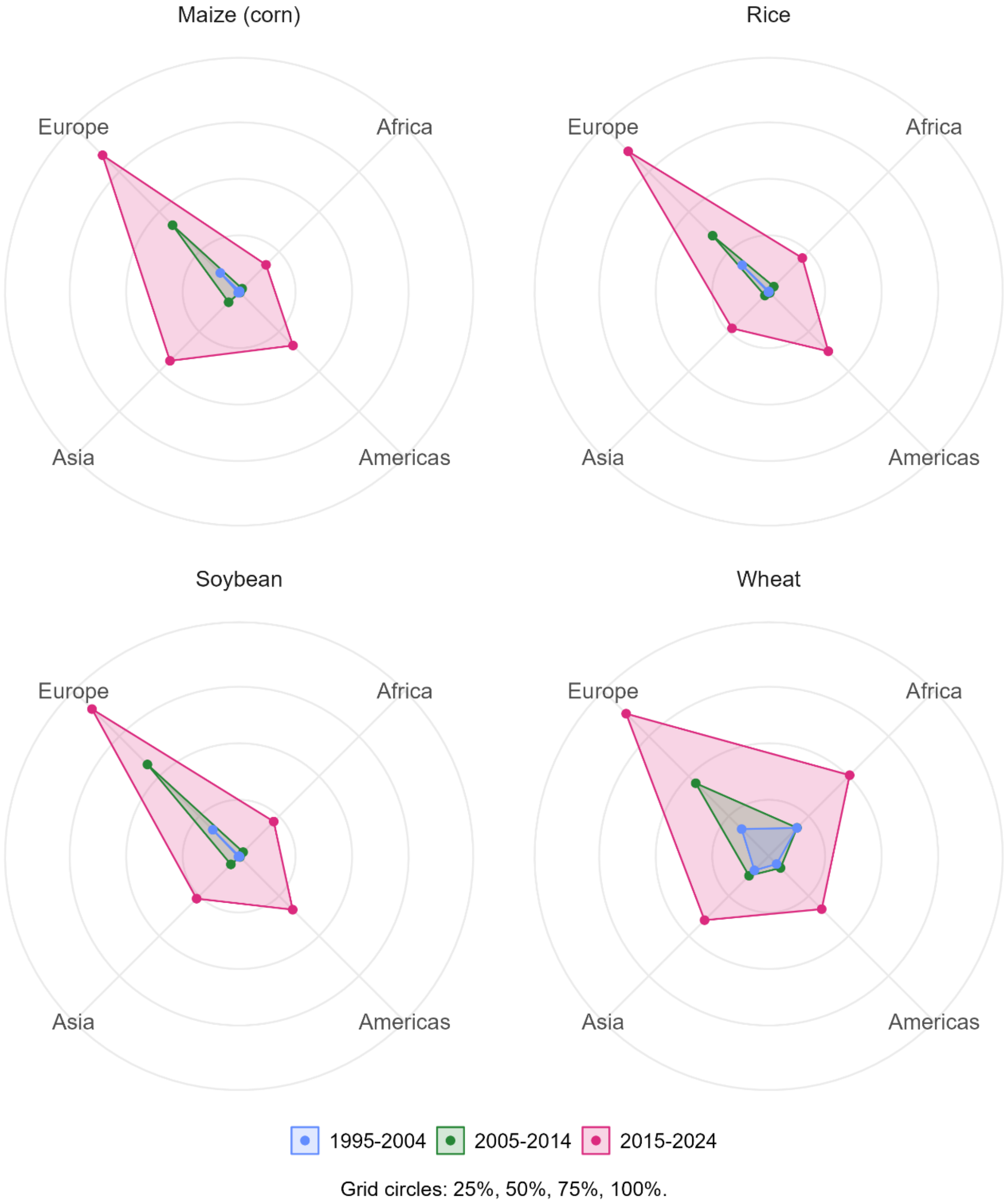

Figure 3: Exposure indicators of harvested areas of major crops to temperature change above 1.5 °C, shares by decade and region. Values for Oceania and its subregions were small and are not shown.

https://doi.org/10.5194/essd-2025-681
Preprint. Discussion started: 27 January 2026

3.2.3 Livestock

Exposure indicators show that the global number of dairy cows exposed to $\Delta T > \Delta T_{1.5}$ increased six-fold from 14 to 88 million animals over the period considered, while the number of exposed chicken broilers grew nearly 20-fold, from 370 to about 6600 million animals globally. These corresponded to exposures to $\Delta T > \Delta T_{1.5}$ of 35% for both species in the most recent decade 2015–2024 (Fig. 4, 5). Exposure to $\Delta T > \Delta T_2$ was about 10%. Sub-regionally, similarly to results for crops, Europe recorded the largest exposure values for both dairy cows (> 80%), followed by Central Asia and Western Asia (70%), Eastern Asia (60%). Oceania had almost no exposure over the study period.

Exposure indicators for chicken broilers were similar in patterns to that of dairy cows, with very high exposure on average during the most recent decade 2015–2024 seen in Europe (> 80%) and Central Asia (80%), Western Asia (70%) and Eastern Asia (60%), followed by Northern Africa (60%) and Western Africa (33%). Regions in the Americas had exposure values generally around 30%, while in Oceania this animal category had virtually no exposure to climate change.

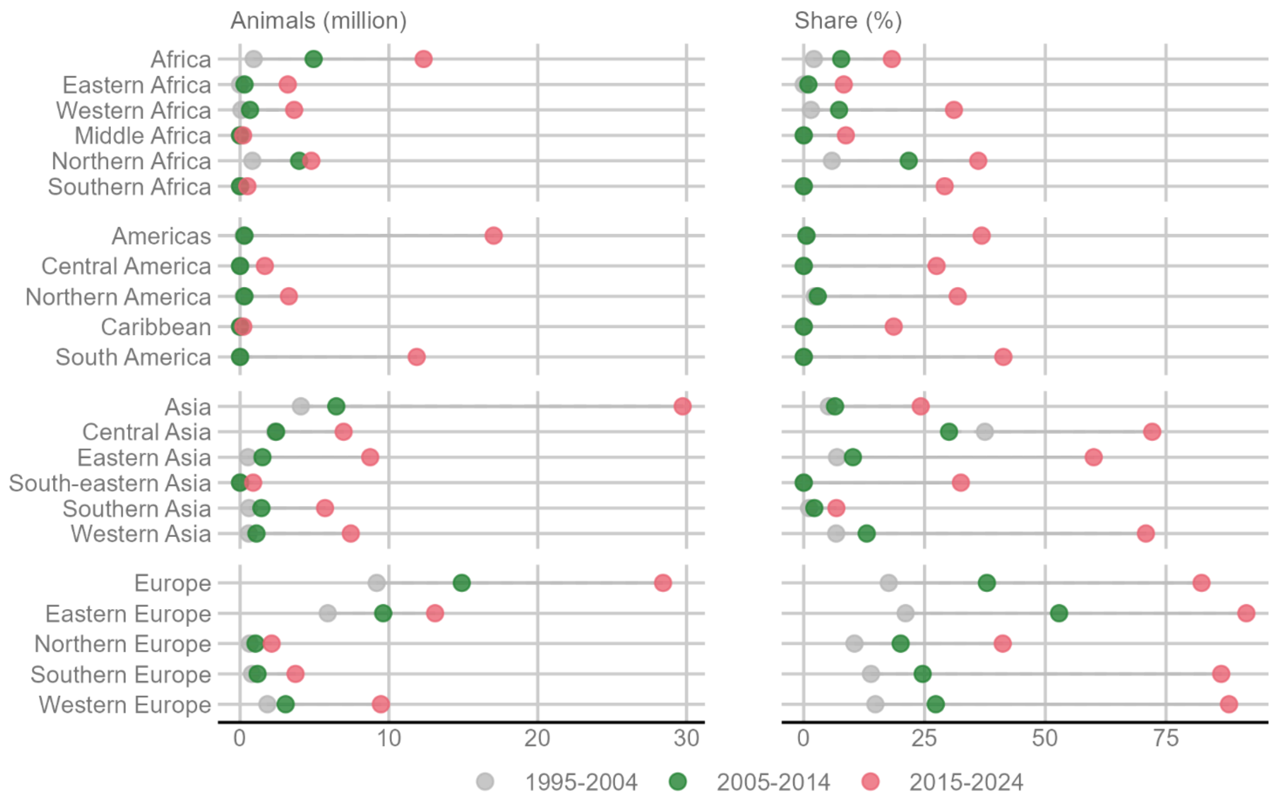

Figure 4: Exposure indicators of dairy cows to temperature change above 1.5 °C, by region and subregion, and in absolute numbers and shares. Values for Oceania and its subregions were small and are not shown.

https://doi.org/10.5194/essd-2025-681
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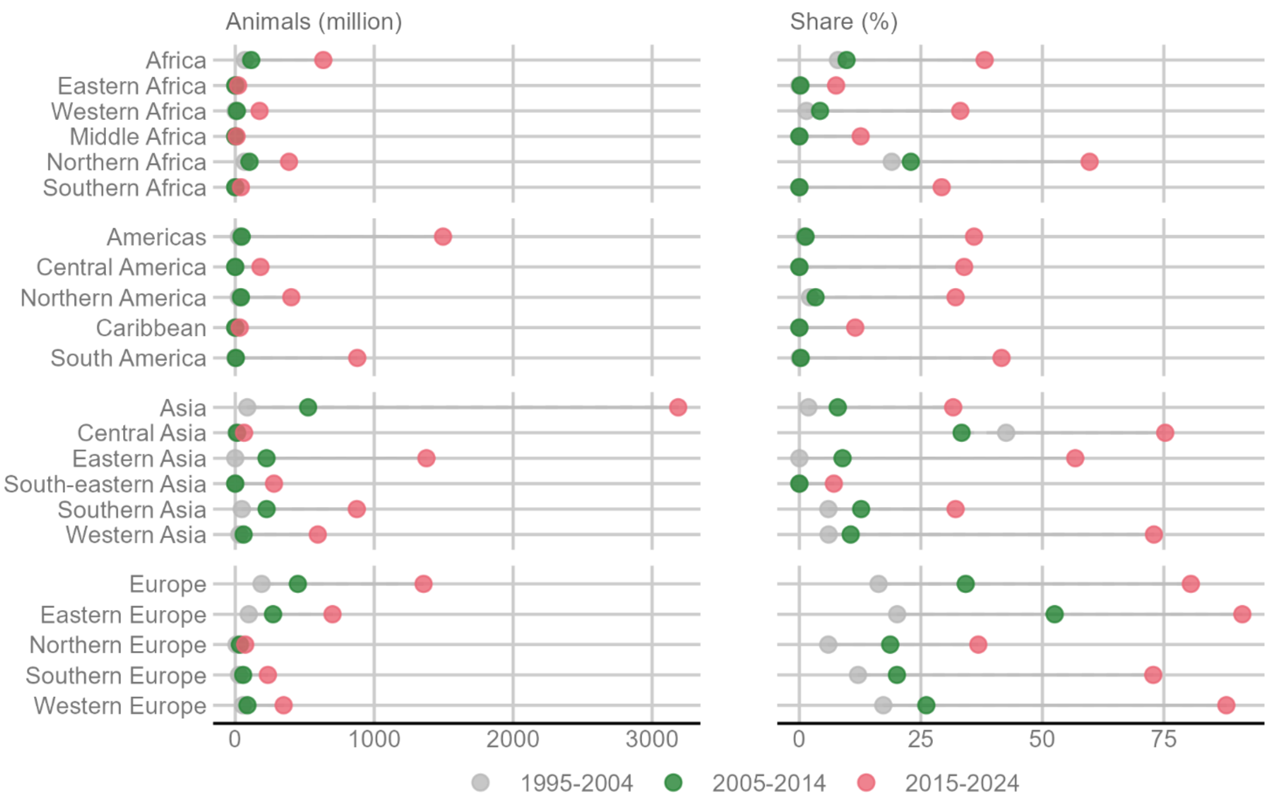

Figure 5: Exposure indicators of chickens broilers to temperature change above 1.5 °C, by region and subregion, and in absolute numbers and shares. Values for Oceania and its subregions were small and are not shown.

4. Discussion

The results presented, while not previously documented in this form, are consistent with basic agronomic knowledge and observed climate trends. Notably, they show that wheat, being predominantly grown in temperate to high latitude regions that have witnessed the largest observed temperature change since 1995, was the crop species most exposed to $\Delta T > \Delta T_{1.5}$ (75% in the most recent decade; of which half already exposed to $\Delta T > \Delta T_2$). Conversely, paddy rice cultivation area, being mainly located in tropical countries that have seen the least historical warming, had the lowest exposure values to $\Delta T > \Delta T_{1.5}$ (20%, of which nearly none exposed to $\Delta T > \Delta T_2$). In addition, the newly computed indicators suggest a near-exponential acceleration of exposure over the study period. This trend, not previously highlighted in the literature, contrasts with the near-linear trends of observed global and regional temperature changes. This is potentially worrisome for the future, considering growing concerns of more accelerated temperature changes in the coming years (Hansen et al., 2023).

With respect to the main staple crops that support world global calorie supply and thus are a cornerstone of world food security, results highlight 80-fold increases in the exposed area of rice and soybean, 35-fold increase for maize, five-fold for wheat, with some regions already reaching saturation, i.e., over 80% of European wheat area is already exposed today to $\Delta T > \Delta T_2$.

https://doi.org/10.5194/essd-2025-681
Preprint. Discussion started: 27 January 2026

We performed additional preliminary analyses investigating linkages between trends in the exposure indicators presented and available time-series of agricultural production statistics in FAOSTAT (FAO, 2023; FAO, 2024; Kennedy et al., 2023). These show that while exposure of wheat area underwent a five-fold increase from 1995 to 2024, wheat productivity grew from 2.5 to 3.6 t/ha. Yet wheat yields grew at a decelerated pace over the last three decades, consistently with the accelerated pace of exposure discussed above, from a mean annual growth of 1.8% (1995–2004) to 1.0% (2015–2024). Importantly, wheat yields appear to have stalled since the year 2005 in Western and Northern Europe (at nearly 7 t/ha) and in Central Asia (at 1.5 t/ha), subregions for which the wheat exposure indicators to $\Delta T > \Delta T_2$ showed the highest values in the two most recent decades starting in year 2005. At the same time, our simplified analysis shows that not every exposure to temperature change implies negative pressure, at least in the near term. Wheat yields in Eastern Europe grew over the study period from 2.5 to 3.7 t/ha, despite this region being the most exposed worldwide (>70%). This suggests that the warming observed in this region—whose wheat area is dominated by Ukraine and the Russian Federation—may have helped to overcome previous cold temperature limitations to crop growth (Hansen et al., 2010).

5. Conclusions

The exposure indicators proposed provide a useful view of exposure across crops and world regions, based on clear definitions and readily available and regularly available statistics that cover all world countries and regions with relevant agricultural and climate information. Our analysis shows that Europe was the region with the largest exposure to historically observed temperature change, with more than 90% of its rural population (nearly 100% in Eastern, Southern and Western Europe), 95% of its agricultural land area, 90% of its dairy cattle, 100% of its maize and 97% of its wheat harvested area experiencing temperature change above 1.5 °C in 2024. Other regions of significant exposure included Central America, Central Asia, Eastern Asia, Northern America (about all the agricultural land and area exposed to more than 1.5 °C warming), followed by Western Asia (90%) and Western Africa (80%).

It is noteworthy that the highest values in the computed exposure indicators tended to be for those crops and regions where experts expect the most severe future impacts from climate change, whether through a combination of existing adverse climatic factors (for instance, preponderance of arid or semi-arid zones in Central Asia, Western Asia and Northern Africa) and/or because of perceived or real poor adaptive capacity (for instance, most African regions, Central America and the Caribbeans, Oceania Small Island States outside of Australia and New Zealand). The next step in this research will be to better understand the links between the computed exposure indicators and actual agricultural risk, based on observed production dynamics, so that the information can be used as an important input for adaptation planning in specific regions. This is a daunting task, one that will require integration of the statistical approach presented here with scenario-analysis and crop modeling, including at finer sub-national and intra-annual scales, to help disentangle the role of socio-economic drivers that have enabled continued progress in agricultural output to date from purely agroclimatic trends that may represent current or future risk to production in specific world regions.

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Data Availability. All input data are available in FAOSTAT at: https://www.fao.org/faostat/en/#home. The indicators are available at: https://doi.org/10.5281/zenodo.12665841 (Tubiello, 2025). The NASA GISS temperature data are available at: https://data.giss.nasa.gov/gistemp/ (GISTEMP Team, 2024).

Authors' contributions. FNT and GC conceived the research and wrote the paper. NR supported data analysis, the database creation, and manuscript refinement. RR, GS, NL and MH provided temperature change data and data interpretation. CR supported data analysis and data discussion.

Competing interests. Author Francesco N. Tubiello is a member of the editorial board of the journal.

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