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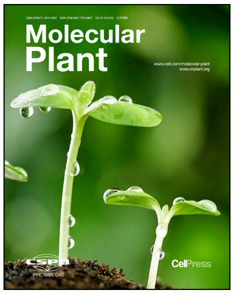

Redefining agroecological zones in China to mitigate climate change impacts on maize production

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PII: S1674-2052(25)00311-9

DOI: https://doi.org/10.1016/j.molp.2025.09.005

Reference: MOLP 1983

To appear in: *Molecular Plant*

Received Date: 3 March 2025

Revised Date: 9 July 2025

Accepted Date: 5 September 2025

Please cite this article as: Tang C., Wang C., Zhang Z., Cao Y., Bulut M., Xiao Y., Li X., Xiong T., Yan J., and Guo T. (2025). Redefining agroecological zones in China to mitigate climate change impacts on maize production. Molecular Plant doi: https://doi.org/10.1016/j.molp.2025.09.005.

Redefining agroecological zones in China to mitigate climate change impacts on maize production

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Short Summary:
This study introduces Multi-Dimensional Environment (MDE) zoning to enhance maize resilience and improve stagnant yields in China amidst climate change. Utilizing comprehensive environmental and yield data, MDE zoning accurately identifies areas for targeted, climate-adaptive breeding. The tool provides a flexible framework for updates using annual variety testing and daily environmental data, optimizing production and resource allocation.

Dear Editors:

Global maize yields are stagnating, with over 50% of China's growing areas experiencing yield plateaus (Gerber et al., 2024). Climate change significantly contributes to this stagnation (Rizzo et al., 2022; Tigchelaar et al., 2018). Current breeding efforts for climate-adapted maize are still in the early stages (Xiong et al., 2022). A major challenge is that existing agroecological zones (AEZs) was defined without considering evolving climatic variations essential for effective breeding (Table S1). Traditional AEZs in China, based on static environmental factors (Li, 2009), aid agricultural planning but are less effectively for guiding breeding practices. Instead, mega-environment (ME) concepts use yield data from multi-environment trials (MET) to identify genotype-by-environment interaction (G×E) patterns, offering better delineation of homogeneous zones (Yan et al., 2023). However, MEs require labor-intensive MET experiments, complicating the process amid climate change. To address these challenges, we propose a new approach that combines high-resolution, daily-scale environmental data with muti-location, multi-year yield data from METs nationwide. This scalable tool, called multi-dimensional environment (MDE) zoning, segments large maize-growing areas into distinct environmental zones, enhancing breeding efficiency in changing climates.

We defined MDE zones by identifying environmental variables affecting grain yield in national trials and grouping grid-level sites in China accordingly (Figure S1). We evaluated the tool's performance by comparing the new MDE zones with traditional ones regarding geographical coverages and yield variations. We propose three strategies to leverage this tool to improve breeding efficiency and maximize future production.

Define MDE zones

We used a nationwide variety testing (NVT) dataset of 1,502 pre-commercial varieties tested across 2,781 trials from 2016 to 2021, covering nearly all climate types in China's maize-growing regions (Figure S2-S3, Dataset S1). Trial environmental data included temperature, soil, humidity, radiation, and wind strength (Dataset S2). LASSO regressions identified three critical growth windows and 165 significant environmental variables influencing maize yield (Figures S4-S5, Tables S2-S3). The model performed well based on various evaluation metrics (Table S4). G×E was insignificant, expected given the broad geographical range of the NVT dataset, though it remains important at smaller scale (Figures S6).

Using identified variables, we delineated MDE zones via clustering analysis and evaluated its robustness (Table S5). This analysis used a nationwide grid containing 118,486 nodes, resulting in six noncontiguous zones representing distinct environments (Dataset S3, Figure 1A). Comparisons among MDE zones showed significant differences in key environmental factors (Figure S7). We examined how each environmental category shapes MDE zones independently and found that temperature, humidity, and radiation primarily influence delineation, while soil characteristics refine the resolution (Figure S8).

Performance of MDE zones

We compared the geographical coverage of the six MDE zones with the six traditional AEZs (Figure 1A). MDE Zone 0 aligns with the Northern Zone but extends along the Hu line into southwest China. MDE Zone 1 overlaps with the Huang-Huai-Hai Zone and includes tropical areas. MDE Zone 2 primarily occupies central and southern China, largely corresponding to the Southern Zone. MDE Zone 3 is located in the low-altitude regions of northwest China and does not match any AEZs. MDE Zone 4 covers high-altitude areas in the northwest, aligning with the Northwest Zone. Lastly, MDE Zone 5 includes the high-altitude regions in the west, featuring Mount Everest and the Tibetan Plateau Zone.

We compared yield performance of individual AEZs with their overlapping MDE zones to better understand their relationships (Figure 1B). Analyzing a county-level maize production (CMP) dataset from 1980 to 2015 revealed considerable yield variations among MDE zones overlapping a single AEZ (Dataset S4). For instance, the Northern AEZ overlaps with MDE Zones 0 and 3, where Zone 0 shows a continuous yield increase, while Zone 3 experiences a rapid increase followed by a plateau. The Southwestern AEZ overlaps with MDE Zones 0, 2, and 5, with Zone 5 exhibiting markedly different yield trend. These findings suggest that individual AEZs contain diverse environments, indicating that traditional AEZs may be less suitable for specific adaptation breeding.

We analyzed production trends across the MDE zones with the CMP dataset. While all zones show increasing total production, growth rates vary (Figure S9A-B). We focused on average annual yields (Figure 1C). MDE Zones 3-5 exhibit two phases of yield increases: an initial rapid rise of 0.20 tonnes per hectare (t/ha) annually, followed by a slower increase of 0.07 t/ha. In contrast, Zones 0-2 show one single phase with lower growth rates, yielding less than 0.1 t/ha annually. We further examined annual yield increases of the tested varieties in NVT experiments (Figure 1D). Only Zone 3 shows a significant upward yield trend, though it has recently slowed. This increase is primarily attributed to new varieties, assuming consistent environmental conditions and management from 2016 to 2021, as supported by no significant yield differences for recognized varieties ZD958 and XY335 (Figure S9C-D). These results highlight variations in maize production trends among MDE zones in the CMP and NVT datasets.

A mismatch exists between yield per unit area and planting area across MDE zones (Table S6). Higher-yielding zones generally have smaller planting areas. For instance, MDE Zone 0 represents 36.2% of the planting area but has a low average yield of 5.08 t/ha. Strategic shifts in breeding goals and crop distribution could enhance yields and boost national production without expanding cropland.

New breeding strategies

The first strategy of our zoning tool is to pinpoint representative testing sites by grouping locations within an MDE zone into subzones with more homogeneous environments. For MDE Zones 0, we identified five subzones (Figure 1E). Two subzones (Z0-a and Z0-b) yield nearly 5 t/ha, while the others yield less, indicating local environmental influences (Figure 1F). We then applied a spatial coverage optimization algorithm to select a cost-effective set of testing sites that capture environmental variations among subzones. For

Zone 0, we recommended 58 representative sites, down from 281 in the 2020 NVT trials (Figure S10). Similarly, for Zone 1, we identified five subzones and 41 representative sites, reducing the original 140 sites (Figures S11-S12). This approach helps breeders and decision-makers redesign the testing network for improved effectiveness and broad coverage.

The second strategy tailors breeding objectives for each MDE zone to address varying climate impacts on maize yields. Our analysis of the NVT dataset identified four key temperature-related factors: 2-meter air temperature, dew point temperature, precipitation, and thermal radiation (Figure 1G). Increased 2-meter air temperature boosts yields in Zones 0, 3, and 4, but negatively impacts Zones 1-2. Higher dew point temperature improves yields in Zones 0 and 2 while decreasing them in Zone 4. Precipitation positively affects yields in Zones 3-4, whereas higher thermal radiation harms yields in most zones. Zone 5 was excluded due to a smaller sample size. These findings highlight significant environmental variability across MDE zones, with further analysis revealing heterogenous yield impacts at the subzone scale (Figure S13). To guide climate-adapted breeding, we developed a model illustrating the non-linear relationship between rising temperatures and yield changes (Figure 1H). Zones 3-4 can increase yields with rising temperatures, while Zone 0 risks reduced yields as it nears upper limit. Zones 1-2 face significant yield risks from current temperature.

The third strategy, variety migration, involves transferring varieties to new areas projected to share similar environmental conditions due to climate change. These varieties can be used as foundational breeding materials for new varieties. We projected future temperature trends using growing degree days (GDD) based on two socio-economic pathways (O'Neill et al., 2017). Our analysis shows that projected GDD accumulations consistently exceed historical s from 1995 to 2014, though the increase varies by zone. We established three migration routes based on GDD projections: from Zone 1 to 3, and from Zone 2 to 4 and 0, where historical GDD trends in existing zones align with future trends in the target zones (Figure 1I). These routes can inform future breeding practices and maize production.

Discussion

This research underscores the need to redefine target environments to boost maize production in China, where yields have only modestly increased over the past two decades. We developed the MDE zoning tool to capture environmental variations in maize-growing areas, along with three strategies to enhance production and resource allocation. The tool also provides a flexible framework for ongoing updates based on annual variety testing and daily-scale environmental data for more precise breeding.

This study has several limitations. First, experiments are needed to validate the accuracy of MDE zones. Although analysis of MDE Zone 1 demonstrated that higher yield correlations within the zone (0.53 between North and South Zone 1) than between zones (0.45 and 0.38 with Out Zone 1) using a published dataset (Liu et al., 2021), additional validation is required (Figure S14). Second, we assume existing varieties can be relocated without constraints such as pest pressures or soil compatibility. Third, MDE zoning relies on mathematical algorithms that can be improved with newer methods. Enhancement to the MDE zoning tool include incorporating extreme weather events and socio-economic factors. With diverse, high-quality data and rigorous testing, the MDE zoning framework can be effectively adapted for new areas.

Data and code availability:

Supplemental Methods.
Supplemental Figures: S1-S14.
Supplemental Tables: S1-S6.
Supplemental Datasets: S1-S4.
Supplemental Datasets can be obtained at Mendeley Data. The scripts used for data analysis can also be accessed at Mendeley Data (https://data.mendeley.com/datasets/vmd8xbyjbv/1).

Funding:

This study was supported by the National Key R&D Program of China (2021YFD1201300), the Major Science and Technology Projects in Biological Breeding (2023ZD04067), and the Fundamental Research Funds for the Central Universities (2662025JGPY003).

Author contributions:

TC, YJ, and GT designed and supervised the study. TC, WC, ZZ, CY, XY, and XT performed the data collection and processing. TC and WC analyzed the data. TC, WC, BM, LX, YJ, and GT wrote the manuscript. All authors read and approved the final manuscript.

Declaration of generative AI and AI-assisted technologies in the writing process:

During the preparation of this work, the authors used GTP4 for language polishing. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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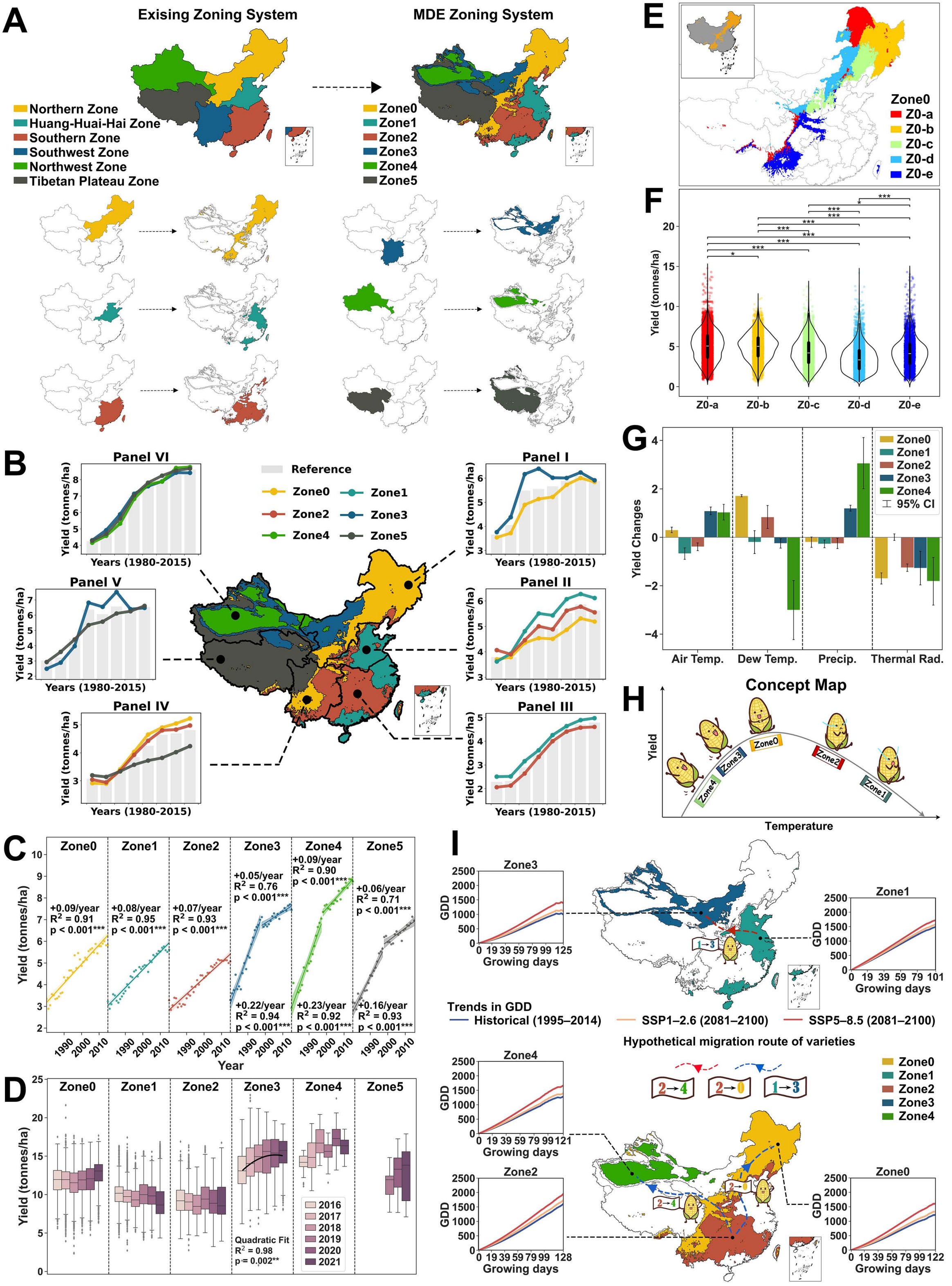
Figure Legend

Figure 1. China's redefined agroecological zones for maize and implications for yield trends. (A) China's agroecological zones (AEZs) and new multi-dimensional environmental (MDE) zones for maize. (B) Annual yield from 1980 to 2015 across AEZs and overlapping MDE zones, calculated at five-year interval. (C) Maize production trends across six MDE zones using the CMP dataset. (D) Yield gain trends across the six MDE zones using the NVT dataset. (E) Spatial distribution of five non-contiguous sub-zones within MDE Zone 0. (F) Annual yield distributions across the five sub-zones in MDE Zone 0 from 1980 to 2015. Asterisks indicate statistical significance: $*p<0.05$, $**p<0.01$, $***p<0.001$. (G) Heterogeneous effects of climate change factors on maize yields across six MDE zones, excluding Zone 5 due to small sample size. Examined factors: 2-meter air temperature (Air Temp.), dew point temperature (Dew Temp.), precipitation (Precip.), and thermal radiation (Thermal Rad.). Error bars indicate standard error at a 95% confidence interval. (H) Conceptual graph of the non-linear relationship between temperature and yield. (I) Accumulated growing degree days (GDD) under historical and future climate scenarios across six MDE zones, along with potential migration routes for varieties. The map of China adheres to the standard map GS(2024)0650.


A
Exising Zoning System
MDE Zoning System
Northern Zone
Huang-Huai-Hai Zone
Southern Zone
Southwest Zone
Northwest Zone
Tibetan Plateau Zone
Zone0
Zone1
Zone2
Zone3
Zone4
Zone5
B
Panel VI
Panel V
Panel IV
Panel I
Panel II
Panel III
Reference
Yield (tonnes/ha)
Years (1980-2015)
C
Zone0 +0.09/year R^2 = 0.91 p < 0.001***
Zone1 +0.08/year R^2 = 0.95 p < 0.001***
Zone2 +0.07/year R^2 = 0.93 p < 0.001***
Zone3 +0.05/year R^2 = 0.76 p < 0.001*** +0.22/year R^2 = 0.94 p < 0.001***
Zone4 +0.09/year R^2 = 0.90 p < 0.001*** +0.23/year R^2 = 0.92 p < 0.001***
Zone5 +0.06/year R^2 = 0.71 p < 0.001*** +0.16/year R^2 = 0.93 p < 0.001***
Year
D
2016
2017
2018
2019
2020
2021
Quadratic Fit R^2 = 0.98 p = 0.002**
E
Zone0
Z0-a
Z0-b
Z0-c
Z0-d
Z0-e
F
Yield (tonnes/ha)
G
Yield Changes
95% CI
Air Temp.
Dew Temp.
Precip.
Thermal Rad.
H
Concept Map
Yield
Temperature
I
GDD
Growing days
Trends in GDD
Historical (1995–2014)
SSP1–2.6 (2081–2100)
SSP5–8.5 (2081–2100)
Hypothetical migration route of varieties
1→3
2→4
2→0