

warm-dry years producing the largest reductions and yield loss increasing with temperature and VPD but decreasing with precipitation (Li et al., 2021).

Beyond extremes, the balance between atmospheric evaporative demand and soil moisture is critical. Including interactions between VPD and root-zone soil moisture greatly improves statistical prediction of maize yield anomalies, and estimates that ignore soil moisture can overstate climate-induced yield damage by about a factor of two. Similar work in China shows that maize benefits only when atmospheric moisture demand and soil moisture remain in relative balance; accounting for soil moisture halves projected yield losses compared with using atmospheric demand alone (Zhao et al., 2023).

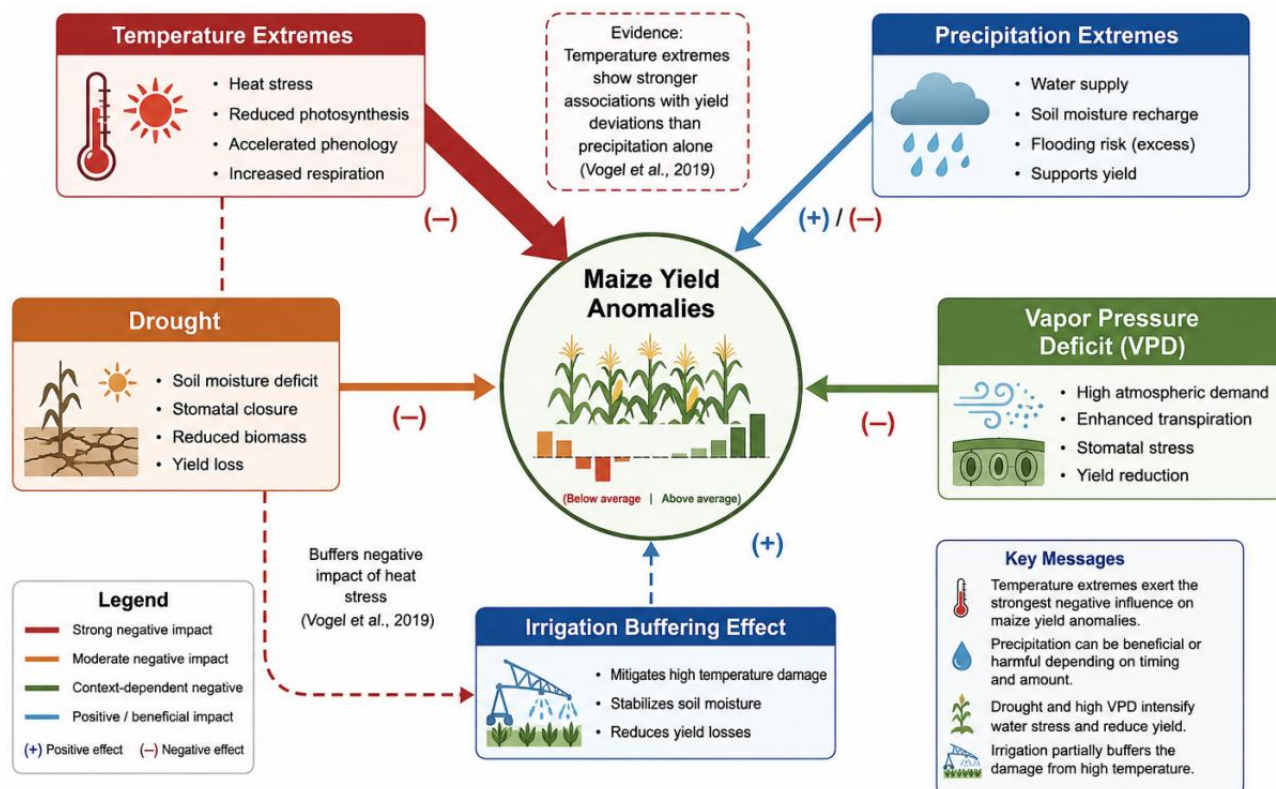


Figure 1 Climate extreme drivers of maize yield anomalies at regional to global scales

### 2.3 Synergistic mechanism of soil and climate factors

Soil fertility and climate interact to determine both average yield and its stability over time. Long-term experiments show that balanced NPK fertilization not only raises mean maize yield but also improves the stability of relative yield anomalies, while models that combine climate variables with nutrient status explain far more variation in yield anomalies than climate alone (Zhu et al., 2024). In diverse maize systems, soil moisture and temperature jointly drive yield damage, and predictions that include both components outperform those relying only on temperature and precipitation, underscoring the tight soil-climate coupling.

Nitrogen supply particularly modulates maize sensitivity to climate change. In low-input systems, higher N fertilization increases the crop's responsiveness to elevated CO<sub>2</sub>, higher temperatures, and altered rainfall, making intensively managed maize more sensitive-and thus more climatically risky-than low-input maize (Falconnier et al., 2020). At larger scales, management intensification (including improved nutrients and technologies) accounts for most historical yield gains, but its benefits are increasingly constrained by warming and drought, meaning that future intensification must explicitly incorporate climate adaptation to sustain yield trends (Medina and Tian, 2023).

Maize yield depends on sufficient N, P, and K to build a productive canopy and reproductive sink, while climate factors-especially temperature extremes, drought, VPD, and soil moisture-govern year-to-year variability. Nutrient