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Agronomic Strategies for Climate Extremes: Breeding Resilient Ideotypes and Crop Diversification

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Heat waves, droughts and erratic rainfall are now routine threats to food production. This article reviews two complementary agronomic responses: breeding crop *ideotypes* designed for stress, and diversifying cropping systems so that no single failure becomes a catastrophe. Drawing on global syntheses published in *Nature*, *PNAS*, *Nature Climate Change* and *Global Change Biology*, it shows that genetic and systems-level adaptation address different parts of the risk: breeding raises the performance floor of individual crops, while diversification stabilises the whole system. The strongest strategy combines both.

Introduction

Wheat, rice, maize and soybean supply roughly two-thirds of human caloric intake (Zhao et al., 2017), so even modest climate-driven losses in these crops ripple through global food security. Climate change is not only raising mean temperatures; it is increasing the frequency and severity of extremes that strike during short, sensitive growth stages such as flowering and grain filling. Agronomy has two broad levers in response. The first is genetic: redesigning the plant so that it tolerates or escapes stress. The second is systemic: redesigning the field, farm and landscape so that stress on one crop does not translate into loss of the whole harvest. This article examines both, quantifies what is known, and outlines how they can be combined.

The Scale of the Problem

The evidence that extremes cost real production is now global and quantitative. Lesk et al. (2016) analysed national production data for 16 cereals across 177 countries over 1964-2007 and found that droughts and extreme heat significantly reduced national cereal production by 9-10%, while no global effect could be detected for floods or extreme cold. Droughts reduced both harvested area and yield, whereas extreme heat acted mainly on yield. Notably, the damage was larger in industrialised systems: in North America, Europe and Australasia, droughts cut production by about 19.9% on average, roughly double the global mean (McGill University, 2016). Lesk and colleagues attributed this partly to uniform, yield-maximising farming over large areas, whereas smallholders often use risk-minimising practices. Temperature trends add a chronic burden on top of acute shocks. Zhao *et al*. (2017) combined four independent methods (grid-based and point-based crop models, statistical regressions and field-warming experiments) and estimated that, without CO_2 fertilisation, adaptation or genetic improvement, each 1 °C rise in global mean temperature would reduce global yields of wheat by 6.0%, rice by 3.2%, maize by 7.4% and soybean by 3.1%. For maize, the multi-method estimate was -7.4 ± 4.5% per °C, a reminder that uncertainty is large and regionally variable.

Table 1. Quantified climate impacts on major cereals and legumes

Indicator	Estimate	Scope	Source
Cereal production loss from drought or extreme heat	9-10%	177 countries, 1964-2007	Lesk *et al.* (2016)
Drought loss in N. America, Europe, Australasia	≈19.9%	Same dataset, regional subset	Lesk *et al.* (2016)
Yield change per +1 °C: wheat	-6.0%	Global, four methods	Zhao *et al.* (2017)
Yield change per +1 °C: rice	-3.2%	Global, four methods	Zhao *et al.* (2017)
Yield change per +1 °C: maize	-7.4%	Global, four methods	Zhao *et al.* (2017)
Yield change per +1 °C: soybean	-3.1%	Global, four methods	Zhao *et al.* (2017)

The scale of avoidable loss is also informative. Challinor *et al.* (2014) analysed more than 1,700 published simulations and found that, without adaptation, aggregate production of wheat, rice and maize is expected to decline in temperate and tropical regions by about 2 °C of local warming. Crop-level adaptations raised simulated yields by an average of 7-15%, being more effective for wheat and rice than maize. They also noted that increases in yield *variability* are likely. This is the central point for the rest of this article: adaptation helps on average, but extremes are about variance, and variance needs a systems answer as well as a genetic one.

Breeding Resilient Ideotypes

The ideotype concept

The term ideotype was introduced by Donald (1968), who argued that breeders should design a plant model with a defined combination of traits expected to perform well in a target environment, rather than relying only on selecting for yield after the fact. Applied to climate extremes, the question becomes which morphological and physiological traits let a crop either escape, avoid or tolerate stress, and how to select for them efficiently.

Traits that matter under heat and drought

Wheat offers the best-documented example. Langridge and Reynolds (2021) review the strategies used to improve heat and drought tolerance in wheat, including genetic analysis, targeting specific physiological traits, and direct selection under stress, supported by advances in phenotyping and genomic resources. Their central message is that breeding must deliver stable yield across good and bad seasons while preserving high yield under optimal conditions. Cossani and Reynolds (2012) argue that physiological traits associated with heat adaptation are the best available 'handle' for genetic improvement because they represent favourable combinations of alleles, and that the strategy is to combine traits linked to the main drivers of yield. Canopy temperature, a cheap measurement that integrates many physiological responses, is one of the best-studied selection tools: cooler canopies under stress generally indicate better access to water and better heat dissipation.

Table 2. Components of a climate-resilient ideotype (synthesis)

Stress strategy	Target trait	Why it helps	Basis
Escape	Phenology matched to the season (flowering before peak heat or terminal drought)	Avoids the most damaging window	Donald (1968) concept; Langridge & Reynolds (2021)
Avoidance	Cooler canopy, deeper and more efficient roots, rapid ground cover	Maintains water uptake and limits evaporative loss	Cossani & Reynolds (2012)
Tolerance	Stay-green, stored stem carbohydrates, heat-stable reproductive development	Sustains grain filling when current photosynthesis falls	Cossani & Reynolds (2012)
Stability	Selection across contrasting environments and seasons	Reduces genotype-by-environment penalties	Langridge & Reynolds (2021)

Tools that speed up ideotype breeding

High-throughput phenotyping (canopy temperature, spectral indices, ground cover from drones), marker-assisted and genomic selection, and multi-environment trials allow breeders to test physiological hypotheses at scale. Physiological breeding, which crosses parents carrying complementary traits, has been applied at CIMMYT for drought and heat adaptation (Cossani & Reynolds, 2012). The practical lesson is that ideotypes should be region-specific. A trait that is advantageous under terminal drought in a rainfed system may impose a penalty under irrigated or waterlogged conditions.

Limits of breeding alone

Breeding cycles are long, and traits can trade off. Heat tolerance, drought tolerance and yield potential do not always combine easily, and a variety bred for one extreme can be vulnerable to another. Breeding also leaves the production system exposed to a common vulnerability: if a region grows one dominant variety and the season goes wrong, everything fails together. Lesk et al. (2016) raised this uniformity problem for industrialized cereal systems.

Crop Diversification

Evidence for stability at national scale

Renard and Tilman (2019) used five decades (1961-2010) of FAO data on annual yields of 176 crop species in 91 nations. They found that greater effective crop diversity at the national level was associated with greater year-to-year stability of total harvest, with stabilizing effects similar in magnitude to the destabilizing effect of precipitation variability. The mechanism is statistical but intuitive: when one crop is hurt by heat, another may be less affected and compensate, so total harvest swings less. A small gain in stability sharply reduces the probability of years with major crop losses. Follow-up work showed the effect depends on effective diversity, meaning the number of crops sharing area roughly equally, rather than a simple count of species.

Evidence for production and ecosystem services at field scale

Beillouin *et al.* (2021) synthesised 95 meta-analyses covering 5,156 experiments, more than 54,500 paired observations, 120 crop species and 85 countries. Diversification increased crop production by a median of 14% and also improved associated biodiversity and ecosystem services. Importantly, results varied substantially between strategies, with agroforestry, intercropping, cover crops, crop rotation and variety mixtures each performing differently.

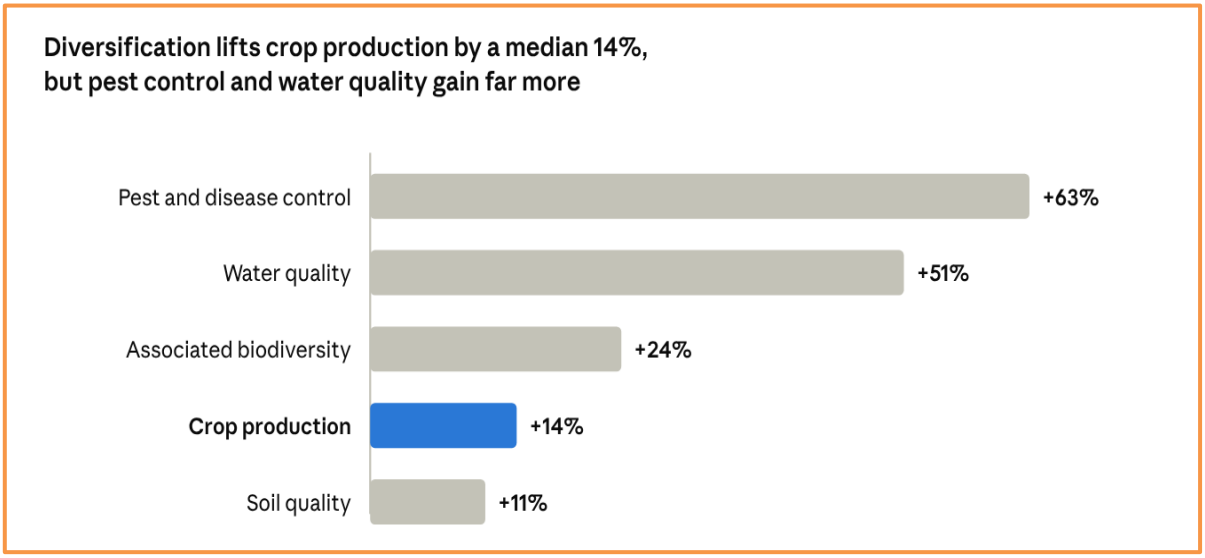


Fig 1. Median effects of crop diversification relative to simplified systems

Practical diversification options

The following are the main practices compared in the syntheses above. Their suitability depends on climate, soils, labour and markets.

Table 3. Diversification practices and their role under climate extremes

Practice	Main resilience mechanism	Typical constraint
Crop rotation (e.g. cereal–legume)	Breaks pest cycles, improves soil structure and nitrogen supply	Needs market for rotation crops
Intercropping	Spreads risk across species; better resource use	Machinery and management complexity
Cover crops	Protects soil, conserves moisture	Water use and seeding cost
Variety mixtures	Buffers against disease and uneven stress	Requires compatible varieties
Agroforestry	Microclimate buffering, deeper resource capture	Slow returns, land tenure

Beillouin *et al.* (2021) highlighted agroforestry-based systems as particularly strong performers for several ecosystem services, although outcomes remain context dependent.

Limits of diversification

Diversification is not free. Additional crops can require new machinery, knowledge and markets, and not every combination raises yield; trade-offs occur. Diversification also does not directly raise the heat or drought threshold of any individual crop, which is where breeding contributes.

Integrating Breeding and Diversification

The two strategies address different components of risk. Breeding changes the *response* of each crop to stress, shifting the yield floor upward. Diversification changes the portfolio of responses, so that failure of one component is buffered by others. Renard and Tilman (2019) themselves frame diversity as complementary to drought-tolerant varieties, irrigation and trade rather than as a replacement.

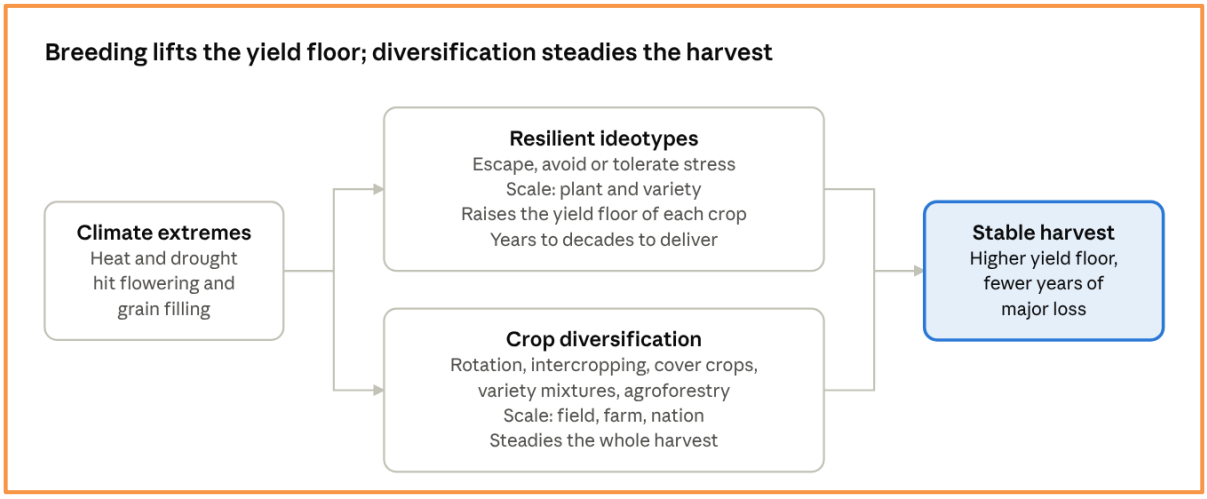


Fig 2. Conceptual framework: extremes act on plants and on whole systems, so each strategy covers a different part of the risk

Priorities for Research and Policy

First, the evidence base on variability remains thinner than on mean yields (Challinor *et al.*, 2014). Studies should report variance and extreme-year outcomes, not only averages. Second, ideotype programmes need multi-environment testing that includes realistic combinations of heat and drought, since these frequently coincide in the field. Third, policy must remove barriers to diversification, including markets, extension, seed systems and insurance schemes that currently reward monocultures. Fourth, farmers' knowledge and smallholder risk-minimising practices, noted by Lesk *et al.* (2016), deserve inclusion in design rather than being treated as a deficit.

Conclusion

Climate extremes expose two kinds of vulnerability: plants that fail under stress, and systems that fail together. Resilient ideotypes address the first through targeted, stress-adaptive traits; diversification addresses the second by spreading and offsetting risk. The quantitative evidence is consistent: unmitigated warming reduces major crop yields by several percent per degree (Zhao *et al*., 2017), extremes cut national cereal output by around a tenth (Lesk *et al*., 2016), adaptation can recover 7-15% in simulations (Challinor et al., 2014), and diversification raises both yield and stability (Beillouin *et al*., 2021; Renard & Tilman, 2019). The agronomic task is therefore not choosing between breeding and diversification but designing them together.

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