Introduction to Abiotic Stresses

Part 1

Effect on crop plants

Plant response

Breeding strategies

Drought

Salt

Heat

Flooding

Cold

Heavy metal

Dr. Shailendra Sharma
Genetics and Plant Breeding

All the non-living environmental factors that can negatively or even harmfully affect the growth and productivity of plants and hence reduced crop yields

- Drought/moisture
- Extreme temperature (heat, cold/chilling)
- Salinity/alkalinity/sodicity
- Flooding/waterlogging/submergence
- Soil factors
- Mineral toxicity
- Nutrient deficiency
- -------------

With increasing challenges posed by increasing population and extreme weather conditions change, it is predicted that drastic climate changes will become even more frequent and severe, further reducing crop yields, especially in the tropics and subtropics.

Drought

Drought stress can be simply defined as a shortage of water which induces morphological, biochemical, physiological, and molecular changes.

It is one of the consequences of climate change that has a negative impact on crop growth and yield.

All of these changes reduce plant growth and crop production among the most important cereal crops.

Drought stress can occur at any growth stage and depends on the local environment.

Heat Stress

Heat stress causes a series of changes that adversely affect plant development.

At high temperatures, enzyme functions can be disrupted with irreversible denaturation of proteins (Howarth 2005).

If temperature rises to extreme levels, severe cellular injuries may occur followed by immediate cell death within a few minutes (Howarth 2005 ;Schoffl et al. 1998).

Slower heat injuries include loss of membrane integrity, inhibition of protein synthesis, enzyme inactivation in chloroplasts and mitochondria, and protein degradation (Howarth 2005).

Heat stress also affects cell cycle & cell division through changing the microtubules organization (Smertenko et al. 1997).

These injuries together cause starvation, growth inhibition, decreased ion flux, accumulation of toxic compounds & ROS (Howarth 2005 ;Schoffl et al. 1998).

High temperature leads to modification of membrane properties, and liquid viscosity inside plant cell organelles (Źróbek-Sokolnik2012).

The increased fluidity of membrane lipids, and protein denaturation and aggregation are immediate injuries occurring after exposure to high temperature (Howarth 2005).

Salinity

Soil salinity is one of the most serious factors limiting productivity of agricultural crops.

In soil containing high amount of salts, plant uptake higher concentration of soluble salts that negatively affect the uptake of water through the root system due to higher osmotic pressure.

Limited water in plant cells influences its turgidity and ultimately changes the membrane stability (Sairam et al, 2002).

Salt stress is known to affect the seed germination, plant growth, water deficit, ion imbalance and cause several biochemical lesions in various plants.

Sodium chloride (NaCl) is the most predominant salt in saline soil which increases the concentration of Na^+ and Cl^- level in the soil, and affects the uptake of essential nutrients like Ca^{++}, Mg^{++} and K^+ by the plants and subsequently increases the uptake of Na^+ and Cl^- in susceptible plants(Khan et al, 1999).

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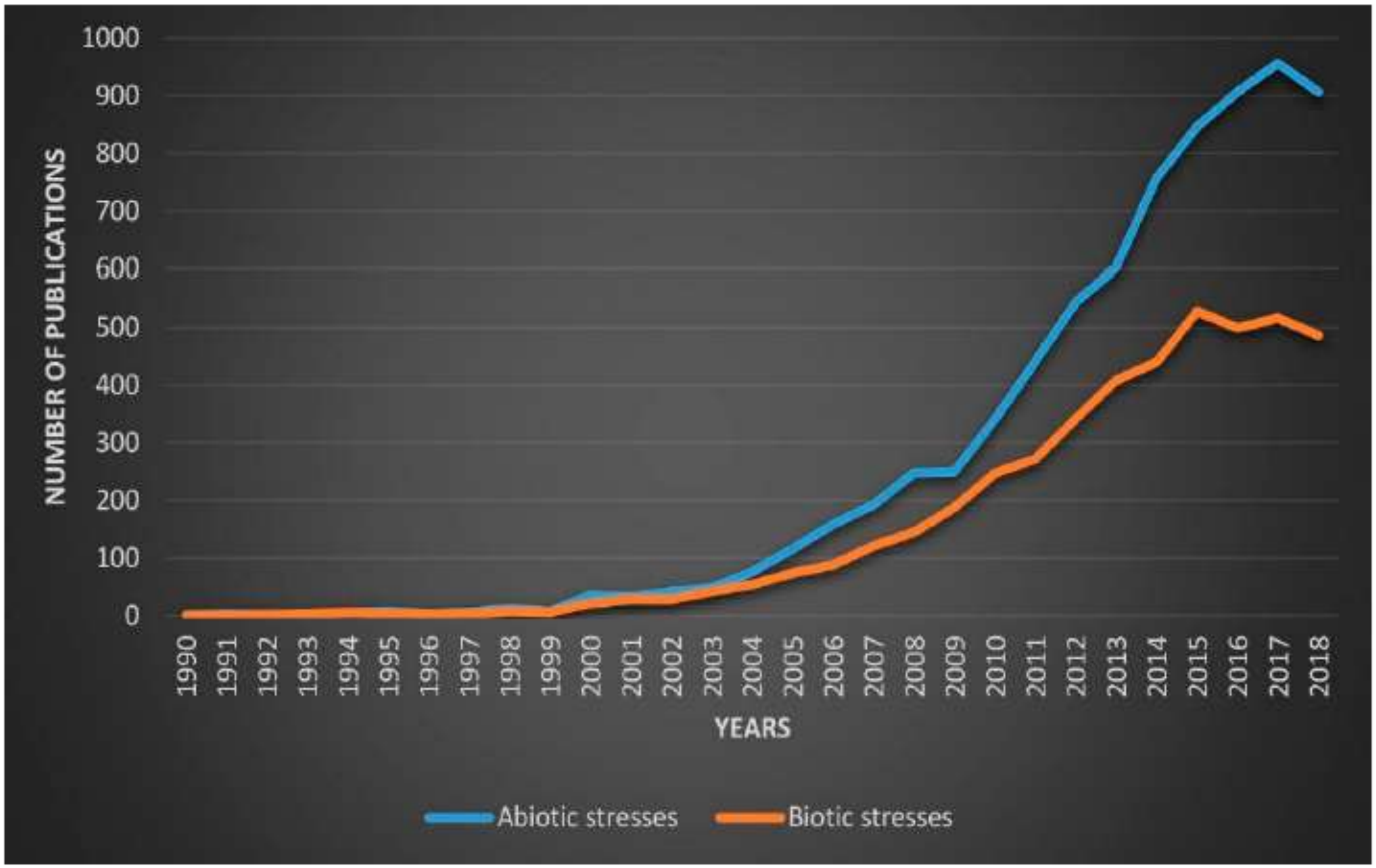

Figure 3. The number of publications per year related to abiotic and biotic stresses from Jan/1990–Nov/2018. Source: PubMed (Keywords (abiotic stresses, drought, cold, heat, salinity and water-logging), (biotic stresses, bacteria, virus, fungi, insects, parasites, and weeds) used to search the number of publications in PubMed).

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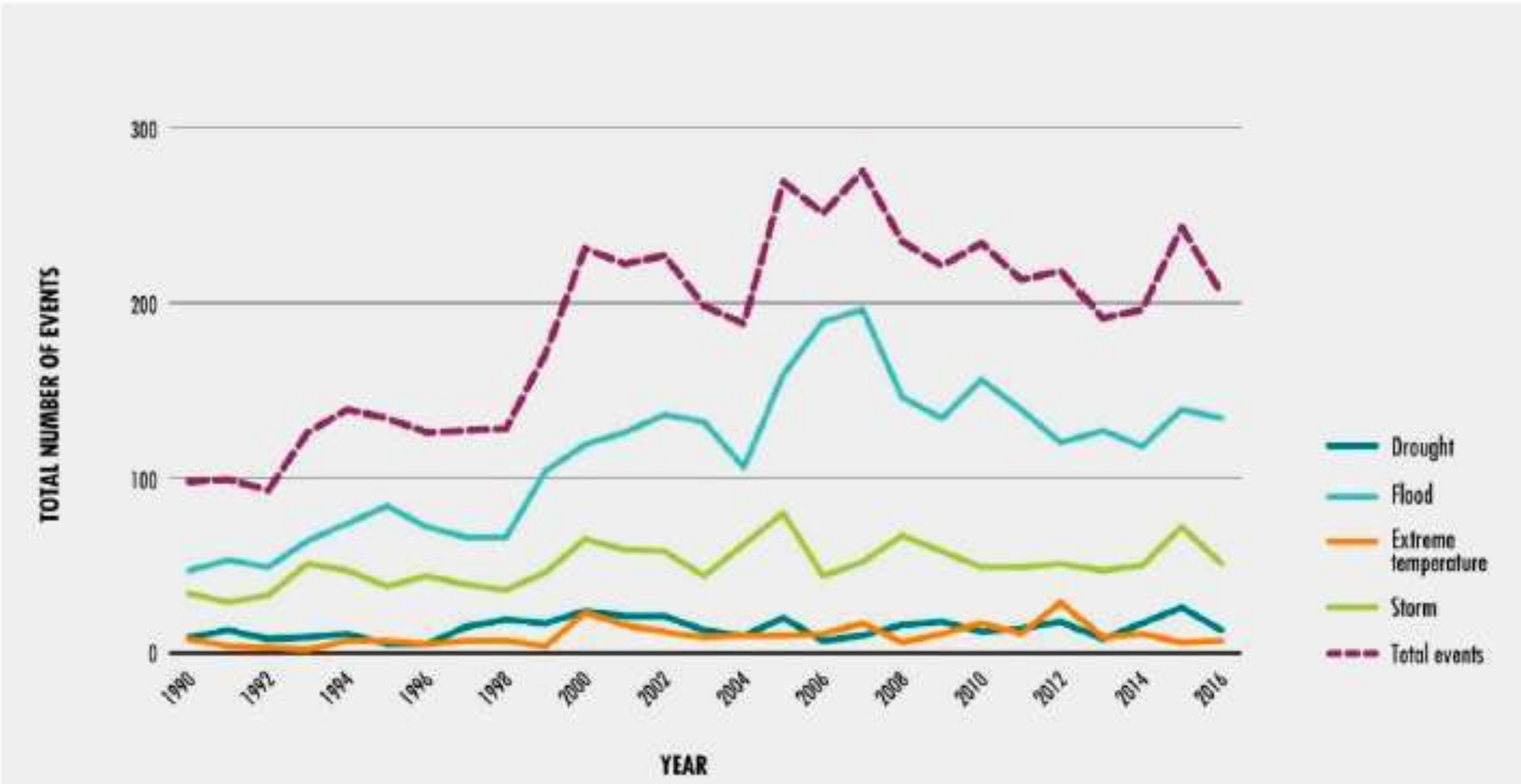

Figure 2. Increasing number of extreme climate-related events occurred during 1990–2016. Source: Food and Agriculture Organization (FAO) based on data from Emergency Events Database (EM-DAT) (https://www.emdat.be/) [24,25].

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Genetic strategies for improving crop yields

https://doi.org/10.1038/s41586-019-1679-0

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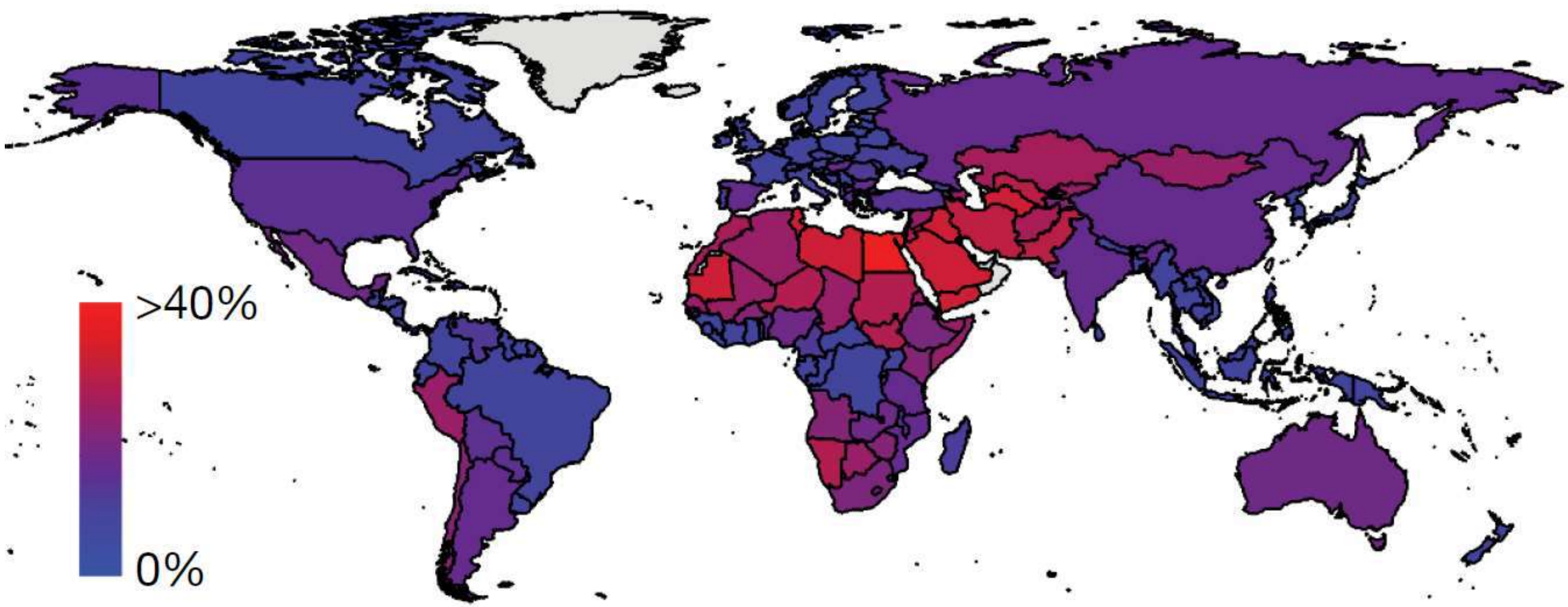
Aridity stress



Predicted national-scale yield loss for maize, rice, wheat and soybean averaged from 1950-2000

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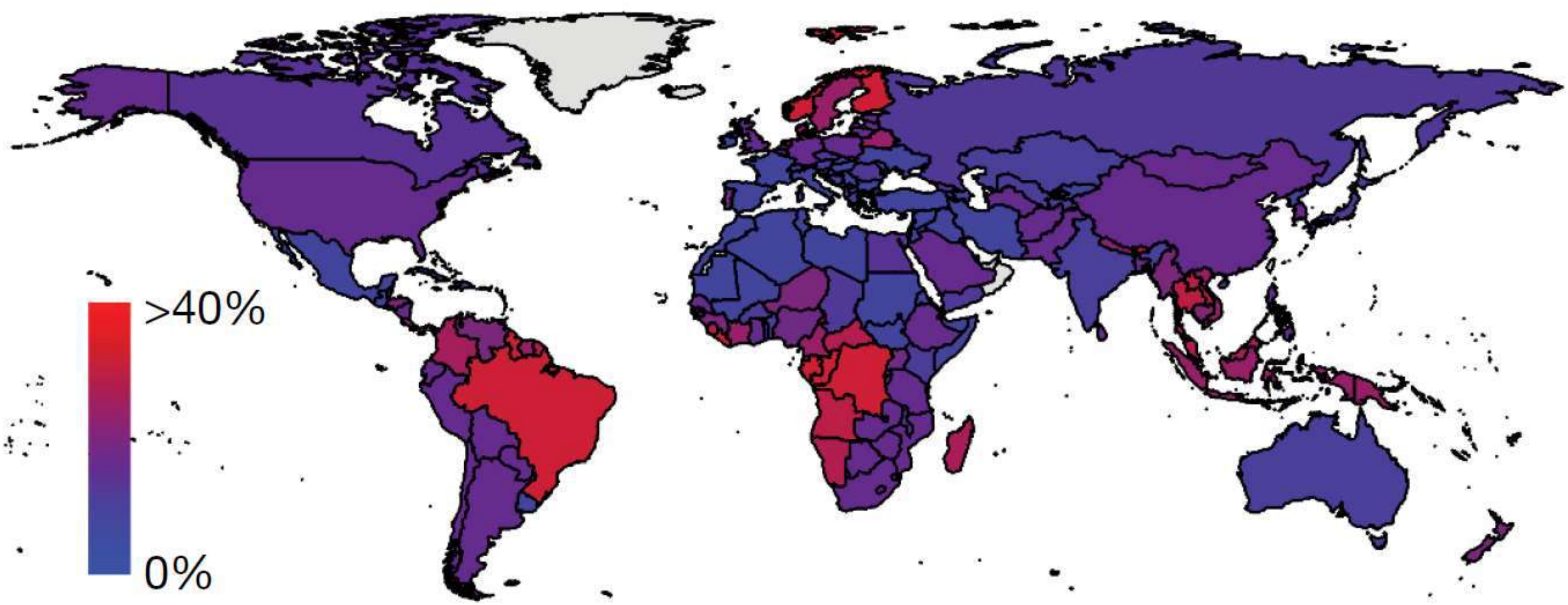
Heat stress



Predicted national-scale yield loss for maize, rice, wheat and soybean averaged from 1994-2010

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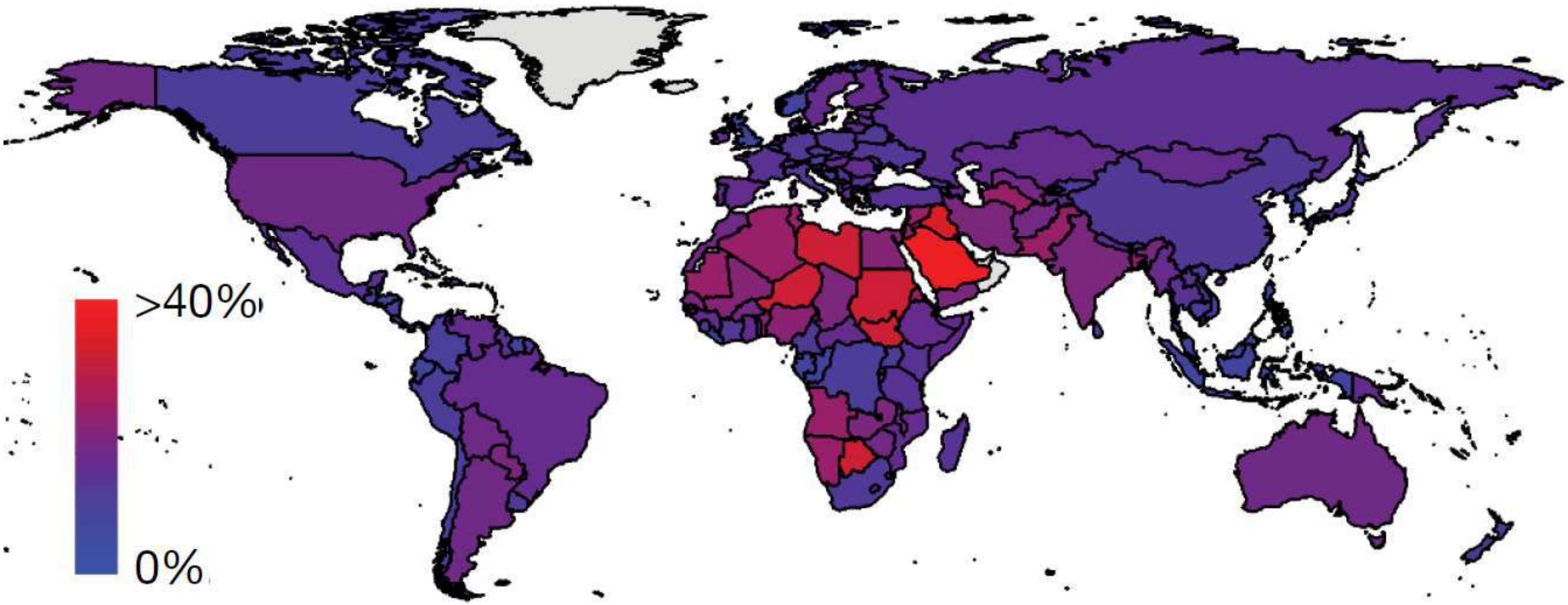
Nutrient stress



Predicted national-scale yield loss for maize, rice, wheat and soybean in 2009

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Genetic strategies for improving crop yields

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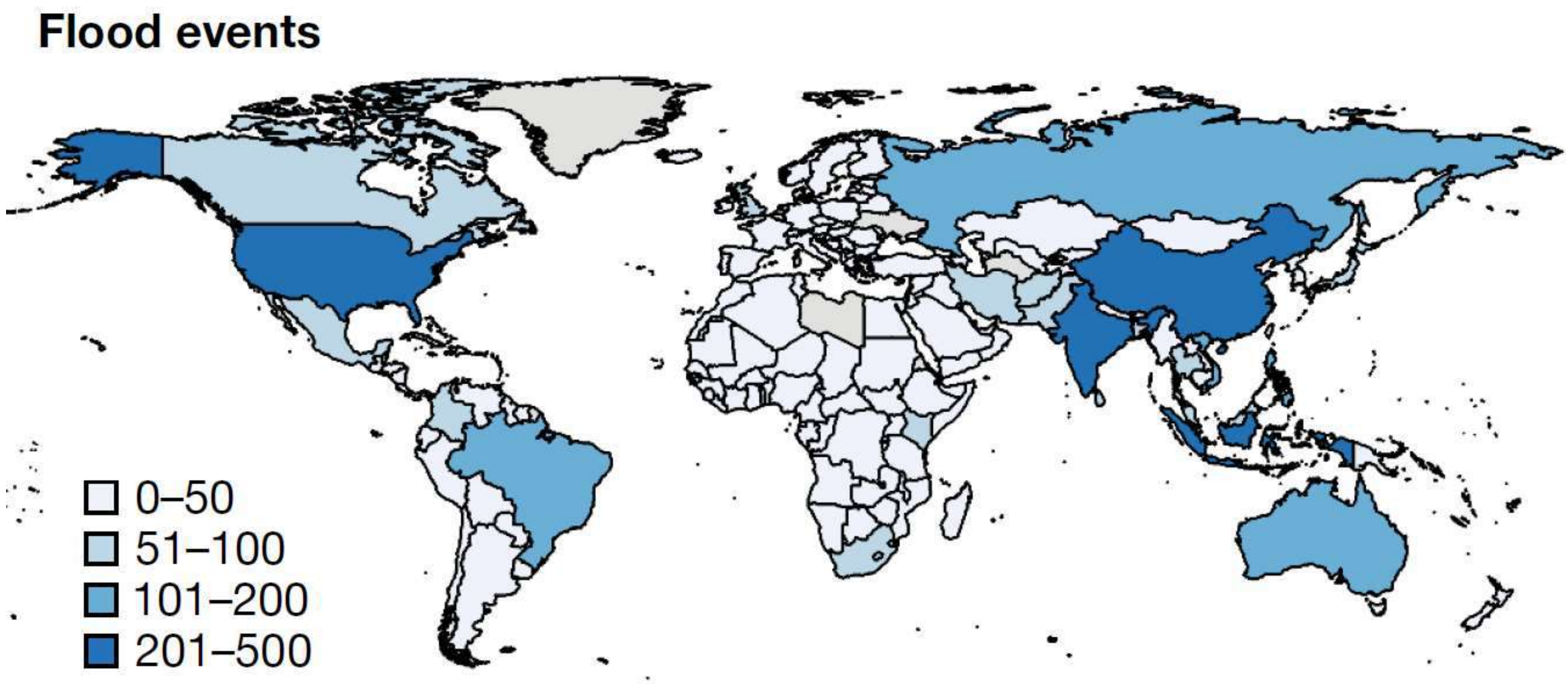


Number of large flood events from 1985 to 2010

Yield-defining traits and opportunities for crop improvements

This Review discusses several traits that are essential for crop performance, including the genetic variation and plasticity that are relevant for improvement (left) and advanced and emerging approaches for addressing trait improvements (right). Stress resilience coupled with high yields is aided by hardwired traits and temporal responses to a dynamic environment. Opportunities for improvement include capturing natural genetic variation, the functional characterization of genes, the manipulation of endogenous or transferred genes with appropriate regulatory control, the development of low-cost and safe small molecules that can be delivered to plants before stress or during recovery, and improved plant health through interactions with symbiotic microorganisms.

Yield-defining traits

Shoot traits and plasticity

Inflorescence architecture and fertility
Shoot-to-root biomass
Photosynthesis
Stomatal movement and density regulation
Assimilate loading and partitioning
Senescence timing

Root traits and plasticity

Architecture and anatomy
Growth dynamics
Nutrient acquisition and use efficiency
Microbial interactions

Stress resilience

Drought, salinity, flooding and extreme temperatures (abiotic)
Pests and pathogens (biotic)
Tempered response to minimize growth penalty

Opportunities

Natural genetic variation

Stress resilience and recovery mechanisms
Trait pyramiding

Gene engineering and editing

Spatial, temporal and inducible control of genes and networks
Improving protein function, targeting and turnover
Enhancing metabolite pathway and flux
Introducing synthetic traits

Beneficial soil and leaf microbiome

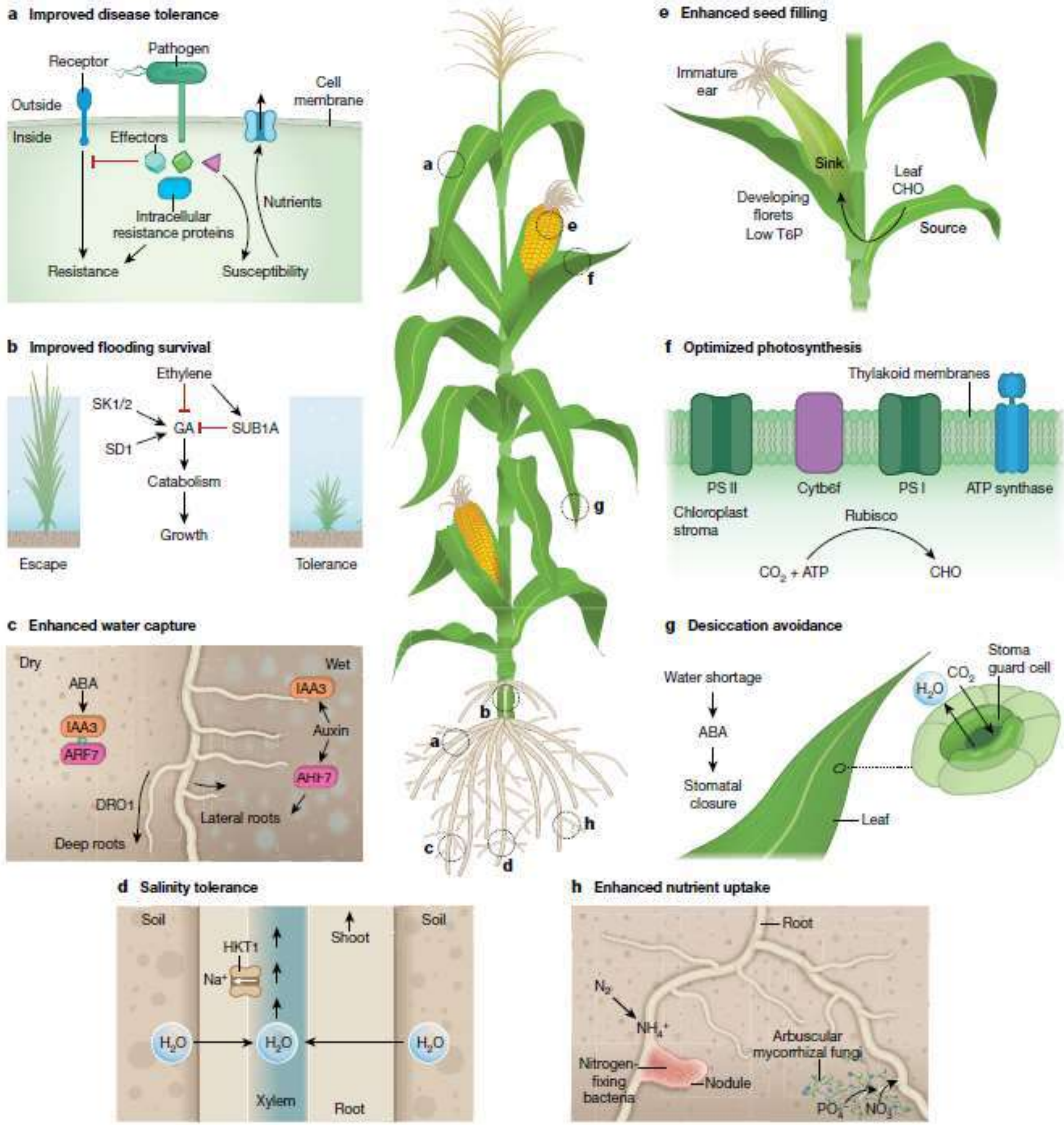
Seeding and supplementation
Attraction of beneficial microorganisms

Small-molecule delivery

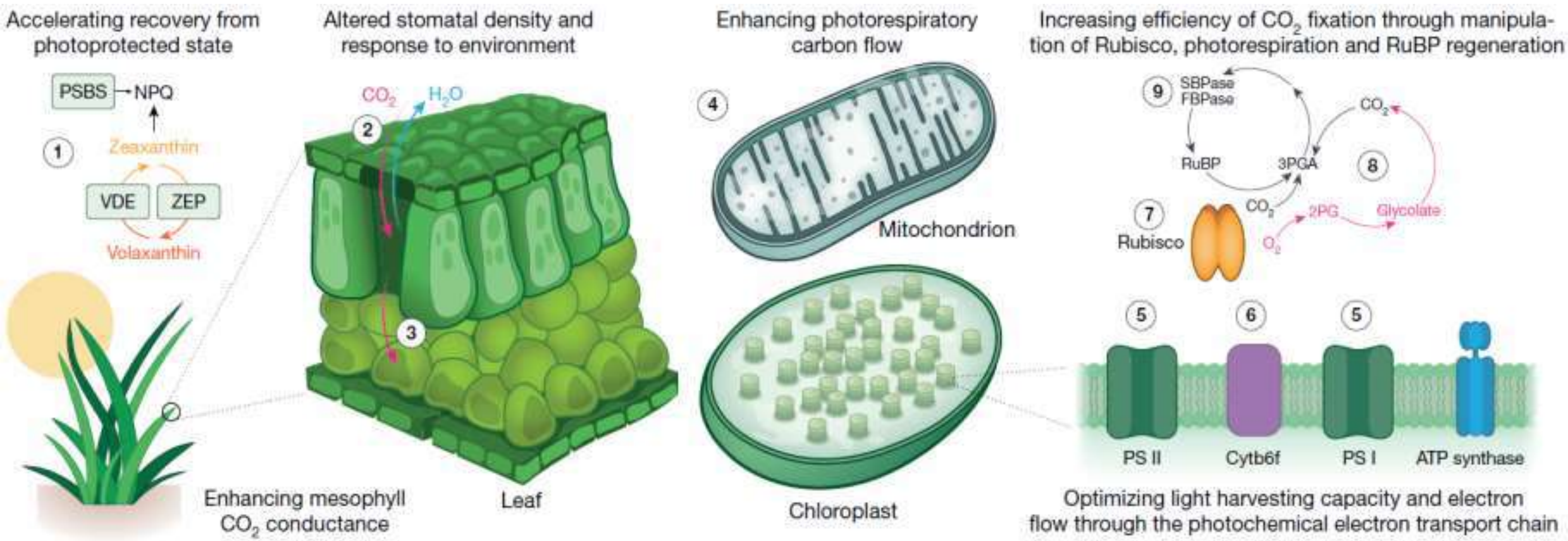
Response activation
Metabolic regulation

Sensor use for crop management

Cellular, organ, canopy and remote

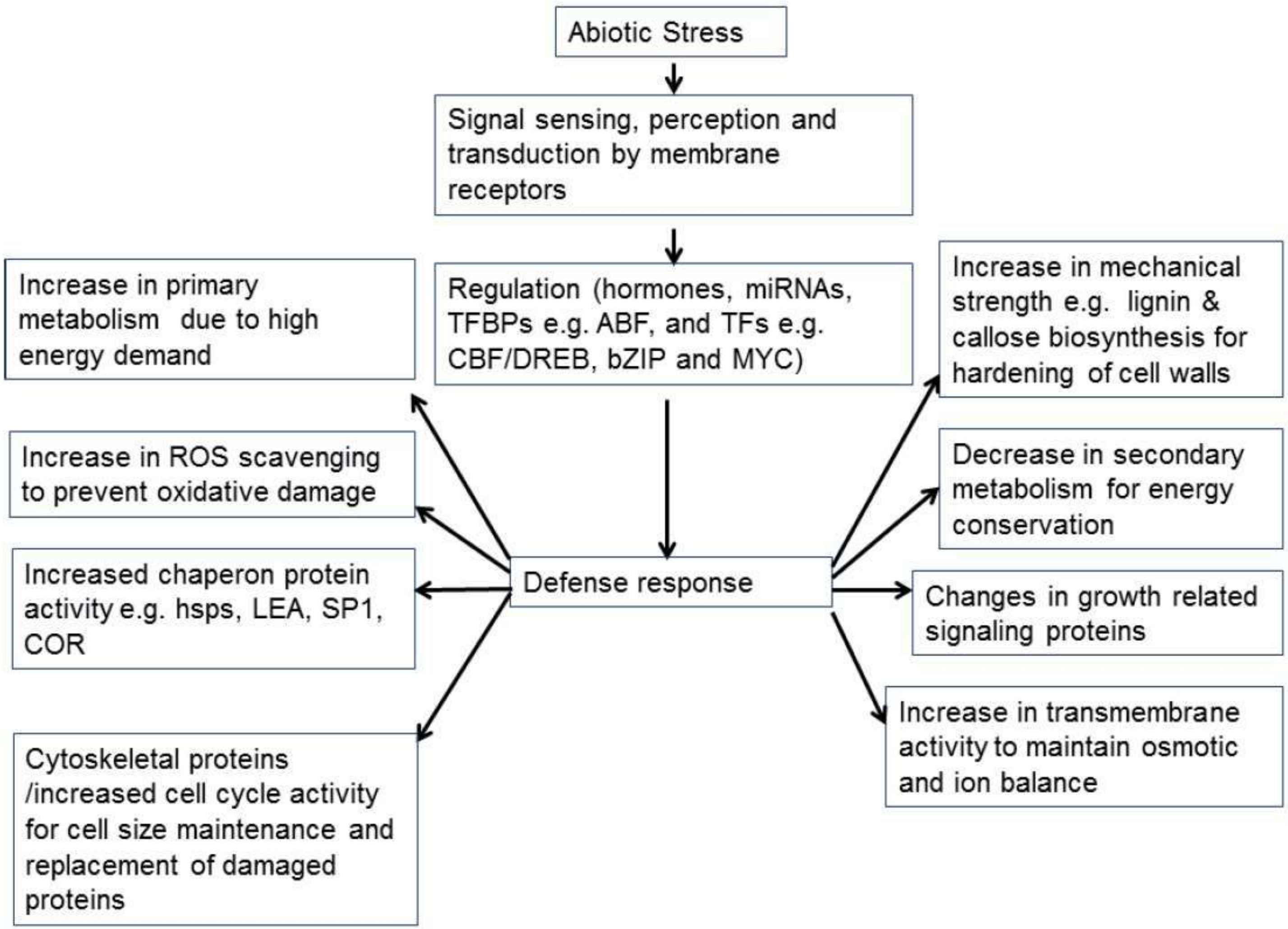


Paths to increased crop yield in suboptimal environments



Targets for improving the efficiency of photosynthesis and primary carbon metabolism that have experimental support for success. Transgenic manipulations of photosynthetic metabolism that lead to improved photosynthetic efficiency.

Abiotic stress response in plants



From: Chapter 9 by Geoffrey Onaga and Kerstin Wydra
Advances in Plant Tolerance to Abiotic Stresse (http://dx.doi.org/10.5772/64350)

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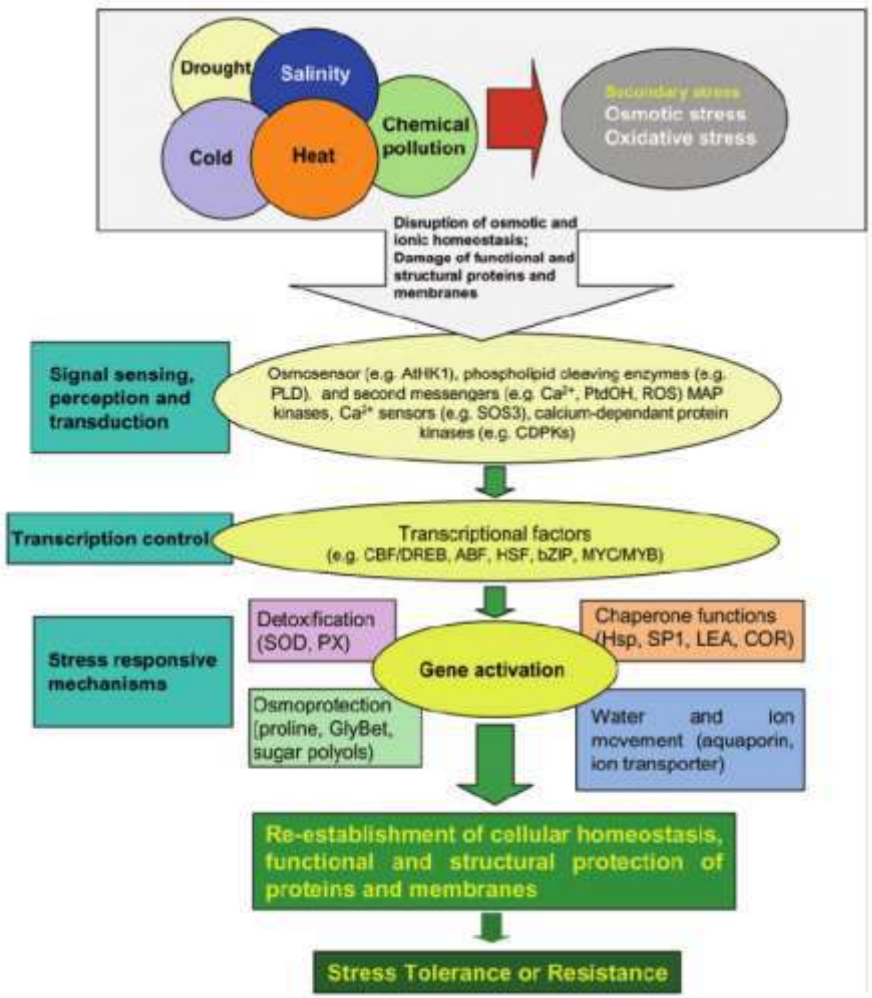
Stress	Consequences	Plant Responses
Heat stress	High temperature lead to high evaporation and water deficit. The consequent increased turnover of enzymes leads to plant death.	Efficient protein repair systems and general protein stability support survival, temperature can lead to acclimation.
Chilling and cold stress	Biochemical reactions proceed at slower rate, photosyntesis proceeds, carbon dioxide fixation lags, leading to oxigen radical damage. Indeed, freezing lead to ice crystal formation that can distrupt cells membranes.	Cessation of growth in adaptable species may be overcome by changes in metabolism. Ice crystal formation can be prevent by osmolyte accumulation and synthesis of hydrophilic proteins.
Drought	Inability to water transport to leaves leads to photosyntesis declines.	Leaf rolling and other morphological adaptations. Stoma closure reduces evaporative transpiration induced by ABA. Accumulation of metabolities, consequently lower internal water potential and water attracting.
Flooding and submergence	Generates anoxic or microaerobic conditions interfering with mitochondrial respiration.	Development of cavities mostly in the roots that facilitate the exchange of oxigen and ethylene between shoot and root (aerenchyma).
Heavy metal accumulation and metal stress	In excess, detoxification reactions may be insufficient or storage capacity may exceeded.	Excess of metal ions may be countered by export or vacuolar deposition but metal ions may also generate oxygen radicals.
High light stress	Excess light can lead to increased production of highly reactive intermediates and by-products that can potentially cause photo-oxidative damage and inhibit photosynthesis.	Exposure of a plant to light exceeding what is utilized in photochemistry leads to inactivation of photosynthetic functions and the production of reactive oxygen species (ROS). The effects of these ROS can be the oxidation of lipids, proteins, and enzymes necessary for the proper functioning of the chloroplast and the cell as a whole.

Table 1. Consequences of abiotic stress and plant responses

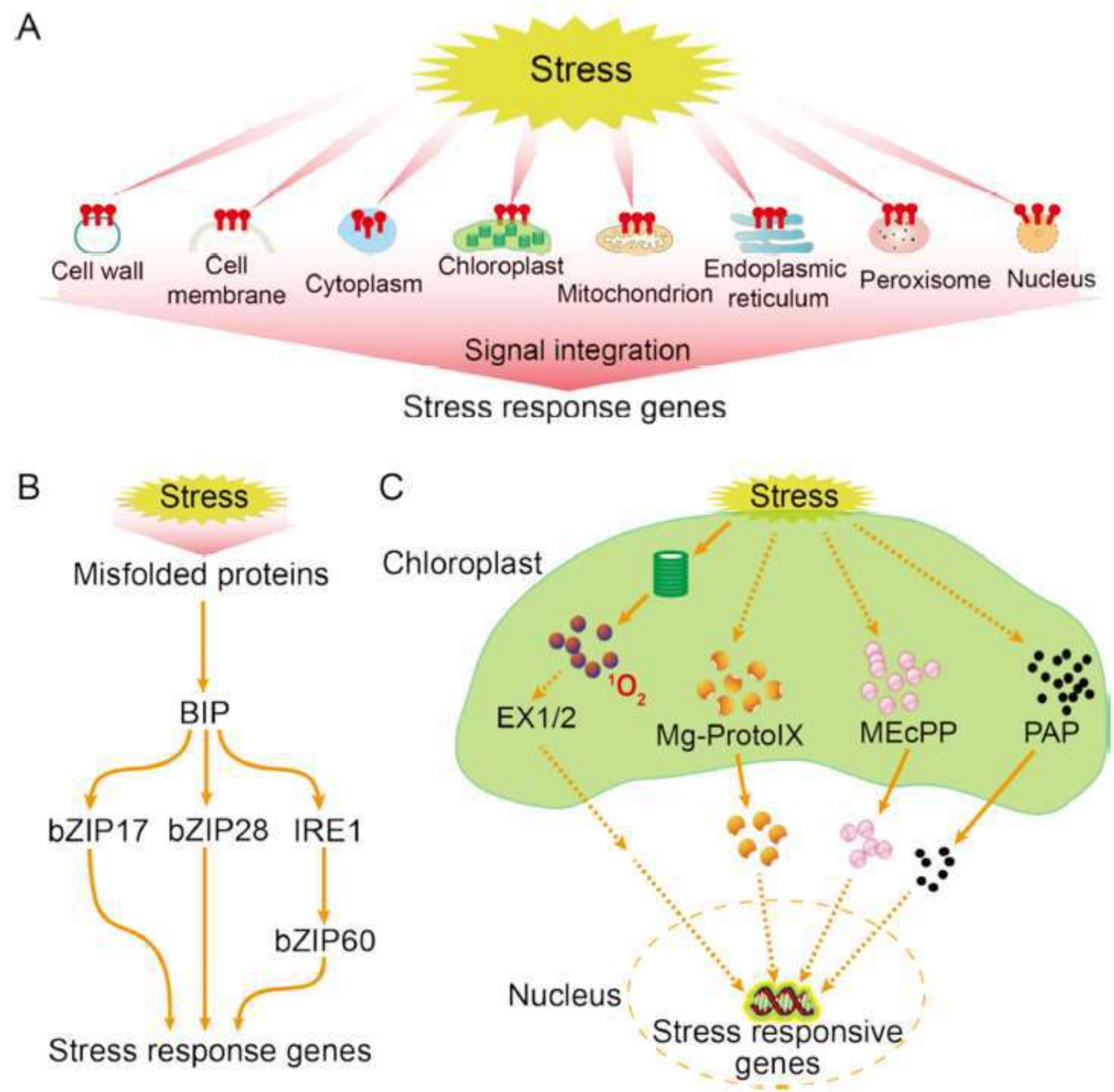
Loredana F. Ciarmiello, Pasqualina Woodrow, Amodio Fuggi, Giovanni Pontecorvo and Petronia Carillo (2011). Plant Genes for Abiotic Stress, Abiotic Stress in Plants - Mechanisms and Adaptations, Prof. Arun Shanker (Ed.), ISBN: 978-953-307-394-1, InTech, Available from: http://www.intechopen.com/books/abioticstress-in-plants-mechanisms-and-adaptations/plant-genes-for-abiotic-stress

The complexity of the plant response to abiotic stress

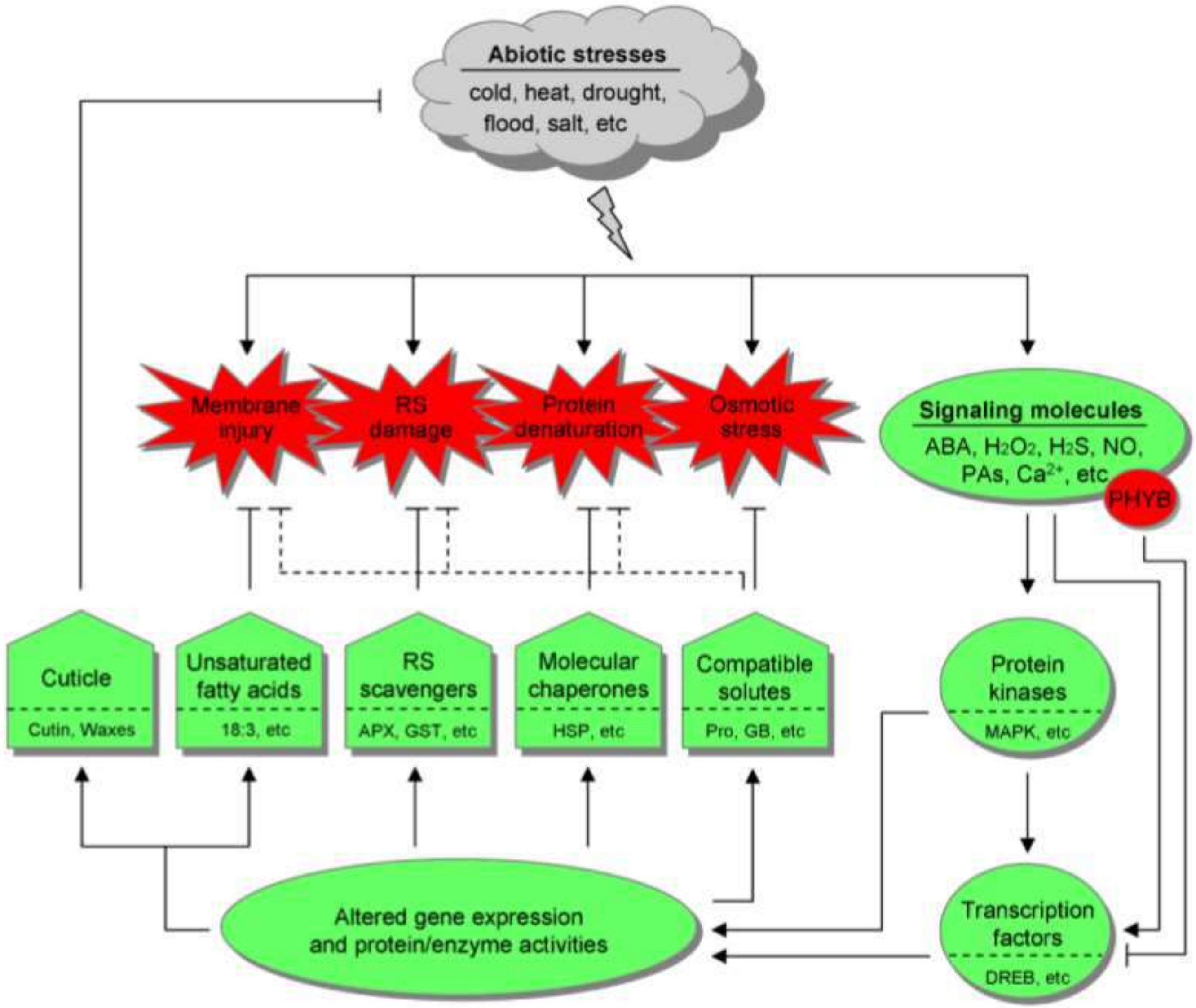


Wang et al. (2003) Planta 218: 1–14 (DOI 10.1007/s00425-003-1105-5)

Stress sensing and signaling in different cell organelles

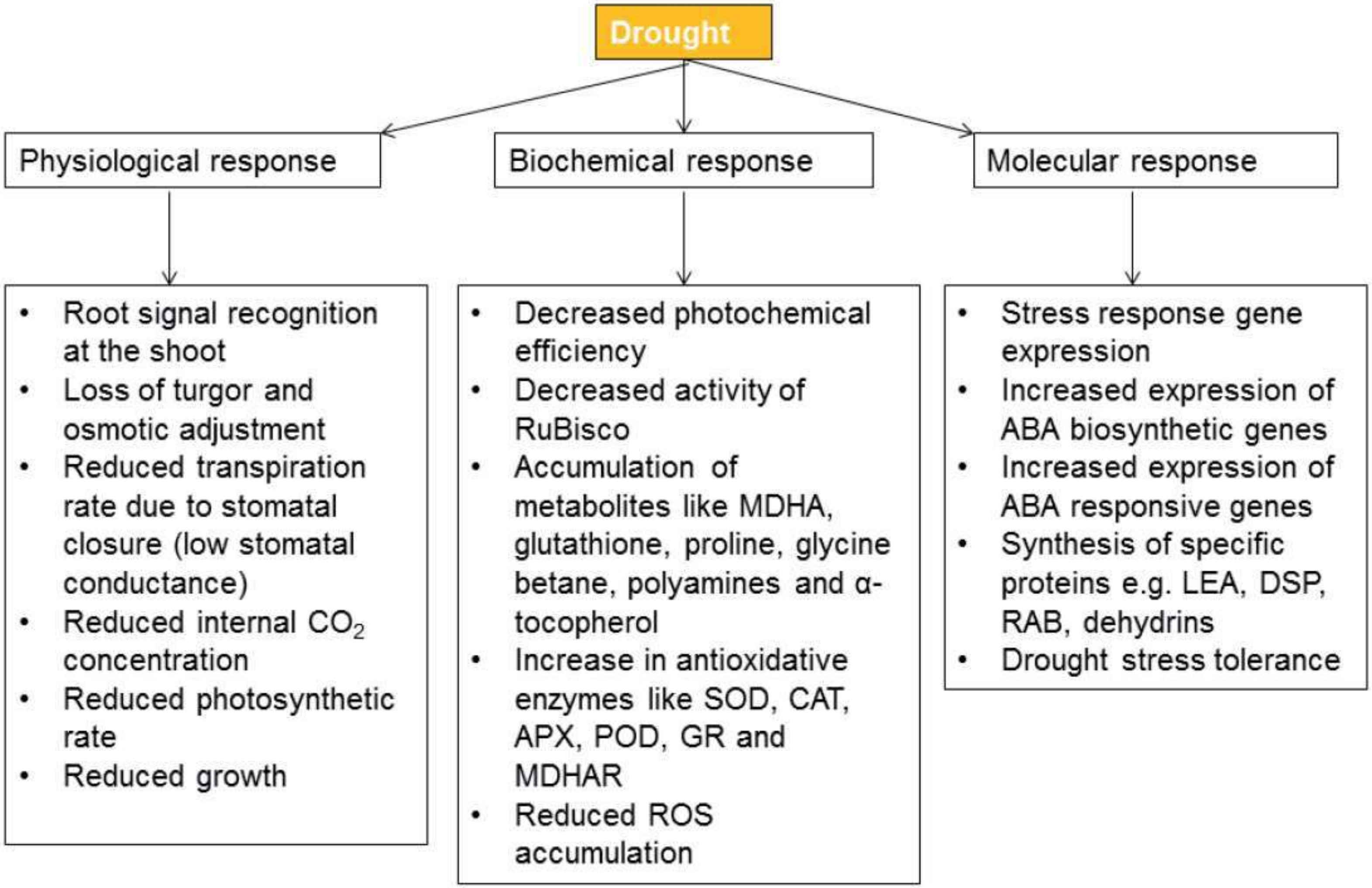


The general defense systems and the underlying regulatory network in botanic responses to abiotic stresses



(For details consult: He et al. (2018) Frontiers in Plant Science Article Volume 9 Article: 1771)

Physiological, biochemical, and molecular basis of drought stress tolerance in plants



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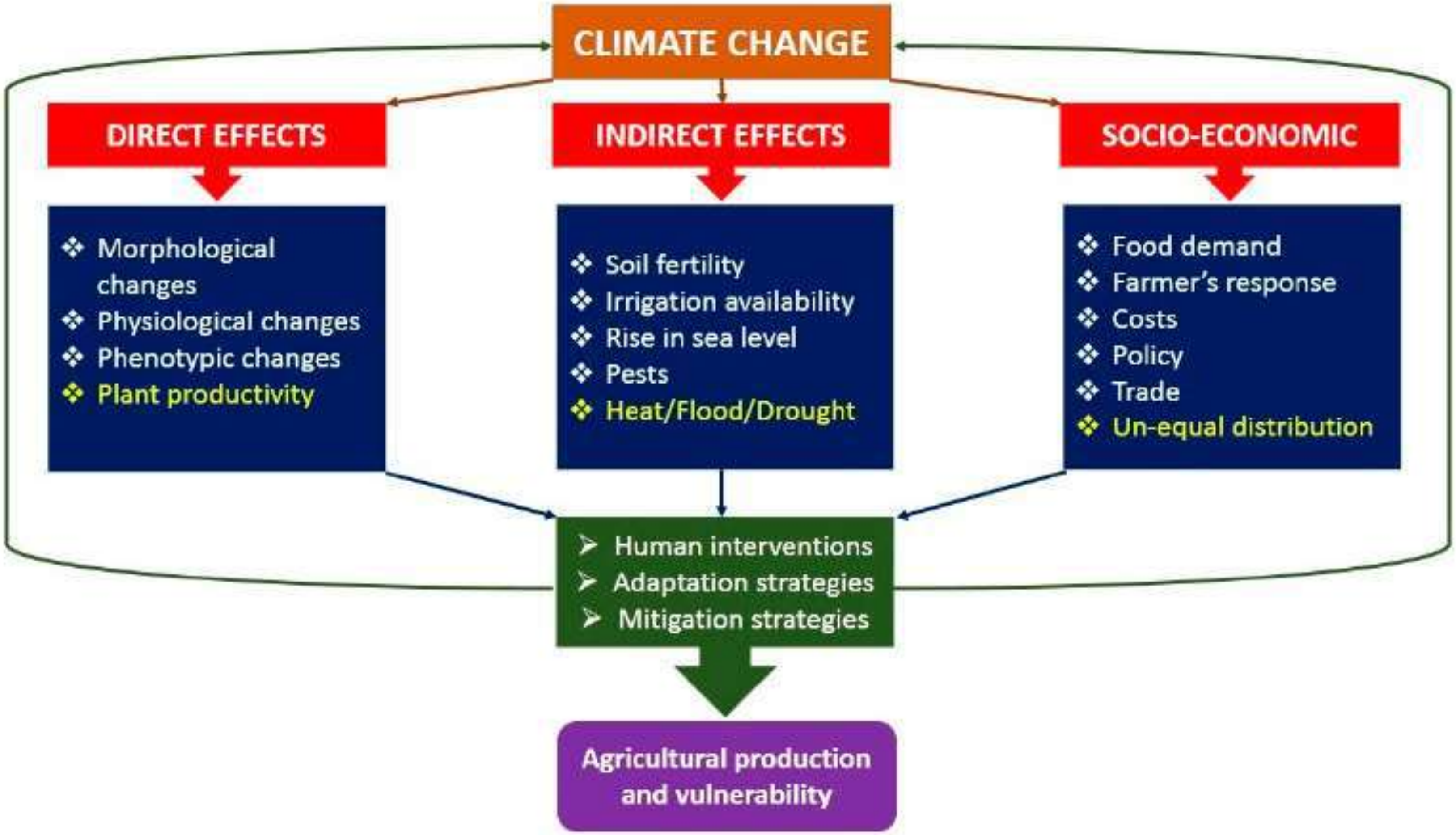

Figure 1. Direct, indirect and socio-economic effects of climate change on agricultural production.

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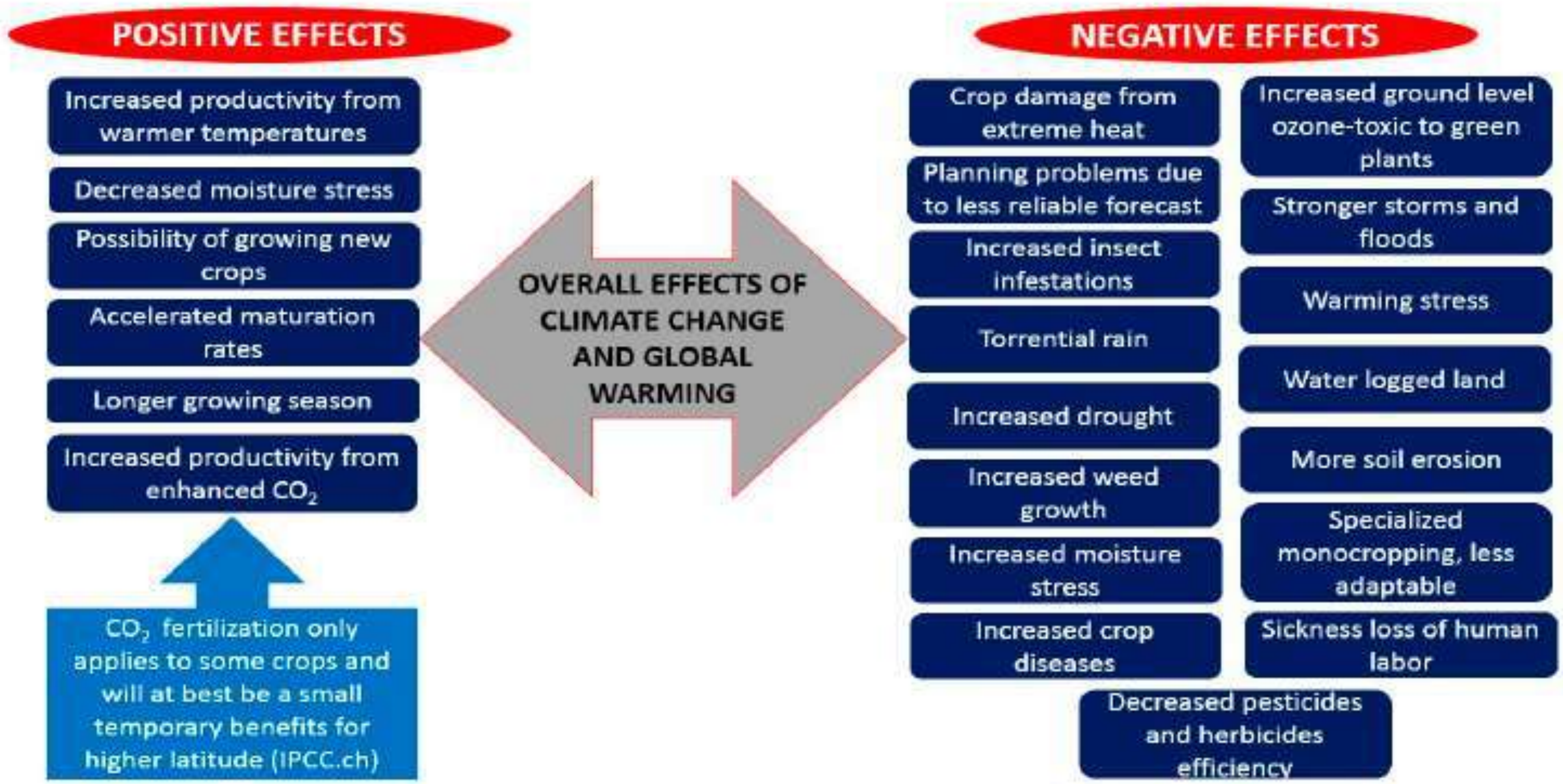

Figure 4. Overall positive and negative effects of climate change and global warming on crops and humans.

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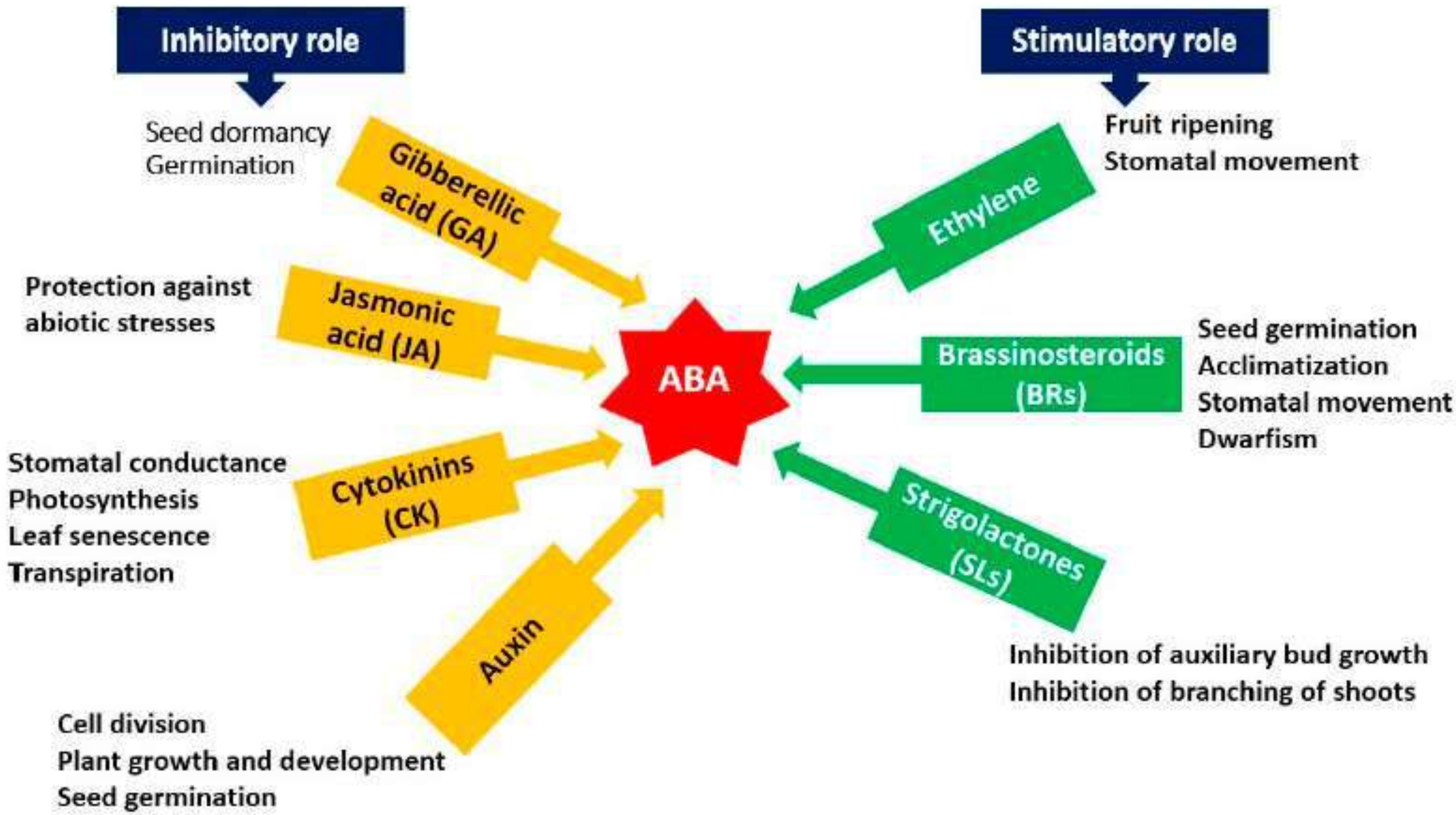

Figure 5. Hormonal crosstalk related to different stresses.

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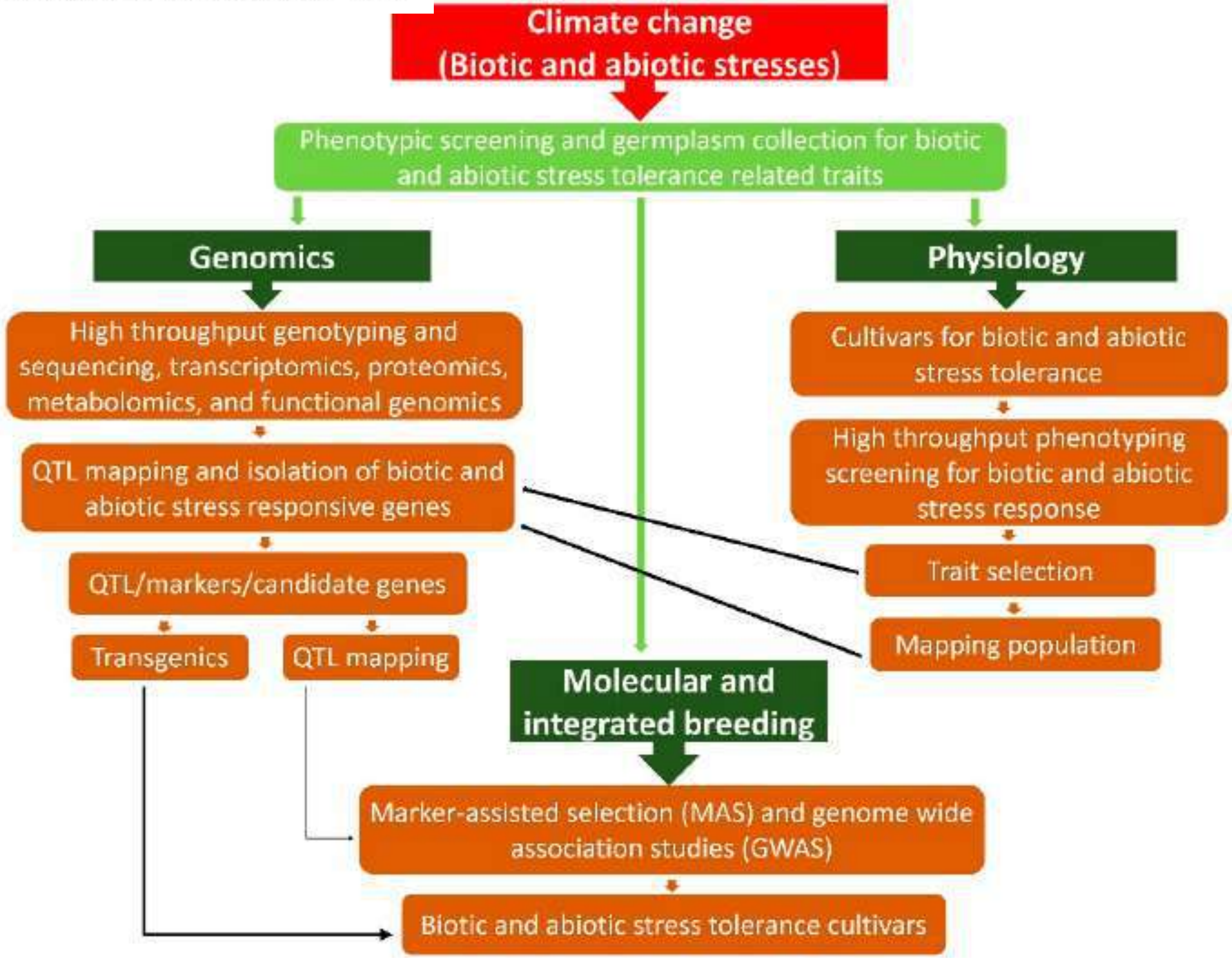

Figure 6. A step-wise presentation of physiological, molecular breeding and genomics approaches to develop biotic and abiotic stress tolerance cultivars.

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Figure 7. A model of CRISPR/Cas9 based genome engineering to develop transgenic plants or abiotic stress tolerance cultivars.

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Schöffl, F., Prändl, R., and Reindl, A (1998) Regulation of the Heat-Shock Response *Plant Physiol.* 117, 1135–1141. doi: 10.1104/pp.117.4.1135

Smertenko A, Draber P, Viklicky V, Opatrny Z (1997) Heat stress affects the organization of microtubules and cell division in Nicotiana tabacum cells. Plant, Cell and Environment (1997) 20, 1534-1542

Źróbek-Sokolnik A. Temperature stress and responses of plants. In: Environmental adaptations and stress tolerance of plants in the era of climate change. Ahmad P, Prasad MN V, editors. New York, NY: Springer New York; 2012. p. 113–134.