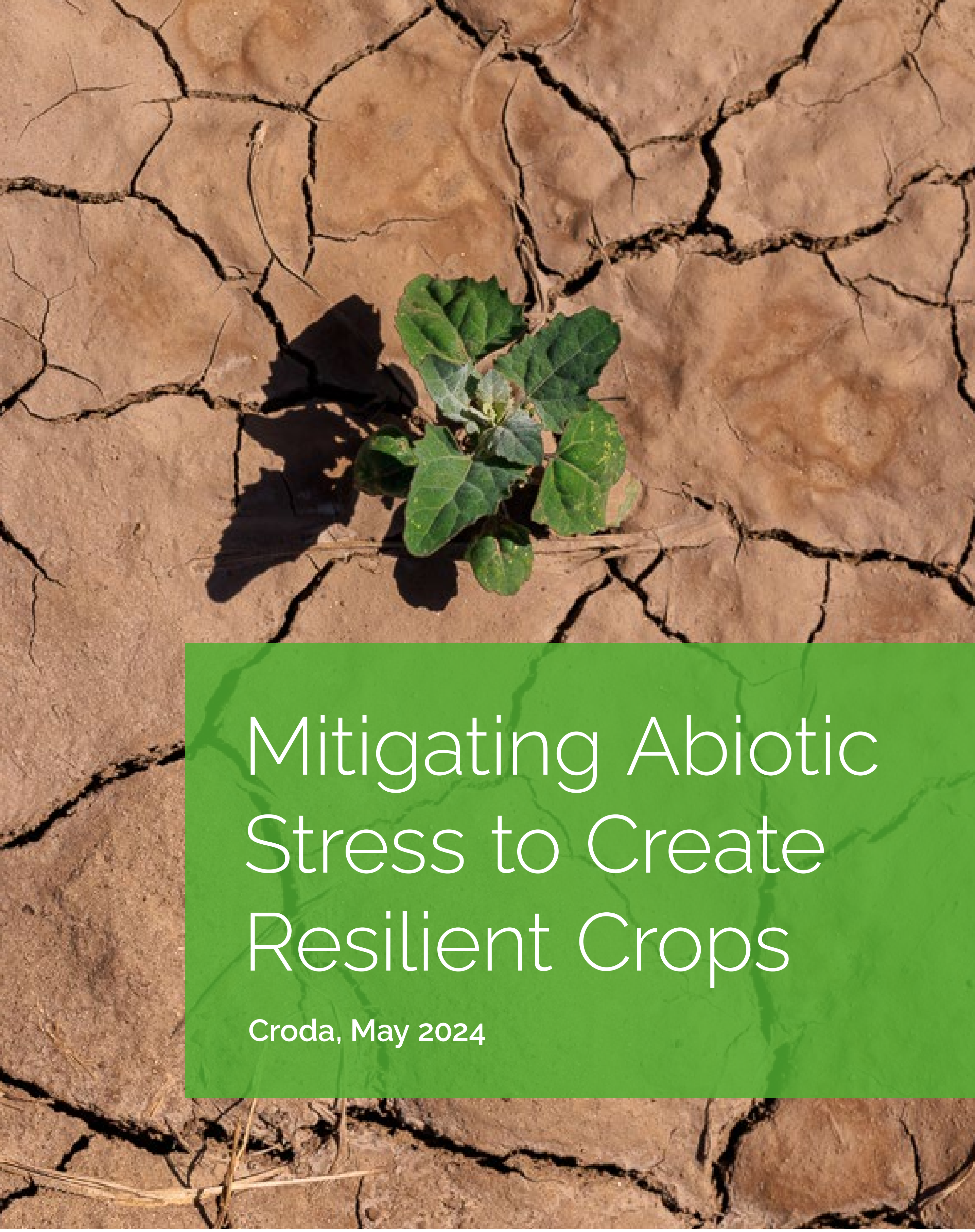

Mitigating Abiotic Stress to Create Resilient Crops

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CRODA | Agriculture

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Why should we care about abiotic stress?

Abiotic stress is any environmental condition that can prevent the plant from reaching its full genetic potential. In 2020-2022, Brazil enjoyed two record harvests. Then in 2023-2024, El Niño struck. Residual ground water from the rainy season, combined with intense heat, created a nationwide mix of water stress, heat stress, or both. Across the country, farmers saw an average 20% loss in productivity due to these combined abiotic stresses.

The environment is complicated and varied, and abiotic stress has always been a problem for farmers, especially those in more extreme climates.

Now, as climate change brings increasingly erratic weather, the impact of abiotic stresses is worsening everywhere,

even in regions with historically mild and stable climates. Some estimates suggest abiotic stresses already cause over $170bn (£138bn) per annum in crop losses .

Plants that are better able to resist the particular abiotic stresses they may encounter over their lives will have better yields and greater stability. Some improvements will be incremental, some transformative. Some will simply counteract the effects of changing climate conditions. Addressing abiotic stress is not a single or perfect solution, but all advances will improve yields relative to what will happen if we do nothing. At scale, these will boost farmers' profits, insulate them against climate change, and improve global food supply without destroying ecosystems to expand production.

This paper will explore the problem, discuss emerging solutions, and explore some big picture challenges we must overcome to drive progress in abiotic stress mitigation.

[1] *https://www.researchgate.net/publication/352331452_Rewilding_crops_for_climate_resilience_economic_analysis_and_de_novo_domestication_strategies*

Abiotic stresses

Drought: Lack of water affects almost every aspect of plant physiology and biochemistry.

Waterlogging: Excess water in the soil can lead to hypoxia or anoxia (lack of oxygen), and fungal disease, affecting root function and nutrient uptake.

Salinity: High levels of salts in the soil can interfere with the plant's ability to absorb water and nutrients, leading to ionic and osmotic stress.

pH: Very high or low soil pH can reduce key nutrients and beneficial microbes, and increase toxic metals which inhibit growth, as well as directly damaging root structure.

Temperature: Both extreme cold (chilling and freezing stress) and extreme heat can damage plant tissues, proteins, and membranes, affecting growth and development.

Heavy Metal: Heavy metals like lead, cadmium, mercury, and arsenic in soil can be toxic to plants.

Nutrient Imbalance: Too few or too many essential nutrients can disrupt plant metabolic processes and growth.

Light: Insufficient light limits photosynthesis, while excessive light intensity can lead to photoinhibition and damage plant cells.

Wind: Strong winds can physically damage plants and cause desiccation (drying out).

Pollution: Air pollutants such as ozone, sulphur dioxide, and nitrogen oxides can enter leaf stomata and disrupt internal processes.

How do plants respond to abiotic stress?

Abiotic stress affects plants in many fundamental ways. It can cause direct damage to the plant, and also trigger protective responses with complex repercussions – not always positive. These biological mechanisms are many and varied, but some key examples are briefly outlined below. It is these types of responses that many abiotic stress solutions are looking to harness, augment, modify, or constrain.

1. Cellular and Molecular Effects

- **Osmotic Stress:** Many abiotic stresses, such as drought and salinity, lead to osmotic stress, which reduces the plant's ability to absorb water. This can cause cells to lose turgor pressure, essential for maintaining cell structure and function.
- **Oxidative Stress:** Stress conditions often promote the production of reactive oxygen species (ROS), which can be useful in small numbers but damage proteins, lipids, and DNA when overproduced.
- **Altered Gene Expression:** Plants respond to abiotic stresses by changing the expression levels of hundreds of genes, leading to stress adaptation over time. These are usually beneficial but may have complicated trade-offs. Studying these underlying mechanisms is valuable for resilience research and breeding programmes.

2. Physiological Responses

- **Water Use Efficiency:** Under drought conditions, plants may close their stomata to prevent water loss. While this conserves water, it also reduces carbon dioxide intake, limiting photosynthesis.
- **Flowering and Seed Production:** Stress conditions can affect flowering and reduce seed set and quality, as the plant allocates resources to survival rather than reproduction.
- **Rooting:** Plants can adapt resources allocated to roots and modify their root architecture in response to water availability.
- **Hormonal Signalling:** Many physiological responses are mediated by hormones, notably Abscisic Acid (ABA), which closes stomata and promotes seed dormancy, as well as Ethylene, Salicylic Acid, and Jasmonic Acid.

As this shows, the response of plants to abiotic stress is complex and involves responses at multiple levels, from molecular and cellular adjustments to physiological and developmental shifts. Furthermore, stresses can impact differently at different stages – germination, seedling establishment, young plants – requiring a suite of solutions for different plants and environments.

Nonetheless, some groundbreaking work has been done in abiotic stress. Much more is expected in the coming years.

How the agricultural industry is responding to abiotic stress

Abiotic stress solutions often start with identifying crops of value that are facing abiotic stress, and studying their stress response mechanisms by submitting them to controlled stresses (heat, cold, water levels, salinity, etc) in labs, growth chambers or greenhouses.

This can be done without intervention, purely to gather data on stress responses. Or as part of a controlled experiment where the same crop is given different abiotic stress interventions, to compare performance to each other and to a control group.

Responses can be measured in a variety of ways to determine whether the intervention was effective. This can range from visual observations of plant health, to multispectral imaging (reflectance and absorption patterns can detect markers of healthy seeds and plants, such as chlorophyll, nutrients, or moisture content), to RNA measurements that detect which genes are active in resilient plants.

Abiotic stress mitigation remains a relatively small area of commercial interest, compared to interventions such as seed treatments and fertilisers. But it is rapidly growing in importance as the climate changes, and a number of companies and researchers are working on exciting solutions. In this section, we highlight some of the types of solutions that are emerging.

Priming

Priming involves partially hydrating seeds to a level at which physiological processes can start, but not enough to allow actual germination, i.e. protrusion of the root tip. The result of priming is that seeds will germinate faster and more uniformly once planted. This can be valuable for lots of reasons – as it produces larger, more uniform plants – and it will play an increasingly important role in mitigating abiotic stress.

Priming gets the seed beyond its early germination phase, where it is most vulnerable to environmental stresses. Tailored priming conditions can also be used to stimulate specific defence mechanisms such as antioxidants and osmoprotectants, that make it more resilient to stresses.

Some seeds can experience dormancy, a state that prevents germination until conditions are right for them. Other seeds can even go into secondary dormancy, when conditions are suboptimal. In nature, this increases the chance of survival of the seedling, but for industrialised crop production it is far from ideal. Priming can relieve primary dormancy, or prevent secondary dormancy, by getting the seed beyond the physiological point where it may return to dormancy. For example a lettuce seed becomes dormant at temperatures above ~22 °C, but a primed seed can germinate up to ~36 °C, allowing it to grow at the farmer's desired time in a much wider range of conditions.

Other seeds simply don't germinate well, or at all, under stress. Priming improves the overall germination even in stressed conditions. For example, below 20 °C, an unprimed tomato seed would have a slow germination, but primed seeds are more likely to germinate, and to germinate faster.

Plants grown from primed seeds progress from seeds to young plants much quicker, sometimes by several days. A faster route to maturity – with developed roots and leaves – means less time in a highly vulnerable state where a sudden change of weather could be the end of it.

Biostimulants

Biostimulants are chemicals or microorganisms that can be applied to seeds, plants, or soils. Unlike pesticides which aim to protect plants from pests and diseases, biostimulants directly enhance crop performance by stimulating natural processes. Biostimulants work in many different ways, some of which improve resilience to abiotic stress.

A key stress response mechanism that biostimulants can target is antioxidant activity. By signalling to the plant to boost antioxidant production, it enables them to mop up excess reactive oxygen species (ROS), which are often overproduced in stressed plants.

Another promising area is osmoprotectants; small, organic molecules that help plant cells maintain water content, and so ensure normal functioning in hot and dry weather. In saline environments, biostimulants can improve ion balance and reduce the toxic effects of excess sodium, helping plants to grow in conditions that would otherwise be inhospitable.

Biostimulants can be delivered into plants via seed treatments, soil treatments, or foliar sprays. Formulating these can be challenging as they often involve delivering complex molecules or live organisms to the plant, which means creating formulations that keep the biostimulant alive, and ensure it is activated at the precise point it needs to enter the plant. Some of these challenges are discussed in our previous paper on 'Formulating Biologicals' .

"75% of the world's cocoa is grown in West Africa, but extreme weather devastates both global cocoa supply and farmers' lives, and such weather is only getting worse thanks to climate change.

Thanks to antioxidant-boosting biostimulants, we have seen cocoa yields improve by over 35%, and much greater resilience, even in 2023 when El Niño brought a 40% production reduction in Ivory Coast and Ghana."

Hubert Ehouman, UPL

Breeding

There are a variety of ways to do this. Conventional breeding involves finding plants with desirable traits and cross-breeding them. It can include exposing seeds or plants to stress conditions – such as drought, high salinity, extreme temperatures, and nutrient deficiencies – with the aim of inducing physiological and biochemical changes that improve stress tolerance. It is an established method, but slow and labour-intensive.

A faster and more targeted approach is to detect molecular or genetic markers associated with desirable traits and breed those. For example, research by Professor Amaral da Silva and others looked at why some soybeans are more resilient to high temperatures and drought than others. They found that, under stress, some soybean seeds cling to their chlorophyll, which should break down as they grow, leading to shorter life. Through DNA testing and chlorophyll measurements, they identified that certain genes were correlated with chlorophyll breakdown under stressful conditions. That opens the door to breeding programmes for plants with these genes, which will be more resilient to the hot, dry conditions that are increasingly common in the world's largest soybean producing areas.

An even more targeted, but also more challenging, approach is genetic engineering. That involves directly manipulating a plant's genome to insert or modify genes associated with abiotic stress tolerance.

Technologies like CRISPR/Cas9 allow for precise editing of the plant genome to enhance or suppress specific genes related to stress tolerance. So far this is largely confined to the lab. Plant genetics involves multiple genes and complex interactions with the environment, making it hard to reliably create improvements that will translate to the real world. Regulatory approval is also lengthy and challenging for gene edited crops. However gene editing is being used for research purposes to identify promising genes for stress tolerance, which can inform natural breeding programmes, and may play an important role in future crop programmes as the technology and public acceptance matures.

[2] *https://www.incotec.com/mediaassets/files/incotec/whitepaper-biologicals.pdf?la=en-GB*
[3] *https://bmcplantbiol.biomedcentral.com/articles/10.1186/s12870-016-0729-0*

Good farming practices

Not all solutions are technological. Good practices in farming strategies will also be increasingly needed. These include reducing stressful conditions, for example by planting trees to create shade and wind protection, and efficient water and soil management and irrigation to ensure plants get enough – but not too much – water and nutrients.

It will also need changing farming practices, for example long term overuse of fertiliser can alter soil pH, necessitating more precision use of chemicals, or new alternatives that use biological organisms to improve soil nutrients in natural ways.

And new technologies – such as soil moisture sensors, drones, and automated irrigation systems – will play an ever growing role in optimising water and nutrient delivery, and monitoring plant health in real time to enable more precise, data-driven interventions against abiotic stress.

Challenges and possible solutions

Whilst there is some innovation directed towards developing solutions to abiotic stress, we are only just scratching the surface. The area remains challenging with a wide variety of research avenues still to explore in all the areas discussed above.

In this final section we discuss some of the outstanding challenges and possible solutions. It is not intended to be exhaustive, but to stimulate thinking and provide a foundation for conversations that advance the industry.

No silver bullet: "As yet there is little evidence on universal stress response mechanisms across or within species" says Ben Scheres of Rijk Zwaan. "We don't know if we need to find solutions crop by crop, or if there may be some generalisable mechanisms we can target broadly".

His colleague Agnieszka Doroszuk adds "More academic research into genetics and physiology of stress responses could help better understand these mechanisms at a fundamental level, which may unlock generalisable solutions, or at least help define what is and isn't possible. For example, where are the points you can manipulate to get resilience to salinity? That would be the holy grail and allow broad solutions, but it may not exist. We may need to do it crop by crop, but if so, that would also be good to know. We should, as an industry, invest in long term knowledge building here." Syngenta's Rosa Dominguez-Espinosa reaches a similar conclusion: "There would be a lot of value in more work to understand the raw materials and fundamental biological mechanisms of abiotic stress solutions".

Moving from the lab to field: Whilst in vitro controlled experiments give signals of effectiveness, the real world is far messier. Validating promising lab results in the field is expensive, especially as it may take a few seasons for the abiotic stresses being targeted to arise naturally. Reproducing lab conditions for breeding is challenging. And even then, it may not be successful – the conditions that created a stress tolerant plant in the lab may not be the same in the field.

More test beds for studying solutions under real world conditions could help. On site breeding programmes could also help select plants for specific climatic conditions. "Further studies of wild ancestors of crops may also yield insights" says Ben Scheres, "since many of today's crops have been bred for yield, size and taste, but not necessarily for abiotic resilience, whereas nature is primarily focused on survival".

Better measurement will also help. "We have shown how multispectral analysis can classify promising approaches early," says Professor Amaral da Silva, "and we are developing a SNP (Single nucleotide polymorphisms)-

array for detecting genetic variations, that will greatly help with understanding which variations show promise". Genomics, proteomics, and metabolomics all promise deep insights into the physiological and molecular mechanisms underlying stress tolerance, opening new avenues for breeding.

Deploying new technologies: New technologies, some of which must first be better understood, could speed progress in abiotic stress solutions. Nanotechnology can help release compounds to the seed. Molecular biology including CRISPR precision gene editing techniques could be used to modify seeds to be more resilient. Much more work is needed to understand the role these can play in crop treatments.

AI can analyse a growing body of plant measurement data and chemical libraries to quickly understand biological response mechanisms, and propose chemical interventions that could adapt those responses for stressful environments. All of this will need ever more collaboration and data sharing between researchers and companies. Well-structured initiatives are needed that allow organisations to work together and share data for their mutual benefit, without risking IP, such as the one being pioneered by CropXR (see box).

Despite the barriers, Professor Amaral da Silva is optimistic: "We need multidisciplinary research to overcome problems. Analysis of in situ metabolism, including image and genetic analysis, has allowed – and will allow – considerable progress in understanding and developing solutions for abiotic stress. Next, nanotechnology, artificial intelligence, and molecular biology, promise a revolution that will produce the most sustainable agriculture seen by humanity."

CropXR

The EUR 15m CropXR project is a 10 year initiative in the Netherlands focused on developing more resilient crops through 'smart breeding' techniques. It brings together over 20 universities, breeding companies, and technology companies, to combine plant biology, agricultural sciences, and plant breeding with experimental research, artificial intelligence, and computational modeling to identify new solutions to crop stress.

Registering new products: "A lot of abiotic stress products involve cutting edge technologies, such as new biostimulants, and these can be hard to register" says Agnieszka Doroszuk. "These products are complex and hard to standardise in ways regulators want, and this is not helped by varied and evolving regulatory systems around the world". Long term there is need for clearer, more consistent regulation.

But even if rules become clearer, such complex products will need the companies developing them to build or access new expertise in product testing, gathering reliable efficacy data, and navigating regulatory frameworks to register products in different markets.

[4] *https://cropxr.org/*

Changing how we think about crop care: Developing effective products is only part of the battle – farmers also need to be willing to use them.

Some of that will be achieved by running trials, and gathering data for farmers to evaluate. Hubert Ehouman from UPL notes that "In West Africa we achieved scale, and helped smallholders who lack the time and money, by running demonstrations on small plots at a few hundred farms, alongside education, so farmers can see the results of abiotic stress products for themselves".

But not all treatments are visibly transformational, and mindsets will need to shift when thinking about abiotic stress. "Many farmers are used to products like insecticides with observable effects" says Rosa Dominguez-Espinosa. "Abiotic stress products show their benefits better when there are environmental stresses, so a mild summer may show small differences between a field without stress mitigation, leading farmers to conclude they have little return of investments. It is better to think of them like an insurance policy, which they always need to have in place, so that they don't see profits obliterated in a year of extreme weather. We need to communicate strategies for dealing with abiotic stress differently to the way we communicate other agricultural products."

How Croda Agriculture can help

Croda and Incotec invite discussion and collaboration with industry and academia to explore and address the challenges of developing and deploying abiotic stress solutions.

We have a range of expertise we can bring to the table, borne out of our research into new actives against abiotic stress, experience of formulating seed and foliar treatments including those based on biologicals and complex organic compounds, and work on testing and validating the efficacy of new seed and foliar products.

But this is a new and rapidly evolving area with a vast amount not yet known, and we are only one player. As this whitepaper shows, collaboration will accelerate innovation and bring new abiotic stress products to market, and we want to hear from others working in this space to explore projects where we can deploy our combined expertise to accelerate innovation.

About Croda Agriculture

Croda Agriculture aims to enhance agricultural performance through innovative delivery technologies.

We support our customers with targeted delivery, technology and customized innovation to increase sustainability, improve agricultural yields and contribute to global food security.

Collaboration will accelerate innovation and bring new abiotic stress products to market.

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