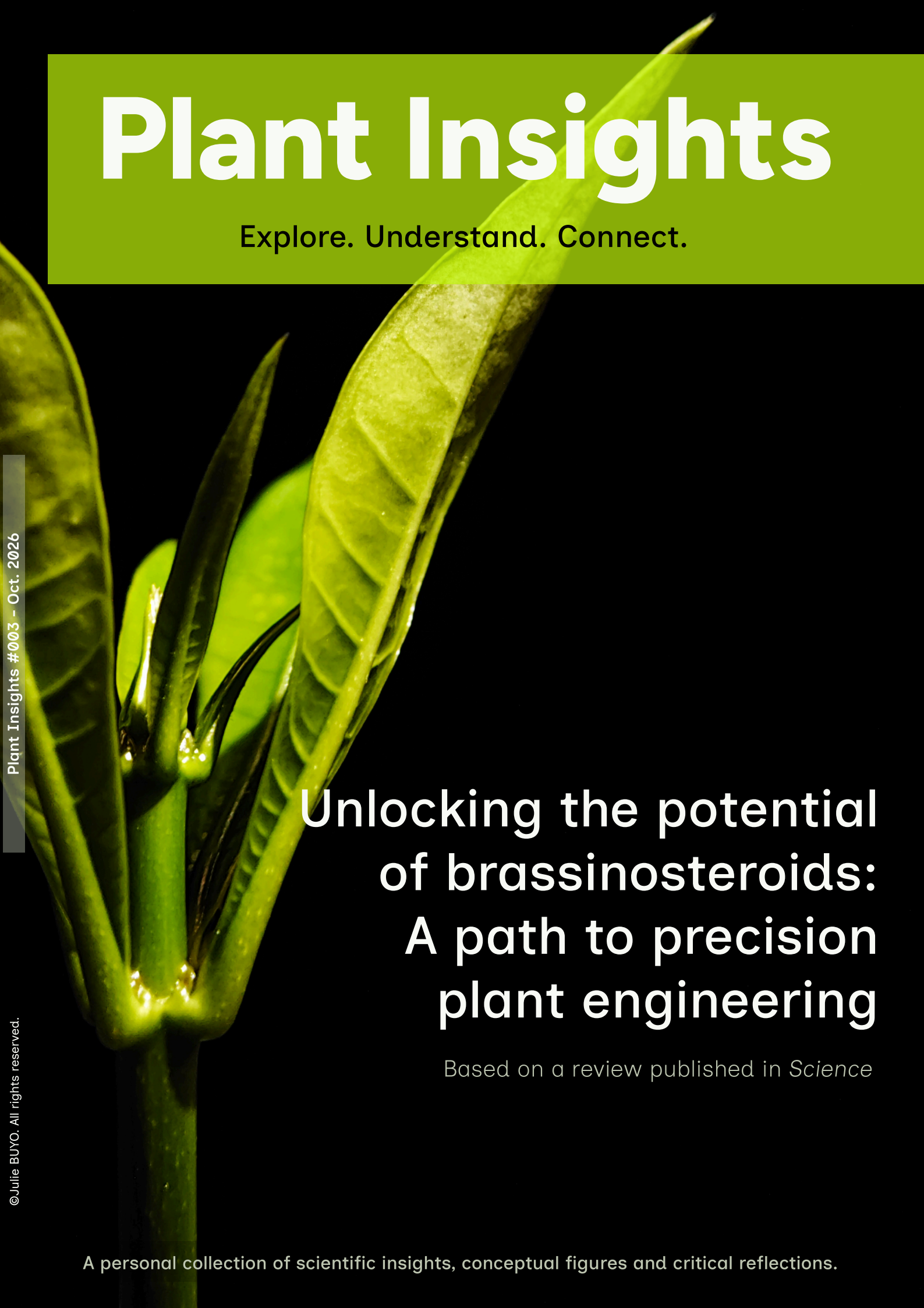
Plant Insights

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Unlocking the potential of brassinosteroids: A path to precision plant engineering

Based on a review published in *Science*

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A personal collection of scientific insights, conceptual figures and critical reflections.

How can a key plant growth hormone be harnessed to improve crops without triggering the side effects that have so far limited its use ?

Why It Matters ?

Global food demand keeps rising on limited arable land under a rapidly changing climate. Brassinosteroids (BRs) are plant steroid hormones that regulate growth, architecture and stress responses: they control cell division, cell elongation, leaf angle, plant height, and grain number. But broad manipulation of this pathway causes pleiotropic effects, including severe dwarfism, so the agricultural challenge is no longer to manipulate the pathway globally, but to tune it precisely, cell by cell and tissue by tissue.

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Authors: Nemanja Vukašinović · Trevor M. Nolan · Eugenia Russinova
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KEY INSIGHTS

01. BR signaling is more complex than previously thought

Single-cell technologies, proteomics and protein–protein interaction studies show that BR signaling varies even between neighboring cells, and long-term live-cell imaging reveals that it oscillates across the cell cycle, dropping sharply during mitotic divisions and recovering in G1. Regulation is highly localized.

02. Cellular context determines the response

In the Arabidopsis root, epidermal BRI1 knockouts reduce meristem size, whereas cortex-specific knockouts leave the meristem unchanged but impair cell expansion in the elongation zone: two adjacent tissues, two distinct functions. The same hormone is interpreted differently depending on tissue, developmental stage and time.

03. BRs act locally, not over long distances

BRs do not undergo long-distance transport.
Their distribution depends on local biosynthesis, movement through plasmodesmata, and active export into the apoplast by ABCB-type transporters. Local alterations therefore tend to have localized effects.

04. Targeted modulation unlocks agronomic potential

Tissue or organ-restricted manipulation has already delivered yield gains in the field: the maize lac1 mutant, clustered-spikelet rice, and CRISPR-based BR attenuation in wheat. Three crops, three organs, three different traits improved, with the details of each success story revealing a single principle, developed below.



"A hormone does not define a response: the cellular context interprets it."

TAKE-HOME MESSAGE

Improving crops through brassinosteroids is not about increasing or decreasing the pathway everywhere. The key is to control where, when, and in which cells the signaling acts, so that yield gains are not paid for with growth penalties.

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FROM GLOBAL MANIPULATION TO TISSUE-SPECIFIC PRECISION

Why the same hormone pathway must be tuned locally, not globally

A SINGLE GLOBAL DIAL

WHAT HAPPENS ?

Brassinosteroids are positive regulators of both cell proliferation and cell elongation, and their transcription factors BES1 and BZR1 regulate thousands of genes, including core cell cycle genes and cell wall-loosening genes. Raising or lowering the whole pathway therefore reprograms growth everywhere at once.

WHY IT FAILS ?

Different tissues and zones require different hormone levels. In the Arabidopsis root, 10 pM of hormone is enough to rescue meristem defects, while 10-fold higher concentrations are needed for full cell expansion in the elongation zone. Global manipulation cannot satisfy both: exogenous treatments disrupt meristem function and cause premature elongation. Constitutive disruption causes severe dwarfism, often sterility, and constitutive overexpression of BR catabolic genes strongly suppresses growth.

OUTCOME

Dwarfism · Sterility · Yield penalty · Variable field results

CHANGE THE SCALE, NOT THE HORMONE

Two pathway properties make this possible: brassinosteroid perturbations typically do not alter cell fate or tissue identity, and the hormone is not efficiently transported over long distances, so the intervention can be aimed.

THREE LOCAL SWITCHES

WHAT HAPPENS ?

The same pathway is tuned one tissue at a time, at the right developmental moment, using tissue-specific promoters, tissue-specific CRISPR knockouts, or natural alleles.
Each local adjustment carries its own benefit while the rest of the plant keeps growing.

Targeted tissue	Local outcome
Root	Grafting wild-type roots onto bri1 mutant shoots restores root biomass and enhances root branching, a phenotype that could improve water and nutrient acquisition under drought or compacted soils.
Leaf	The maize lac1 mutant, defective in a BR C-22 hydroxylase, develops upright upper leaves that enhance photosynthetic efficiency and reduce shade avoidance under dense planting; field trials showed yield gains at high densities.
Panicle	In clustered-spikelet rice, local activation of the BR-catabolic gene BRD3 in secondary branch meristems prolongs the transition to spikelet meristem identity, increasing panicle branching and grain number without affecting grain size.

OUTCOME

Each switch acts alone · Growth preserved everywhere else

SAME PATHWAY → RIGHT TISSUE → RIGHT TIME = GAIN WITHOUT PENALTY

Precision begins when the plant gains a trait without abandoning growth.

Figure Legend

Figure 1. From global manipulation to tissue-specific precision. Brassinosteroid signaling controls cell proliferation and elongation through transcription factors that regulate thousands of genes, and different tissues require different hormone levels, as illustrated by the 10 pM versus 10-fold higher concentrations needed for meristem maintenance versus full cell expansion in the Arabidopsis root. Global manipulation therefore causes pleiotropic penalties such as dwarfism, sterility and yield loss. Because brassinosteroids act locally and do not determine cell fate, the pathway can instead be tuned tissue by tissue: restoring or enhancing root branching through shoot-root decoupling, shaping leaf angle for dense stands as in the maize lac1 mutant, and increasing grain number through localized BR depletion in rice panicle meristems, each without penalizing overall growth. Conceptual figure: Julie BUYO. Based on Vukašinović et al. (2025).

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Connecting research findings to broader scientific perspectives.

Scientific Implications_

Toward predictive, climate-specific design

Routine variety design still lacks infrastructure: no genetically encoded BR sensors exist, so signaling can only be inferred from BES1/BZR1 localization, and crop atlases remain scarce. The predictive path is nonetheless proven in principle [1]: modeling hormone distribution well enough to design targeted interventions is no longer hypothetical.

Broader Perspectives_

Beyond yield as a single target

Climate-resilient varieties must satisfy conflicting constraints: yield under heat and drought, nitrogen efficiency, lodging resistance. The Green Revolution illustrates the cost of ignoring spatial context: Rht semi-dwarfism bought lodging resistance at the price of smaller grains and higher nitrogen inputs.
The spatially restricted BR interventions above avoid these trade-offs, suggesting those penalties were artifacts of a whole-plant intervention [2].

Research Outlook_

Validating climate adaptation in the field

The critical filter is the field, where the wheat ZnF yield gain was actually validated across multi-year trials [2]. Since stress arrives as sequences and combinations, the goal is a portfolio of tissue-specific BR interventions, each matched to a defined stress context, rather than one universal climate-proof variety. And the pathway itself keeps reminding researchers of its complexity: with no BR sensors, unresolved transport mechanisms, and the risk of unexpected interactions between edited and non-edited tissues, every intervention remains a hypothesis to be tested, not a module to be plugged in.

CONNECTIONS_

From model roots to climate-ready crops

The relevance of brassinosteroid research becomes tangible as climate pressures intensify. The review itself frames this only briefly, but its central proposal extends further than its authors state: the tissue specificity revealed in the Arabidopsis root can be read as an engineering principle for climate adaptation. Overexpression of BRL3, a vascular-enriched brassinosteroid receptor, confers drought tolerance in Arabidopsis through accumulation of osmoprotectant metabolites such as proline and sugars, without penalizing growth, whereas ubiquitous BRI1 manipulation gains drought resistance only at the expense of growth. Drought response and growth can be uncoupled, but only when the intervention is spatially restricted [3].

The same logic extends below ground. Micro-grafting between wild-type and BR-null mutants in both Arabidopsis and tomato revealed a division of labor: shoot BR determines how much carbon reaches the root, while root BR dictates how that carbon is distributed along the root, through local control of growth anisotropy and cell wall thickness. A "grow and branch" simulation model built on these two effects successfully predicted root growth and branching across graft combinations. This is the mechanistic basis for engineering root systems built for drying or compacted soils while leaving the shoot program untouched [1].

And it extends to yield itself. A natural haploblock deletion removing the RING-type E3 ligase gene ZnF-B produced semi-dwarf wheat without the Green Revolution Rht alleles, improving grain yield by up to 15.2% in multi-year field trials, by stabilizing the BR signaling repressor TaBKI1. Three systems, three organs, one principle: restricting brassinosteroid manipulation to the right cells converts trade-offs into synergies [2]. These proofs of concept differ in maturity, however: the strongest growth-penalty-free demonstration, BRL3, remains at the model plant stage, while the strongest field validation, ZnF-B wheat, rests on a single gene in a single study.

[1] KHANDAL, H. et al. Root growth and branching are enabled by brassinosteroid-regulated growth anisotropy and carbon allocation. *Nature Communications*. 2025, vol. 16, 3985. DOI 10.1038/s41467-025-59202-6.
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[3] FÁBREGAS, Norma et al. Overexpression of the vascular brassinosteroid receptor BRL3 confers drought resistance without penalizing plant growth. *Nature Communications*. 2018, vol. 9, 4680. DOI 10.1038/s41467-018-06861-3.

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