

25 Years of thermomorphogenesis research: milestones and perspectives

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In 1998, Bill Gray and colleagues showed that warm temperatures trigger arabidopsis hypocotyl elongation in an auxin-dependent manner. This laid the foundation for a vibrant research discipline. With several active members of the ‘thermomorphogenesis’ community, we here reflect on 25 years of elevated ambient temperature research and look to the future.

The beginning

In the early days of molecular genetics, temperature-sensitive mutants became a tool for the dissection of molecular pathways. In the late 1970s, for example, essential genes regulating the budding yeast secretory pathway were identified in this manner [1]. Being trained as a yeast geneticist, Bill (William) Gray, a postdoc in Mark Estelle’s laboratory at Indiana University (USA), and colleagues used a similar approach in *Arabidopsis thaliana* (hereafter arabidopsis). Bill aimed to identify temperature-sensitive alleles of TRANSPORT INHIBITOR RESPONSE 1 (TIR1), which was at the time an unknown auxin coreceptor. Although he was not successful in identifying such *tir1* alleles, his observation that elevated temperature promotes auxin-mediated hypocotyl elongation [2] would lay the foundation for a thriving research discipline known now as thermomorphogenesis. This year the engaged and active thermomorphogenesis community celebrates its 25th anniversary (Figure 1).

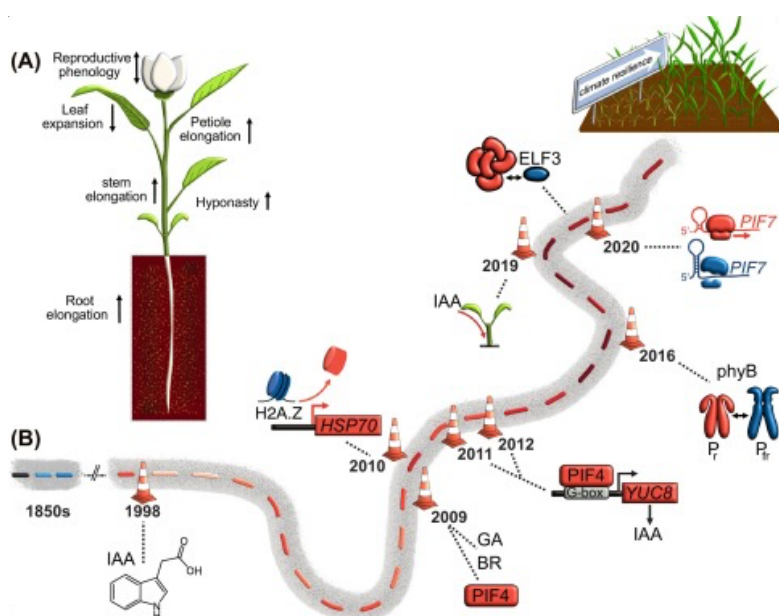


Figure 1. Milestones in 25 years of thermomorphogenesis research. (A) Model thermomorphogenic phenotypes represented on a stylised plant; arrows indicate thermo-induced directions of the corresponding phenotypes. (B) Roadmap of selected important research milestones, starting with the discovery that the auxin indole-3-acetic acid (IAA) mediates temperature-dependent hypocotyl elongation and leading towards the generation of future climate-resilient crops; colours of the centreline markings indicate the global temperature change relative to the 1971–2000 average, based on information from <https://showyourstripes.info/c/globe> with each stripe representing 1 year. Blue and red colours indicate below-average and above-average temperatures, respectively, with darker colours indicating greater deviations from the mean. Abbreviations: ELF3, EARLY FLOWERING 3; PIF4, PHYTOCHROME-INTERACTING FACTOR 4; phyB, phytochrome B.

The Gray study provided the basis for a molecular framework to understand the physiological responses to elevated ambient temperatures. Subsequently, work from the Franklin laboratory provided important insights into the potential benefits that plants obtain from thermomorphogenic growth patterns by showing that, in particular, petiole elongation and hyponastic growth are associated with increased transpiration and lower leaf temperatures (Figure 1A). This indicates that thermomorphogenesis stimulates leaf cooling by enhancing evaporation, suggesting a possible functional relevance to plants, at least under laboratory conditions [3]. However, in natural and agricultural settings the situation is undoubtedly more complex as plants have to deal with multiple environmental factors at the same time (see also later).

Molecular signalling and thermosensing

The publication of Gray's seminal results [2] did not immediately spark follow-up studies. It was not until 2009, when the Franklin laboratory identified the bHLH transcription factor PHYTOCHROME-INTERACTING FACTOR 4 (PIF4) [4] as a key regulator of thermomorphogenic signalling, paving the way for subsequent discoveries including the identification of the first thermosensors. In the same year, a second important study was published, describing gibberellins and brassinosteroids as phytohormones that, in addition to auxin, coordinate thermosensitive shoot growth [5], as we now know, downstream of PIF4. These two papers [4,5], together with the finding that PIF4 directly regulates specific auxin biosynthesis genes like YUCCA8 [6,7], inspired many scientists. Increasing numbers of groups from related disciplines (photobiology, phytohormone biology, natural variation, flowering regulation, epigenetics, thermotolerance, cellular signalling, immunity, post-transcriptional regulation, miRNA biogenesis) stepped in and started to elucidate how plants respond to elevated ambient temperatures. Not least, the research interest was fuelled by the emerging awareness of rapid global warming and the need to harness crops to safeguard food security. The prospect of contributing to climate change mitigation is still a major driver for many of the authors of this forum to devote resources to gain fundamental knowledge on thermomorphogenesis regulation and understanding of its functional consequences.

Studying warm temperature signalling is not a trivial task because temperature, being essentially molecular motion, is a versatile signal and has no ligand properties nor distinct physical features. For many years, it therefore remained unclear whether specific thermosensors had evolved in plants. Finding bona fide thermosensors has been, and remains, a major goal. Although not entailing a dedicated sensor, a warm temperature relay cascade was uncovered by the Wigge laboratory in 2010, showing that eviction of the noncanonical histone H2A.Z from the chromatin of temperature-inducible genes is required for thermomorphogenic responses [8]. Building on earlier work from the Whitelam, Schäfer, and Halliday laboratories, the Wigge and Casal laboratories showed that phytochrome B (phyB) is a thermosensor using a combination of omics, biochemistry, spectroscopy, and genetics, hence revealing that thermomorphogenesis requires a surveillance system directly linked to light responses [9,10]. Subsequently, temperature-dependent phase transition of EARLY FLOWERING 3 (ELF3) into biomolecular condensates and temperature-dependent conformational changes in the PIF7 mRNA structure resulting in enhanced translation were shown to also sense temperature changes [11,12]. Thus, various thermosensing mechanisms at the DNA, RNA, and protein levels have been uncovered and more are expected to be found.

Where do we go from here?

Based on the early findings on the involvement of PIF4, auxin, and other hormones [2,4–7], and by the identification of thermosensory mechanisms, thermomorphogenesis has become an established field in the plant sciences. However, many important points remain to be addressed. One major question is the spatial and temporal regulation of thermomorphogenic responses across organs and tissues, down to potential cell-type specificities. Although a number of studies have specifically addressed this issue (e.g., [13]), we are only now beginning to understand the communication of temperature signals within the plant. Another challenge is to distinguish whether specific thermomorphogenic signalling events exist and to distinguish these from thermodynamic effects on several (if not all) signalling networks, given that temperature impacts every molecule and reaction in the plant, including enzyme activities. This also raises the question of how cold, ambient warm, and heat (tolerance) responses are, if at all, connected. A gradient approach may reveal for example, whether cold regulators are involved in warm temperature responses and vice versa and thus whether there exists a generic response to temperature or whether distinct signalling branches deal with different temperature cues. Part of the answer may be obtained by taking an epigenetic approach, as regulation of different levels of histone H3 lysine 4 methylation appears to be a signalling hub where diverse temperature cues converge [14].

At the organismal level, a potential pitfall of thermomorphogenesis research is that functional hypotheses are relatively easy to formulate when only temperature is considered. For example, temperature-induced root elongation may serve to reach deeper water to meet the demands of increased transpiration and hyponasty is likely to reduce heat flux on the leaves. However, the contribution of thermomorphogenesis and its component traits in natural environments is complex and currently not well understood. One avenue of future research should focus on understanding which thermomorphogenic responses contribute to plant performance in the wild and/or agricultural environments, what fitness costs are associated, and which regulators of the canonical or peripheral pathways are targeted by natural selection to confer a selective advantage. While the community has so far gained understanding of thermomorphogenesis under highly controlled conditions, it is time to expand beyond the laboratory to study thermomorphogenesis in wild species and in crops. It has been reported that thermomorphogenesis does occur in several crop species such as cabbage, tomato, and wheat [15], but the molecular mechanisms need to be further explored to be able to contribute to the generation of climate-resilient varieties (Figure 1B). Emphasis should be placed on the interaction with biotic signals and their potential trade-offs. Global warming will increase pathogen pressure, highlighting the importance of better understanding the interactions between temperature and the biotic environment, which may also apply vice versa to microorganisms that positively influence plant performance in symbiotic interactions. In addition, temperature will influence the way in which abiotic factors such as drought or salt stress are perceived and dealt with. For example, while warm temperature episodes often co-occur with drought, there is an apparent conflict in their optimal responses, since drought-induced stomatal closure may prevent leaf cooling facilitated through increased thermomorphogenesis-mediated transpiration. The crosstalk and potential priming role of thermomorphogenesis in thermotolerance (e.g., do thermomorphogenesis signalling and resulting phenotypes contribute to heat stress survival?) is another critical point that requires further investigation.

Perhaps the greatest challenge for thermomorphogenesis research lies in translation: how do we exploit conceptual breakthroughs in understanding temperature signalling to engineer plant resilience in this era of unprecedented global warming? Despite excellent progress on

understanding the mechanisms underlying individual thermomorphogenic responses over the past 25 years, we may have bigger discoveries to come.

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Declaration of interests

No interests are declared.

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