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The 1972 Meadows report: A wake-up call for plant science

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Classics

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Abstract

The 1972 Meadows report, 'the limits to growth', predicted a global socio-economic tipping point during the twenty-first century. Now supported by 50 years of empirical evidence, this work is a tribute to systems thinking and an invitation to take the current environmental crisis for what it is: neither a transition nor a bifurcation, but an inversion. For instance, we used matter (e.g., fossil fuel) to save time; we will use time to preserve matter (e.g., bioeconomy). We were exploiting ecosystems to fuel production; production will feed ecosystems. We centralised to optimise; we will decentralise to support resilience. In plant science, this new context calls for new research on plant complexity (e.g., multiscale robustness and benefits of variability), also extending to new scientific approaches (e.g., participatory research, art and science). Taking this turn reverses many paradigms and becomes a new responsibility for plant scientists as the world becomes increasingly turbulent.

In 2022, *Quantitative Plant Biology* has showcased new questions in plant science, such as solid versus liquid signalling (van Schijndel et al., 2022) or the new role of threonine in skotomorphogenesis (Tabeta et al., 2022). New quantitative tools were introduced, from non-coding long RNAs identification and classification (Nithin et al., 2022) up to ecosystem natural capital accounting in local territories (Argüello et al., 2022). Several articles took a step back on plant science, with new evolutionary views, for instance, on shoot apical meristems (Wu et al., 2022), while others explored its future, notably with the rise of transdisciplinary approaches such as citizen science (Receveur et al., 2022) and art & science (Bonneval, 2022). *Quantitative Plant Biology* is also a forum for the plant science community to promote systems thinking and explore the complexity behind plant physiology and development (Autran et al., 2021). This extends to the 'how' and 'why' we do research on plants.

In particular, with the rise of social networks and the focus on most recent publications, we, as a community, take the risk of falling into the trap of immediacy, the fuel that promotes (fast) overly reductionistic thinking instead of (slow) systems thinking. *Quantitative Plant Biology* is thus opening a new format to contribute to slow science: in the 'classics' format, you will not read the latest discovery, but instead dig into an article, published more than 20 years ago and which is still seminal in the field. Call it a tranquil resistance to fast fashion in science. I am happy to say that more than ten world leaders in plant science have already agreed to write such a piece in 2023.

Here, I take the liberty of opening this new format with a 50-year-old computational model and corresponding book, the limits to growth (Meadows et al., 1972). World3 is the first computational model of the world, and this already is enough to make it a landmark in the history of science. Many models have followed, the most recent one being Earth4all, with a deeper exploration of socio-economical inequalities (Dixson-Declève et al., 2022). Why should such work be relevant to plant science? The key trigger of the 1972 study was the threat of a shortage of essential resources. In other words, by pointing out the unescapable limit on non-renewables, the model highlights the need to slow down our extraction to give us enough time to switch to circular bioeconomy. This is a call to reconsider our main, and almost only, renewable resource: plants.

The World3 model provides two main messages. A trivial one, first: on a finite planet, one cannot continue to live under the conceptual framework of infinite growth. The second

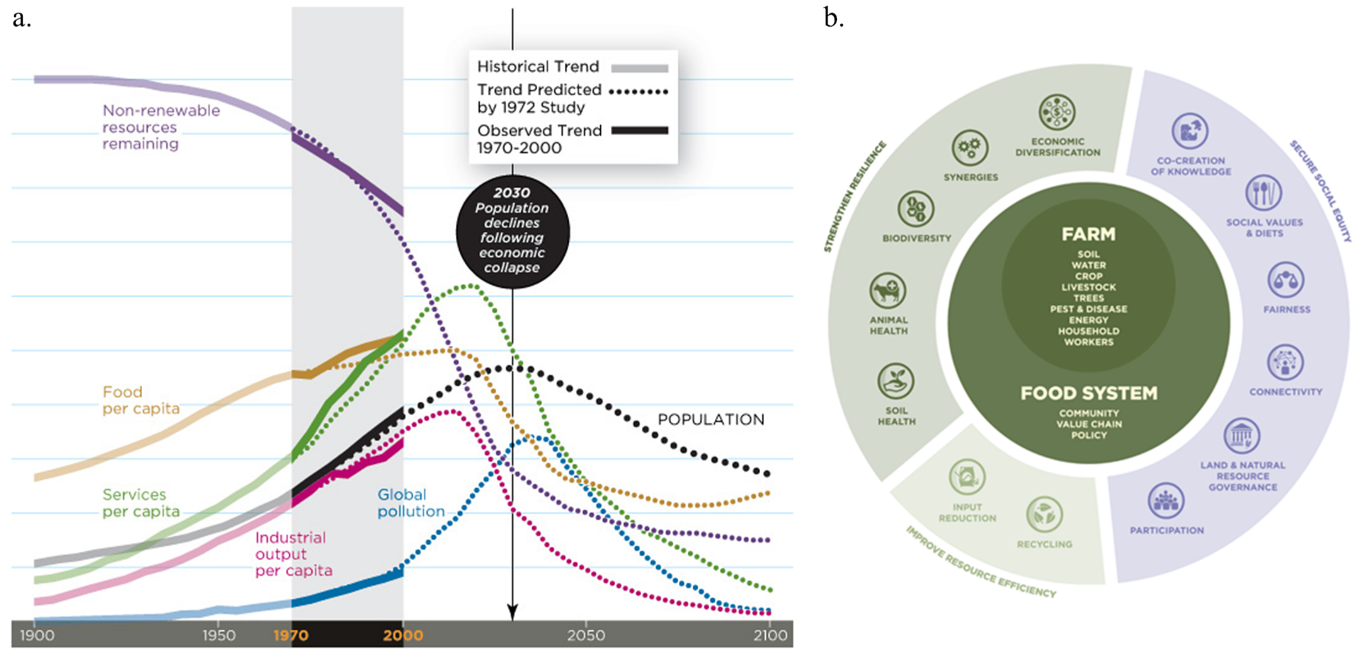

Fig. 1. Lessons from the 1972 Meadows report for plant scientists: systems thinking for resilience. (a) Standard run from the 1972 report (dotted line), revisited with empirical data until 2000 (plain line), and predicting a socio-economic tipping point before 2050 (Adapted from Turner, 2012). (b) New quantitative plant biology questions and framework in agroecology, building on complexity and fuelling resilience (adapted from FAO and HLPE, 2019; Nicholls & Altieri, 2016).

conclusion is much more disturbing and is crystallised in a date: unless a true revolution happens, the business-as-usual model predicts a socio-economic tipping point before 2050 (Figure 1). This shocking news is why the book sold millions and was translated into 35 languages almost immediately. However, with the oil crisis in 1973, this conclusion was actively attacked, buried, and finely forgotten. Until the turn of the century where World3 was re-examined in the light of empirical data accumulated over 30 years, and the conclusion was unchanged: despite all the media attention on sustainable development, we are following World3 scenario #1 (standard run), that is, the business-as-usual route (Figure 1, Meadows et al., 2009; Turner, 2012). Further studies have confirmed this trend, warning about upcoming tipping points for the climate (Steffen et al., 2018) and for ecosystems (Barnosky et al., 2012), further locking humanity on that trajectory. For intensive agriculture, this means that we would have around 20 harvests before the global food system faces at least one of its physical limits: water availability, soil sustainability, phosphate stock, extreme climate events, oil and energy supply.

One could resist this conclusion arguing that we have made much progress in agronomical and economic productivity and that the ecological transition is in progress. The very fact that we are following the business-as-usual scenario means, to say the least, that this is denial: we have not really deviated from the 1972 basic prediction. In fact, such a disappointing outcome was also predicted in the Meadows report and should be revisited today, notably to question some of the proposed scientific solutions to the environmental crisis.

Should we extract more resources (e.g., rare metals through deep sea mining) to prolong our current socio-economic model, including intensive agriculture? According to World3 scenario #2 'unlimited resources', this would only increase the production of pollution without affecting the existence of a tipping point before 2050. Thus, should we also promote cleaner technologies? Yes, of course, but let us not be naïve: this would only delay the tipping point by a few years or decades, because reduced pollution also promotes the exhaustion of arable land to support a growing population, as illustrated in World3 scenario #3 'unlimited resources with controlled pollutions'. Should we thus add increased agricultural productivity to face these challenges? As shown in World3 scenario #4 'unlimited resources with controlled pollutions and increased agricultural productivity', this would promote global pollution (despite the existence of cleaner technologies), without affecting the trajectory. Now in the 2020s, we can experience the predicted turbulence of the business-as-usual scenario in our daily life: mega-fires, mega-flooding, heat waves and heat domes, and shortage in resources with the associated social and geopolitical unrest. What can plant science do about it?

In the worst-case scenario, plant scientists would ignore the Meadows scenarios and put forward reductionistic solutions overlooking known key parameters in the bigger picture. This includes believing that an increase in agricultural productivity is a satisfactory goal to preserve food availability and ecosystem services. As shown all over the world, Norman Borlaug's land-sparing theory is not verified: higher intensification has not reduced the land surface area devoted to agriculture to preserve other ecosystems. This is due to at least two factors: a rebound effect (increased productivity generates new needs, leading to more resource consumption in the end (Hamant, 2020)) and desertification (because intensive agriculture provides short-term benefits but kills soils and ecosystems in the long term, at least in its current form with ploughing, fertilisers and pesticides). In fact, soil degradation is already perceived as a major threat to crop production in certain countries, like Kenya (Moore, 2016). As noted by FAO, 'past agricultural performance is not indicative of future returns' (FAO, 2016). United Nations special rapporteur on the right to food Olivier de Shutter is blunter: 'our food systems are making people sick'.

One key responsibility of plant scientists is to resist the attractive trajectory of efficiency in agriculture in an isolated framework. This means that we will have to set our research questions in the framework of slower and more complex route of resilience in agriculture, that is, agroecology (FAO and HLPE, 2019). Several scenarios show that such sustainable agriculture can feed the world (Couturier et al., 2016; Pretty & Hine, 2001). This involves hardcore quantitative plant biology, extending the complexity to genetic diversity, genetic and environment interactions, and agronomical practices. What would such quantitative plant science look like in the future?

The revolution in plant science is not a cosmetic one. It is not a sustainable development add-on or even a transition. With systems thinking in mind, one can see the emergence of a true inversion, a third way, matching the socio-economic tipping point predicted by World3 (Hamant, 2022). Here are five axes where such inversion happens.

First, the drive for more efficiency will die out because of its counterproductivity. Instead, plant science will focus on socio-ecological resilience, that is, the ability to persist, to adapt and to transform in a fluctuating environment (Folke et al., 2010; Hamant, 2022). This is a total revolution in plant science as the focus will shift away from yield increase and optimisation (only relevant to a stable, controlled, environment), to the mechanisms supporting robustness and adaptability (relevant to a fluctuating environment). For instance, this involves analysing how time can tune regulatory networks (Calderwood et al., 2021), how incoherence generates stability (Creff et al., 2023; Joanito et al., 2018), how local variability generates global reproducibility (Roeder, 2021) or how delays support adaptability (Vidal et al., 2010).

Second, plant scientists will increasingly question and depart from a socio-economic context that fuels the exploitation of ecosystems to increase agricultural production. Beyond systems thinking, this will happen because arable lands and ecosystem services are the most precious parameters for our viability on Earth, and their value and protection will continue to rise. Plant scientists will instead ask how agronomical production can feed ecosystems. This notably involves understanding agroecological practices, from varietal mixtures increasing drought tolerance and pathogen resistance (Barot et al., 2017), to permaculture maintaining soils alive, a basic research which is not incompatible with cutting-edge quantitative technologies, for example, on microbiome (Toju et al., 2018).

Third, plant science projects will no longer take part of fragile global food systems made of only five main seed companies worldwide and producing carbon-heavy and unhealthy ultra-processed foods (whether plant- or animal-based). Instead, plant scientists will get closer to local farmers through citizen science, for example, with participatory plant breeding (Ceccarelli & Grando, 2020), and design local and robust strategies to face a turbulent century. This involves basic research on the open book of heterogeneous situated knowledge.

Fourth, plant science will no longer support projects where non-renewable resources (e.g., oil or metals) are used to increase productivity (e.g., in precision agriculture); instead, plant scientists will explore ways in which time can be used to preserve resources (bioeconomy). This shift might even extend to plant-based materials to build next-generation digital hardware (e.g., Ghanem et al., 2021). In other words, plant scientists will shift from a world of large extractions and poor interactions, to a world of few extraction and rich interactions. This involves systems biology, circular bioeconomy and the development of (slower) biobased material production, as well as science and society projects with local stakeholders (notably to assess and balance available resources and essential needs).

Last, plant science will no longer support competition as a fuel for discovery, simply because in a time of shortage of resources, competition is counterproductive! Instead, cooperation will increasingly become the norm, and a much richer way to produce knowledge. This shift is already happening with the rise of interdisciplinary plant science. Interestingly, plants show us the way: in forests, trees switch from competition to cooperation when resources become scarce (Choler et al., 2001).

Needless to say, this global revolution in plant science must also be accompanied by a new ethics in science publishing and sharing. With a community-based editorial board, a not-for-profit publisher (Cambridge University Press) and partner scientific institution (John Innes Centre), and a fully open-access framework, *Quantitative Plant Biology* takes its part and invites everyone to contribute to an engaging and stimulating future plant science where basic research meets global challenges, notably through Meadows's inspiration on systems thinking.

Conflicts of Interest. The author is also the editor-in-chief of *Quantitative Plant Biology*, which explains the editorial tone of this article.

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