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An enhanced genetics × environment × management framework for yield intensification

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The classic genetics × environment × management framework, used for assessing crop yield, can be extended to include four enabling factors for yield intensification (knowledge, availability of critical goods and services, experience, and capability). The resulting framework, 'GEM4', enables managers and advisors to identify farm-level constraints to yield intensification. The framework may be a useful tool for research and development initiatives at local or global levels supporting crop yield intensification.

Even farms that are in the same location (where soils and climate are largely uniform) and that grow the same cultivars of the same crop may achieve a wide range of yield outcomes. This spread of agronomic efficiency may be observed among farms implementing comparable cropping practices and using similar equipment, suggesting that it is not only biophysical conditions and crop genetic potential that determines yield, but also the characteristics of farm management.

There are complex reasons why gaps between attainable yield and actual yield persist, even when it should be in a farm's financial interest to close yield gaps[1]. Understanding the factors that lead to yield differences among similar farms is an important step in reducing yield gaps and maximizing farm profits. Yield improvement reduces global land requirements for crop production, and is one condition necessary for land sparing[2,3]. The benefits of high productivity are therefore important, whether from the point of view of the farm, consumers, society or the environment.

History of the G × E × M framework

The genetics × environment (G × E) framework has been used by crop scientists and breeders for assessing crop yields since the 1970s, primarily for testing new varieties under different environmental conditions. The history of G × E is summarized in a review by James Tabury[4]. Later, crop scientists extended G × E by incorporating management (M) as an additional factor[5,6,7]. This was useful to explain yield variation due to differences in crop and soil management practices (for example, planting date, choice of tillage and intensity of disease control) and their interactions with G and E. For example, maize cultivars bred for high yield at high plant density have a different yield response to changing plant density than cultivars that are not bred for that trait, indicating that there is a G × M interaction. Although the exact origin of the G × E × M framework is unclear, it is now widely known and referenced[5,6,7].

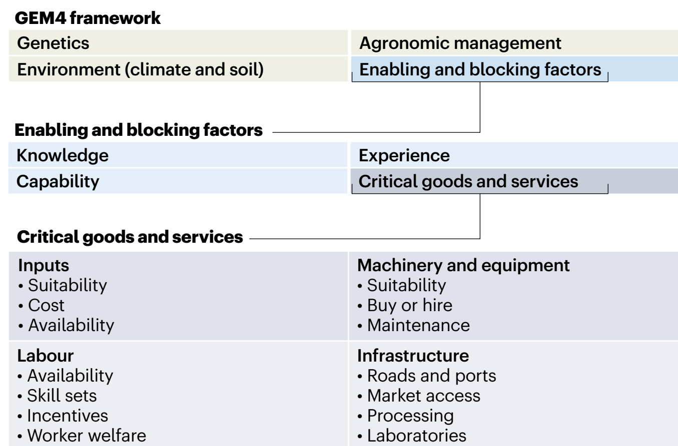

Fig. 1 | Schematic representation of the expanded GEM4 framework. The scheme shows the GEM4 framework (top), the four factors than can enable or block yield intensification (middle) and some subcomponents of critical goods and services (bottom).

Adaptation of the framework for evaluating farm management

Previous use of the G × E × M framework has concerned the impact of cultivar, environment and management variables — and the interactions between them — on crop yield. Here, we expand this framework to include four key factors that enable or block yield intensification at farm level: (1) knowledge, (2) critical goods and services, (3) experience and (4) capability (Fig. 1). The extended conceptual framework (referred to as 'GEM4') can be used as a diagnostic tool by practitioners and policy makers to identify barriers to yield intensification from local to regional levels.

Knowledge. Knowledge provides the theoretical basis for best farming practices, leading to optimal yield and profits. It encompasses (1) formal knowledge (derived from published literature, education and so on); (2) external knowledge (obtained outside the farm from advisors, input and equipment providers, training events, observing the practices of neighbouring farms, and so on); and (3) farm-generated experiential knowledge (derived from routine farm practices and all forms of formal and informal on-farm trials and tests). The core knowledge on practices that lead to yield intensification is not static; there are always possible improvements and efficient farms are always learning. This includes learning from the practices of high-performance peers. The leading commercial farms in the world often participate in agricultural information management systems databases and yield enhancement networks, usually mediated by advisory services[8]. These systems allow comparison between farms under comparable climate–soil conditions and help identify the management practices that lead to high yields and highest farm profits.

Critical goods and services. Successful crop production also requires farms to have access to a range of critical goods and services. This includes supplies of equipment and associated maintenance services; timely availability of quality seed, fertilizer and other inputs; laboratory services for tracking plant nutrition; farm labour that is well trained, skillful and properly equipped; contracting services for field operations; and advisory services. These are needed at an appropriate cost, quality, quantity and timing of availability. Public infrastructure such as roads and ports may also be included as essential items if they have an impact on the availability and cost of the goods and services required by farms. Marketing, processing or other offtake services can also be included because yield intensification is senseless if the additional output cannot be used, stored or sold. The lack of critical goods and services needed for yield intensification is severe in some developing countries, hampering the potential for best-practice, high-yield and high-profit farming in many locations. Even where most goods and services are available, they may be at a different quality and price compared with competitor regions of the world. Availability is therefore not binary, but involves a complex range of differing access, quality and pricing of goods and services.

Experience. Experience arises from applying knowledge and using the necessary goods and services while implementing farm operations. Learning through repetition leads to familiarity, so that the ability to implement becomes embedded and skillful. This is equally true of a small farm with an owner and no employees and a large crop business with thousands of employees. For a large enterprise, experience needs to be institutionalized, so that it gets transferred from more experienced to less experienced colleagues and is not lost when a staff member leaves the company. On a large farm, experience of operating the management systems that collate and use data is also essential for achieving high yields. Such systems are an important part of a well-run, large-scale modern farm business. Experience should ideally go beyond routine operations under normal conditions. A farm with vast experience will be better able to adapt to abnormal conditions, such as a drought, a pest outbreak, a pandemic or low market prices. Newly adopted crops usually take novice farms several seasons to acquire the necessary experience to grow them successfully. Some investments in new commercial farms would have the potential to succeed but sometimes fail because investors do not provide managers with sufficient time to gain the necessary experience. This is particularly true for farm investments in a context where the commercial crop sector is fragile and poorly established, such as sub-Saharan Africa. In such situations, the lack of experience can lead to bankruptcy.

Capability. Even when two neighbouring farms grow the same crop in the same way, have access to the same goods and services, and have the same knowledge and experience, there can still be differences in farm performance. This residual difference is largely attributed to farm capability. The capability of farm management concerns the circumstances and context as well as the characteristics of the farmer or the crop business. For example, financial restrictions may result in limited capacity to perform farming operations on time, with optimal materials and equipment. This issue is widespread among poor smallholder farmers, for whom expenditure on routine crop production must compete with urgent family expenditure on food, healthcare, education and so on. However, large commercial farms may encounter the same issues if financial management is poor and leads to shortages of equipment, inputs, services or processing capacity. On some farms, yields and profits are at levels that the owners consider 'good enough'; in these cases, there may be little awareness or interest in the scope for farm improvement, despite there being yield gaps that could be closed and lead to substantial increases in profits. For these farms, complacency and lack of awareness are barriers to achieving higher yields[1]. Complacency is often seen when the farmer is close to retirement and has lost interest in change. Conversely, many farmers are enthusiastic, energetic, financially solvent, competitive, well trained, competent and knowledgeable — and are keen to improve their operations and maximize their agronomic and commercial potential.

It has been proposed that G × E × M could be improved by adding a social (S) component to give G × E × M × S[9]. Although social development is important, we tend to agree with the literature arguing that excessive emphasis on social development may undermine our intended focus on agronomic improvement towards higher yields[10]. The GEM4 framework should be a relatively simple and practical tool focused on agronomic performance. Moreover, 'capability' should be inclusive of constraints and barriers that prevent farmers from following best agronomic practices when all other components of GEM4 are present. For example, poor smallholders are not capable of maximizing their results if they cannot afford high performance seed, apply inputs or use equipment when needed, even when these are available at the right time and at a fair price. Similarly, managers on a large farm may not be able to apply an input on time if their company has an incompetent procurement department. Although the immediate impact on crop yield could be the same in both examples, only one can be considered a social issue (that is, financially constrained smallholders). Thus, we propose that the GEM4 be framed as a tool that identifies the enabling and blocking factors that limit a farm's ability to achieve the best crop performance. When such constraints are identified, further analysis of the broader causal factors creating that constraint may be necessary.

Potential applications of the GEM4 framework

The expanded GEM4 framework proposed here serves as a basis to identify which factors are most important in blocking yield intensification and, thus, may require strengthening and monitoring. Farms, farm advisors and consultants, private investors, and public policy organizations can use this framework as a checklist to identify factors that block yield intensification. For example, if a yield gap is associated with late planting, the GEM4 framework could help to identify the factors that impede farm operators to plant on time and reflect on what can be done to overcome that limitation. These impeding factors may be associated with lack of knowledge about the benefits of early planting on crop yield (in which case, farm operators should consider stronger engagement in technical trainings, participation in farmer networks, hiring competent advisory services and so on) or a lack of the critical goods and services to plant on time (here, purchasing an extra planter and/or hiring a machinery contractor with larger equipment could help). Even farmers who are aware of the benefit of early planting and have the means to do it may fail to achieve the expected yield benefit as they lack the experience needed to implement it correctly (for example, failure to anticipate late spring frost and seed chilling injury or failure to treat seed against the impact of soil pathogens, leading to poor plant stands). Learning from a farm's own experience (and from others) and relentless field testing can help farmers acquire the experience to exploit the benefits of early plantings. Finally, some farmers may have the knowledge, resources and experience but face poor farm logistics and managerial complacency, leading to late planting. In such a case of limited farm capability, auditing and monitoring the whole farm operation would be needed.

Based on the above, the GEM4 framework could also help orient investments in agricultural research and development programmes and inform policy beyond the farm, as proposed by others[9]. However, proper application of the GEM4 framework requires technically knowledgeable agronomists with a solid understanding of cropping systems. Application of this framework can help improve understanding of constraints to yield intensification. This will then aid targeting of actions to moderate those constraints (for example, through research and extension services to solve knowledge problems, or credits to machinery farmers or contractors to obtain improved planters where both knowledge and a shortage of appropriate equipment are impediments to timely planting). Similarly, the GEM4 framework can be applied for ex ante and/or ex post analysis to inform agricultural research and development programmes about key constraints to yield intensification across countries or regions with diverse socio-economic contexts.

The expanded GEM4 framework could help to understand which factors are blocking yield intensification at local, regional and global levels and identify entry points to remove them. Future application and iteration by other stakeholders should further enhance this tool.

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Competing interests

The authors declare no competing interests.

Additional information

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