



Genotype x Environment x Management (GEM) Reciprocity and Crop Productivity

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Human population growth requires food production to increase at a matching pace. Crop productivity largely depends on GEM reciprocity and variation in any factor may potentially alter the overall response. Introduction of improved cultivars causes interactive responses within the farming system which may produce tangible benefits only in the presence of suitable environments and management practices. The yield gap which is defined as the difference between yield potential and average farm yield varies in extent among regions ranging from moderately high to alarmingly high. Variation in environments and management practices impacts both the quantity and quality of produce. The highest gains can be achieved if factors in the interaction model work complementarily. System efficiency indicators are useful for assessing the overall system performance. In the face of new challenges plant breeding is receptive to shifts in objectives and strategy. Extension experts are trained to transfer technology and help farmers optimise for better gains. The extension service is also crucial for feedback to researchers. Better crop management has helped realize the genetic potential of crop cultivars in specific settings. Once a productivity plateau has been reached following optimization of management practices for specified environments, then further improvement of the system can be attained through new genetic interventions. For higher productivity a stronger linkage among researchers, extension experts, and farmers is vital. To help the decision support systems GEM interactions need precise scientific analysis and interpretation. A general account rather than a specific view on GEM reciprocity is presented.

Keywords: crop productivity, GEM reciprocity, factor interactions, cultivars, environments, management practices, protected cropping, extension services

BACKGROUND

Genotypes, environments, and management practices are the factors that determine crop productivity (Beres et al., 2020). These factors need to be optimised precisely to attain best crop performance as variation in any factor could result in a swayed response. A detailed discussion of the various factors that influence this interaction follows:

GENOTYPIC SELECTION

Crop cultivars are generally compatible with specific environments and management practices (Kang, 1998). To select cultivars for a specific cropping system the growers need the best available genetic materials, ideally bred locally for these conditions. Improved crop cultivars grown in the right environment using optimized management practices will offer the highest value to the farmer (Monjardino et al., 2019). Nevertheless, examples of broad adaptation show that crop cultivars can be bred in one location and released and grown extensively in another (Trethowan et al., 2001; Trethowan et al., 2003). Such broad adaptation arose from the Green Revolution and the deployment and release of semi-dwarf wheat and rice cultivars globally (Trethowan et al., 2007; Oladosu et al., 2017). These gains were realised across a wide range of environments. However, recent gains in productivity of major crops have been much lower and future gains will likely be environment specific (Monjardino et al., 2019), requiring exploitation of the GEM interactions. Farmers may need to have a relatively large set of crop cultivars available to them to select one most suitable for the site.

Subsistence farmers grow produce locally that is used domestically, whereas corporate farmers tend to produce bulk commodity for national and even international markets. The quantity and quality of the produce, therefore, determines its market value which translates into cost-benefit ratios of the farming system.

Genetic diversity helps genetic gain among progenies [Yunbi et al., 2017], and lack of diversity or overlapping of genetic materials may lower the gain. When comparing BC1 and F2 foundation populations derived from 18 different crosses of adapted and exotic maize dent lines a study showed that repeated recombination of F2 had non-significant effect on mean performance and variance (Simic et al., 2003).

C3 AND C4 CROPS

Rising atmospheric CO₂ is driving temperatures and causing water stress which may impact future crop productivity. Simultaneously the CO₂ rise has some beneficial aspects for the crops and C₃ crops may directly increase photosynthesis by elevated CO₂ however C₄ crops may benefit in times and places of drought stress (Leakey, 2009).

Many studies recognize the primary role of temperature in determining the C3/C4 distributions and the success of the crossover temperature model in predicting these distributions. The studies acknowledge that most of the C4 plants were restricted to the herbaceous growth habit (Still et al., 2003).

An investigation involving maize, sorghum, winter wheat, and soybean crops conducted under full irrigation regime reported that the crop water productivity for C4 crops was 89% higher than their C3 counterparts (Kukal and Irmak, 2020).

With the discovery of C4 mechanism a couple of decades ago, an interest emerged in the research community to introduce this

mechanism into C3 crops for higher productivity. The progress so far has been slow due to complexity of the processes involved (Cui, 2021; Covshoff and Hibberd, 2012). It is hard to estimate the exact time frame to change C3 anatomy and integrate the C4 photosynthetic cycle since C4 engineering hinges on more precise genome modification technologies, harmonious introduction of multigene set up into the plant, and ability to control gene expression in space and time (Schuler et al., 2016).

ENVIRONMENTS

Crop yields are affected by soil type, tillage, climate, and the farmer decisions on crop management, crop choice and varietal selection. Various factors outside the control of farmers and landscape characteristics also significantly affect the yields (Bommarco et al., 2013; Perez-Alvarez et al., 2018). While reviewing the factors influencing crop yields Liliane and Charles (2020) suggested that yield influencing factors other than crop choice and varietal selection, could be grouped into three broader categories; a) technological (agricultural practices, managerial decision, etc.), b) biological (diseases, insects, pests, weeds), and c) environmental (climatic condition, soil fertility, topography, water quality, etc.).

Atmospheric Temperature

Atmospheric temperature is an important determinant of plant development. Both extremely high and low temperatures adversely affect crop growth (Wahid et al., 2007). Under high temperatures the phenological development of plants is accelerated (Hatfield and Prueger, 2015). High temperature adversely affects pollen viability and fruit setting in tomato (Aref and John 1995) and other crops (Devasirvatham et al., 2013; Jha et al., 2014). High temperature stress lowers the sugar content of fruit, flower maintenance, and fruit quality and quantity is reduced (Alsamir et al., 2021).

The optimum temperature for growth varies among species (Hatfield and Prueger, 2015). Maximum and minimum temperatures in the 24hr cycle influence plant development depending on the severity of the temperature. The difference in night and day temperature significantly affects growth in ornamentals (Ohtaka et al., 2020) and other crops (Devasirvatham et al., 2016).

Solar Radiation

Solar radiation provides light and heat for photosynthesis. Poor solar radiation undermines photosynthesis whereas suitable conditions help achieve higher productivity (Aguilera et al., 1999). The relationship between intercepted solar radiation and biomass production is presented in **Figure 1**.

Although under low intensity solar radiation growth is slower compared to optimum levels, high intensity solar radiation may stress the plant, impacting growth and development. The solar radiation intensity utilised by plants for photosynthesis ranges from 379 to 710nm, and the PAR fraction is place and time specific (Amthor, 2010).

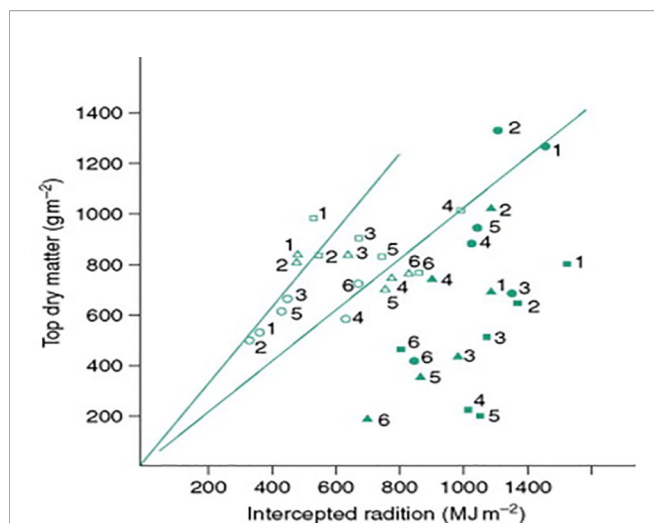


FIGURE 1 | Relationship between biomass produced and amount of solar radiation intercepted by rapeseed crops between sowing and flowering (open symbols) and between flowering and harvest (closed symbols). Different symbols denote different cultivars and numbers next to each symbol indicate order of sowing. Lines drawn indicate RUE 1.0 and 1.5 gMJ^{-1} . (Adopted from: Mendham et al., 1990).

Solar radiation also determines crop phenology and ultimate production (Villegas et al., 2016). The prevalent solar radiation impacts the cropping system of a region (Xia et al., 2014). However, significant variation among genotypes for the induction of photosynthesis in varying levels of light has been observed, indicating that this trait can be optimised genetically in some species (William et al., 2019). Thus, G can be manipulated and to a lesser extent M in the GEM interaction to optimise the use of light.

Soil Media

Productive cropping requires suitable soils (Berg and Smalla, 2009). Soil provides anchorage and supplies aeration, nutrients and water to the roots (**Figure 2**). However, soils differ in their mineral elements and enzymes (Quan and Liang, 2017) and different plant species respond differently to various soil types (Markham et al., 2009). Favourable root environments can allow crop cultivars to express their maximum genetic potential (Abdul-Khalil et al., 2015).

However, greenhouse crop production required a suitable growing medium and unlike field production, the medium used is homogenous. Shallow depth and limited volume of the container necessitates amendment of the growing medium to provide appropriate physical and chemical properties for plant development. Field soils are generally unsuitable for plant production in containers, primarily because they do not provide the adequate aeration, drainage and water holding capacity. Several “soilless” growing medias have been developed to solve this problem (Aggie, 2021). For enhanced plant performance, the depths and attributes of various substrates need to be carefully considered when designing the root media (Kazemi and Mohorko, 2017). However, the E and M

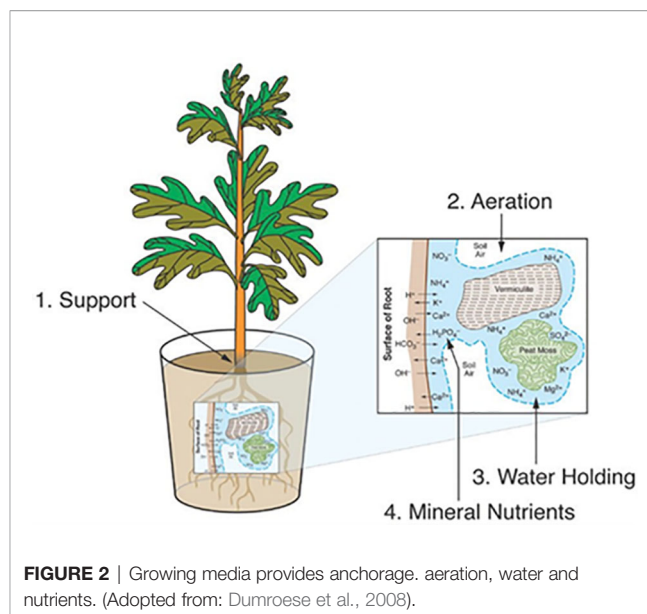


FIGURE 2 | Growing media provides anchorage, aeration, water and nutrients. (Adopted from: Dumroese et al., 2008).

components of the GEM interaction can be controlled in these systems. Thus genetics is the primary way to increase productivity once these factors have been optimised.

Other Environmental Factors

Relative humidity is an important factor which impacts rice response to temperature (Stuerz and Asch, 2021) and is likely to impact other crops. High relative humidity favours plant growth, however, the response was stronger in light compared to dark conditions (Hirai et al., 2000). The number of flower and boll production in cotton was positively correlated with lower humidity (Sawan, 2018). Atmospheric CO_2 also affects plant development; however, the response is complex. Increasing CO_2 will likely increase plant growth and yield (Taub, 2010; Reddy et al., 2010), but the associated impacts of higher temperature and more intense drought will likely negate any benefit (Bloomfield et al., 2019). In these instances, the E component of the GEM interaction will likely drive plant responses.

CROP MANAGEMENT

Water, nutrients, and plant protection are essential for successful crop production. Effective crop management needs precision agriculture principles to be effectively adopted. With precision agriculture new technologies are adopted that use inputs more efficiently and increase production (Finch et al., 2014). Three major precision agricultural technologies include GPS guidance machine control systems, GPS yield and soil maps, and variable-rate input application technologies (USDA, 2021). The precision agriculture technology adoption in USA is illustrated in **Figure 3**. However, there can be significant genotype \times management practice interaction and these should be optimised. For example, sowing crops on raised beds can improve irrigation efficiency of rice and wheat crops (Kukul et al., 2010). Nevertheless, this change required cultivars that

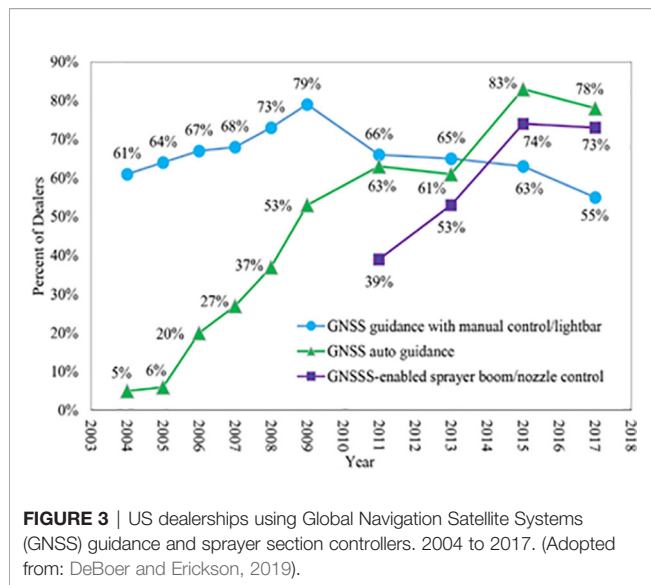


FIGURE 3 | US dealerships using Global Navigation Satellite Systems (GNSS) guidance and sprayer section controllers. 2004 to 2017. (Adopted from: DeBoer and Erickson, 2019).

had spreading canopies rather than the upright habits better suited to sowing in dense stands on flat land (Fischer et al., 2019).

BEST MANAGEMENT PRACTICES AND CONSERVATION PRINCIPLES

Agricultural practices to improve growth, development and crop yields are referred to as crop management. The management practices include seedbed preparation, sowing of seeds, addition of fertilisers and manures, irrigation, crop care and harvesting, storage of the produce and marketing. Best crop management practices help improve productivity and contribute to greater profitability.

The term “best management practice” is used in a variety of contexts and it flexibly transforms its objectives depending on the situation across different crops and geographic regions. Not every best practice is suitable universally and the adequacy may vary across geographic borders. Some widely used best management practices (Singh et al., 2021; Mahmud et al., 2021; Dhaliwal et al., 2021; Liava et al., 2022; and Cottney et al., 2022) for better crop productivity, profitability, and environmental protection may include:

- conservation tillage
- contour farming on slopy lands
- erosion and sedimentation control
- cover cropping
- use of better adapted cultivars
- integrated pest management
- irrigation and nutrient management
- crop rotation
- rotational grazing
- effective marketing
- waste management
- wildlife habitat management

GEM INTERPRETATIONS

Effects due to various factors in the GEM equation will need to be explained carefully when interactions are observed to be significant. It is likely that these interactions are region or even farm specific and will require expertise to interpret in consultation with the farmer. A simple illustration of a three-way interaction is presented in **Figure 4**. In most cases, the farmer can optimise the G and M components of the interaction using the most probable E (based on long-term records) as the baseline.

YIELD GAP

The yield gap can be defined as the difference between yield potential and average farm yield expressed in kg ha⁻¹ (Aggarwal et al., 2008). Innovative and efficient use of resources can increase farm profitability and enhance the system sustainability. Significant yield gaps in different crops have been reported in Australia (**Figure 5**), but the extent may differ in different countries. Clearly, optimal selection of genotypes and management practices for the most probable environment type in any region will decrease yield gaps in most years. Interestingly, on farm wheat yield has been relatively static in Australia for many years (<https://www.csiro.au/en/news/news-releases/2017/australias-wheat-yields-stalled> Retrieved 28.05.2021). However, this statistic did not tell the whole story. The production environment over the period of the study has also declined due to climate change. Farmers were able to maintain productivity under these conditions by adopting better management practices, such as reduced tillage, and better adapted cultivars (Chancellor et al., 2021).

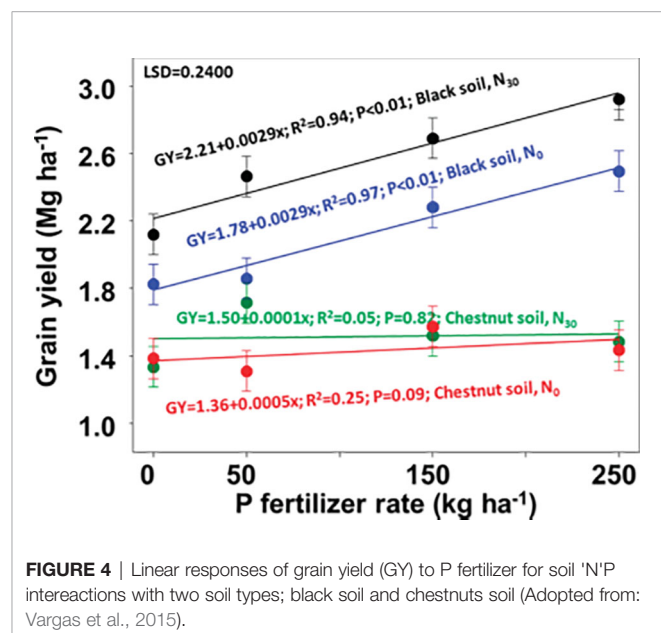
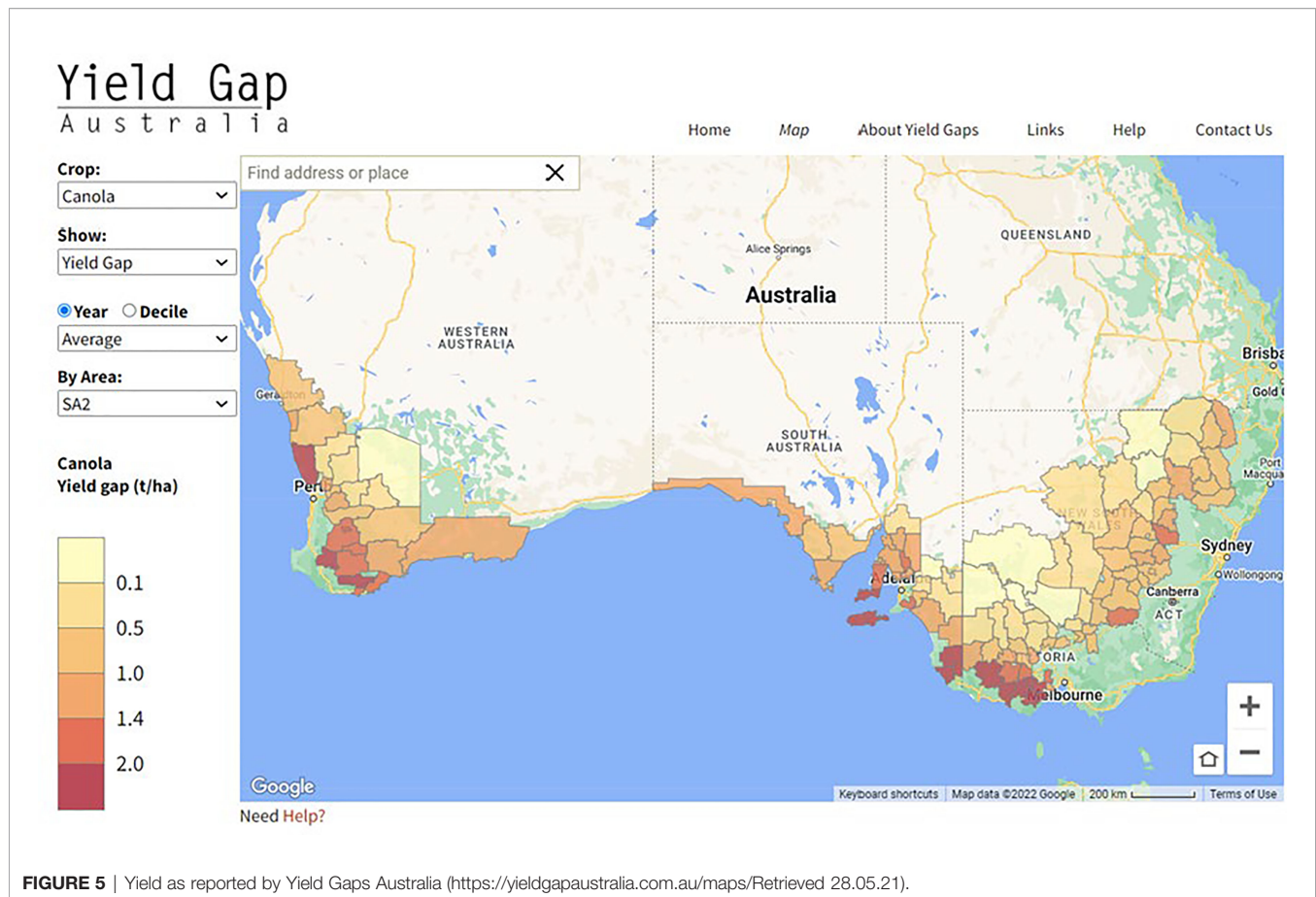


FIGURE 4 | Linear responses of grain yield (GY) to P fertilizer for soil 'N'P interactions with two soil types; black soil and chestnuts soil (Adopted from: Vargas et al., 2015).



A web based interactive application on yield gap with various crops has been presented by Yield Gap Australia.

environment type for the farm or region. This provides a baseline estimation of E.

BRIDGING THE PRODUCTIVITY GAP

At farm level, the following guidelines can help improve efficiency and productivity:

- Evaluation of local adaptation trials. Many countries have national trial networks for the identification of cultivars for release. Extension staff could help interpret these results or organise independent testing. This will help identify suitable G.
- Factors needing improvement could be identified periodically at the farm level through regular monitoring. These include rates of fertilizer and chemical applications, tillage practices, controlled traffic and crop rotations to manage diseases and fertility. This will help optimise M.
- Access information from extension professionals, field days and demonstrations, handouts, online data and contact with successful early technology adopters (Figure 4).
- Maintain good farm weather records long-term. These records, when combined with regional records provided by the Bureau of Meteorology, provide estimates of the likely

CAUSES OF YIELD GAP

Causes of yield gap vary among crops and regions. One example each from Australia and Pakistan representing widely different locations and socio-economic backgrounds is briefly discussed here.

AUSTRALIAN FARMING

Australian farming is characterised by large farm size and mechanised operations (Sheng and Chancellor, 2019; Australia Agronomy, 2019). A systematic study using the shire-level data found high yield gaps in Australia and on average a yield gap of 55% was reported (Hochman et al., 2016). The yield gap could be tackled by addressing the causes using improved technologies including new varieties, new agronomic or management techniques, and timely decisions by the farmer. The national crop variety trials are generally conducted using the best current management practices in the country and therefore demonstrate

the best available technologies locally. Limited knowledge with farmers regarding causes of yield gap is a major reason of low progress but shortage of resources to implement the technological advancements is also evident in certain instances (Fischer et al., 2014). **Figure 6** elaborates the progress with yield gap in Australia over time.

PAKISTANI FARMING

Small farm size and low mechanisation is a dominant feature with Pakistani farm sector (Rehman et al., 2016). Although yields have improved recently the yield gap has shown little improvement in the country (CIMMYT, 2021). Out of grain crops the highest yield gap was recorded in Maize, followed by wheat and rice (Khan et al., 2021) with only 42% of the current potential yield harvested in wheat (ZTBL, 2020).

The crop production constraints are diverse; some are regional while others are crop specific or may arise from the socio-economic background of the farmers. Some general constraints include soil fertility, poor weed management, soil degradation, drought stress, poor crop protection, financing problems, and poor marketing. In Asian rice-wheat system factors including late planting, heat during grain fill, weed competition, leaf and stem fungal diseases (other than rusts), use of unsuitable variety, unavailability of quality seed, inadequate farmer training, soil fertility depletion, inappropriate use and management of fertilizers accounted for 47% of the yield gap (Waddington et al., 2010). The study identified many interactions and cause and effect relationships which accounted for rest of the 53% yield gap.

Unavailability of inputs and high input costs, limited access to credit facilities, and adverse weather conditions are common in some developing countries (Quddus and Kropp, 2020) including Pakistan. Other constraints in developing countries may include, crop damage by wildlife, human disease pandemics, and lack of

infrastructure to transport produce (Makuvaro et al., 2017). These constraints generally impact G and M in the GEM interaction.

CROP QUALITY, VALUE ADDITION AND MARKETING

The crop quality, value addition, and better marketing bring dividends to the farmers. However, to reap those dividends farmers need to be trained with best practices. Izaba (2021) analysed factors determining value addition, and market access and suggested that market access along with farm size, farmer's networks, farmer's perceptions, and employment growth influences were the significant drivers to value addition technology adoption. It was noticed that farmers adopting value addition technologies tended to experience economic growth.

Barriers with establishing a value-added business could be categorised as: regulations, resources, and marketing. Farmers perceive regulations as complicated, ambiguous, and restrictive (Chen et al., 2021).

CROP TECHNOLOGY ADOPTION INDICATORS

The efficiency of a GEM system may be analysed by assessing its various components individually. Although the individual assessments may only partially portray the GEM efficiency, they still indicate the progress made in the technology adoption process. A diligent efficiency analysis will help monitor the system more effectively (Olesen et al., 2011).

GEM system includes genetic factors (e.g. crop cultivars), environments (e.g. growing conditions), and crop management (e.g. various inputs). Better quality produce may deliver higher dividends and marketing techniques including better presentation,

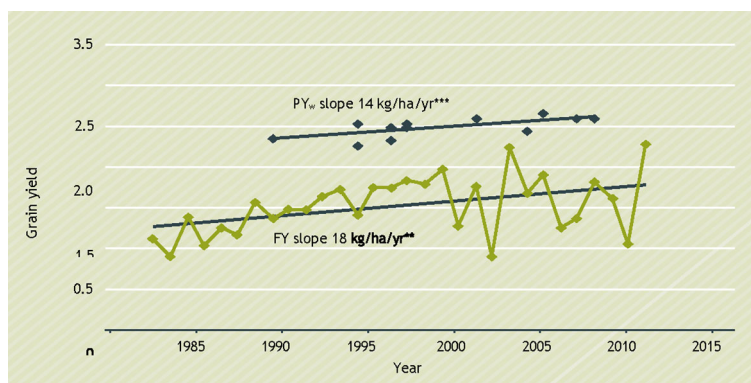


FIGURE 6 | Progress with farm grain yield (FY) and water-limited potential grain yield (PY) of spring wheat in Western Australian over time. PY plot shows progress against year of variety release. The slope difference between FY and PY indicates the yield gap reduction over the years (Source: FY from ABARES (Australian Bureau of Agricultural and Resource Economics and Sciences (2012) and PY from NVT (National Variety Trials) (2009). Adopted from Fischer et al., 2014. **0.01. < $P < 0.05$, *** $P < 0.01$).

value addition, and the right time of marketing were important (Cucagna and Goldsmith, 2018). As corporate farming aims at higher profits it seems prudent that the GEM system also factors in the marketability of the produce.

Adoption indicators depict the effectiveness of the adoption process. The process is considered effective when farmers benefit adequately. The various indicators are summarised in **Table 1**.

BEYOND THE ADOPTION OF BEST PRACTICE

Most crop production systems generally use sub-optimal management practices, although these are often better implemented in protected environments. Protected cropping uses modified growing conditions providing protection from pests, diseases, and adverse weather. Protected cropping could increase profitability and productivity through high-value fresh produce (DPI, 2021). Maintaining best practices under protected environments helps maintain high productivity but how to bring further improvement when at plateau?

Further improvement may require a new genetic intervention which is superior to previously available options. These new cultivars will give rise to a new GEM reciprocity and help the system evolve positively. Through repeated cropping cycles the system will gradually improve and lead to higher productivity.

CONTEMPORARY PLANT BREEDING AND GEM RECIPROCITY

Successful breeding strategies assisted the development of crop cultivars that helped the Green Revolution materialise in the 20th

century (Pingali, 2012). Plant breeding helps improve crops by refining the genetic makeup of the plants. Various authors have defined plant breeding objectives and suggested crop improvement strategies recently (Trethowan et al., 2010; FSANZ, 2013; Messmer, 2015; Allard, 2019).

Traditionally, improved cultivars have better agronomic type, tolerance against abiotic and biotic stresses, shorter maturity period, capacity to compete with weeds, lower water usage, and improved quality (Baenziger et al., 2006). Food crop cultivars are also required to have high yield, meet dietary standards and be compatible with the prevalent cropping systems (Pfeiffer and McClafferty, 2007). Contemporary plant breeding needs to address sustainability, lifestyle changes, and overall productivity of the systems (Voss-Fels et al., 2019; PFMPB, 2021; Hong and Jiayang, 2021). To respond to these challenges contemporary plant breeding needs to promote:

- Cultivars promising higher productivity both in the open field and under protected cropping. Reducing the genotype-phenotype gap is vital for improved productivity.
- Cultivars compatible with sustainable farming systems (organic farming, conservation agriculture).
- Cultivars responsive to higher atmospheric CO₂ concentrations.
- Conservation of crop genetic diversity.
- Efficient use of plant breeding tools including transgenics, genomics, and genetic code editing.
- Improved systems of data capture, management and use including machine learning.
- Mechanical tools to deliver speedy and cost-effective cropping operations.
- Multidisciplinary research to deliver more effective outcomes.

TABLE 1 | GEM adoption indicators.

Productivity factors	Three broader GEM adopter categories		
	Beginner (learning about available technology)	Progressor (making progress)	High achiever (made progress and achieved high)
G – Cultivars	Learning about available cultivars	Used the best available cultivars and making progress	Consistently used the best available cultivars and achieved high
E – Growing conditions			
1. Temperature: a) low b) medium c) high	Learning about the available temperature regimes	Adopted the best available temperature regime and making progress	Consistently adopted the best available temperature regime and achieved high
2. Solar radiation: a) low b) medium c) high	Learning about the available solar radiation windows	Made use of the best available solar radiation window and making progress	Consistently made use of the best available solar radiation window and achieved high
3. Soil or soilless: a) field b) greenhouse	Learning about the available soil/substrate options	Adopted the best available soil/substrate regime and making progress	Consistently adopted the best available soil/substrate regime and achieved high
M - Management			
1. Irrigation: a) rainfed b) irrigated	Learning about the available irrigation options	Adopted the best available irrigation regime and making progress	Consistently adopted the best available irrigation regime and achieved high
2. Nutrients: a) chemical fertiliser b) naturel fertiliser	Learning about the available nutrient/fertilizer options	Adopted the best available nutrient/ fertilizer regime and making progress	Consistently adopted the best available nutrient/fertilizer regime and achieved high
3. Crop protection: a) through chemicals b) through cultural practices	Learning about the available crop protection options	Adopted the best available crop protection regime and making progress	Consistently adopted the best available crop protection regime and achieved high
Value addition and marketing (both quantity and quality of the produce were important)			
Marketing skills: a) average b) improved c) high	Learning how to increase market value of the crop	Adopted the best value practices and making progress	Consistently adopted the best value practices and achieved high

AN APPROACH TO ADDRESS GEM RECIPROCITY

Various conditions including temperature, solar radiation, and soil media define the crop environment. These conditions generally go uninterrupted under field settings. However, under protected cropping such conditions could be optimised to meet production targets (FFS, 2021). Ideally crop management needs to follow the production protocols specified when releasing the cultivars (Zabel et al., 2021). As conditions like temperature, light intensity, and soil substrate are manageable under protected cropping the interaction effects could be better designated as GxM rather than GxE interaction. To better explain the interactions Cooper et al. (2021) suggested a split of the GEM model into (GxM)xE components.

The GEM model depicting wider interactions in the system was proposed by Hatfield and Walthall, 2015. The model defines the boundaries of the interactions and may provide scientific explanations to researchers, extension experts and farmers who have been working to explain the complexity of the interactions differently (Hoffmann et al., 2007).

Multiple layers of each factor exist in the system and interactions within the GEM model need to be studied and explained holistically. To precisely explain the interactions, input from a whole spectrum of disciplines including plant breeding, agronomy, plant protection, biometry, engineering, food science, and extension is needed.

Precise scientific response to GEM analysis was possible once all possible interactions in the system were adequately explained and sources of low and high performance identified. For further elaboration a typical example from a small farm is presented (Table 2). The farmer at this typical farm adopted certain practices (bold faced) but it was uncertain if these practices were optimal at this specific site. A logical way to determine this could be to generate data through well planned GEM experiments at the farm. With three factors, each having multiple layers, the precise analysis would be a challenge. However, decoupling factors into GxE, GxM, and ExM components may help explain the interactions (Walthall et al., 2016). Interestingly, splitting the multi-layered GEM model into components may only partially explain the interactions.

To attain maximum productivity in a GEM system researchers and extension experts need to work closely with the farmers (Shelton and Tracy, 2016), to identify a precise production technology for every individual cultivar (Passioura, 2020).

Although extension is generally considered a one-way process in which the extension experts transfer technology and new ideas to farmers, feedback from farmers to extension and research experts

can be vital. Effective linkage between extension experts and researchers also represents a two-way process that could enhance productivity. The two-way flow of ideas could happen at the time a problem is defined, when testing the recommendations, and when recommendations are adopted (FAO, 2021a).

Agricultural extension is regarded as a broader knowledge system that includes research and agricultural education. FAO and the World Bank refer to this larger system as AKIS/RD (Agricultural Knowledge and Information Systems for Rural Development) (FAO, 2021b).

Defining a comprehensive model to analyse the interactions holistically is a challenge (Cooper et al., 2021). Collaborative work among researchers, extension experts, and farmers may not adequately explain various interactions unless scientific analysis at every stage of the process was made available.

More scientific explanation on GEM reciprocity is required. However, this should not stop coordinated efforts to get stakeholders work together to develop site-specific transition strategies. To address the needs of the system, the slightly different approaches used in each region must be understood (Hoffmann et al., 2007) as their likelihood of success will vary.

Traditionally research and extension have been in the public sector in Australia. Recently, the balance shifted away from the public to private sector. Currently, research and extension exist in a shared domain between the private and public sectors (<https://rirg.fvas.unimelb.edu.au/ag-extension/home> Retrieved 11.09.2021). The private sector is an active part of crop research, and extension and is considered to be a reliable source of information on crop R&D (RIRG, 2021a).

In the absence of a ready to use scientific solution for explaining interactions at every level, a step by step strategy has emerged. The Australian system used a strategy which is gradually improving (DAWE, 2021a). The Australian farming system is evolving under increasingly hostile production conditions, yet crop productivity has improved significantly over time (DAWE, 2021b).

Operating a private-public sector partnership, the Australian system allows researchers and extension staff to work under the same umbrella or in the same team. Farmers are part of the consultative process during the formulation of research and extension strategies (RIRG, 2021b). New technology is rolled out through extension experts who conduct demonstration trials before adoption in farmer's field. Demonstration sites form an important bridge between agricultural research and the adoption of the new technology through site specific testing and evaluation at commercial scale (AFA, 2021). The Australian and other similar examples (FM, 2021) may help pave the way for more responsive strategies to improve productivity of diverse GEM systems.

TABLE 2 | Factors involved in a GEM system at a broadacre crop production farm.

Factor 1 – Cultivars	Factor 2 – Environments	Factor 3 – Crop management
Cultivars – V1	- Natural temperature windows – 1) High, 2) Medium , 3) Low - Soil texture –	- Irrigation options – 1) Rainfed, 2) Irrigated - Fertilizer regimes –
V2	1) Clay, 2) Sandy loam , 3) Sandy - Soil fertility gradient at the farm –	1) Chemical fertilizer , 2) Green manure, 3) Cow manure - Crop protection –
V3	1) High fertility , 2) Medium fertility, 3) Low fertility - Solar radiation windows –	1) Chemicals , 2) Cultural practices
V4	1) High radiation, 2) Medium radiation , 3) Low radiation	

The bold values may represent the typical practices at a crop production farm.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

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AUTHOR CONTRIBUTIONS

TM developed the concept and prepared the manuscript. TA and RT contributed towards improvement of the original ideas. All authors contributed to the article and approved the submitted version.

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