# Modeling genotype × environment × management interactions for a sustainable intensification under rainfed wheat cropping system in Morocco

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## Abstract

Under the conditions of Moroccan rainfed agricultural areas, wheat cropping systems—the population's basic staple food—are subject to a set of limitations that seasonally impact crop production and farmers' incomes, thus national food security. In the last decades, the major constraints were often related to the country's Mediterranean-type climate, through the intense recurrence of drought events and high inter- and intra-annual rainfall fluctuations. Similarly, various forms of soil degradation inhibit the potential of this slowly renewable resource to support wheat crop intensification and ensure livelihoods. However, the limitations sometimes surpass the environmental factors to implicate the inappropriate crop management strategies applied by farmers. In Moroccan rainfed areas, production problems linked to crop management practices result principally from a shortage in the provision of knowledge to Moroccan small farmers, or their indigent economic situation that limits farmers' capacity to adopt, qualitatively and quantitatively, efficient strategies. Advanced technologies (remote sensing or crop modeling) play key roles in assessing wheat cropping systems in Moroccan rainfed areas. Due to the difficulties of using conventional experience-based agronomic research to understand Genotype × Environment × Management (G × E × M) interactions, the substantial benefits of crop modeling approaches present a better alternative to provide insights. They allow the provision of simpler, rapid, less expensive, deep, and potentially more accurate predictive knowledge and understanding of the status of cropping systems. In the present study, we highlight the constraints that surround wheat cropping systems in Moroccan rainfed conditions. We emphasize the efficiency of applying crop modelling to analyze and improve wheat cropping systems through three main themes: (i) preserving food security, (ii) supporting general adaptation strategies to face climate change effects and extreme events, and (iii) recommending within-season and on-farm crop management advice. Under Moroccan context, crop modeling works have mainly contributed to increase understanding and address the climate change effects on wheat productivity. Likewise, these modeling efforts have played a crucial role in assessing crop management strategies and providing recommendations for general agricultural adaptations specific to Moroccan rainfed wheat.

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## Introduction

Between 720 and 811 million people worldwide are food insecure [47], and 194.6 million pre-school children (under 5 years) are malnourished [144]. The world's future challenges are to ensure that there is enough food and to generate adequate income to better feed the poor and hungry people, and thus reduce the number of those suffering food insecurity [116]. The anticipated growth in the global population, which was projected to reach 8 billion in November 2022, will make this challenge more difficult [143], putting even greater pressure on global food security, especially in developing countries that have witnessed a population increase of more than 80% since 2000. Agriculture plays a key role in economic development, poverty reduction, and economic growth. Every 1% increase in agricultural yield translates to a 0.6–1.2% decrease in the percentage of absolute poor [153]. In sub-Saharan Africa, for example, agriculture accounts for more than 35% of the gross domestic product (GDP) of many countries (Mali, Niger, Chad, Liberia, etc.) and employs 53% of the population [157] (https://data.world bank.org/indicator/).

Rainfed agriculture plays a crucial role in global food production as 85% of agricultural lands are rainfed [113, 116] (Table 1). About 60% of the food needs of the world's population are met by produce from rainfed croplands, and this agriculture employs approximately 60% of the population, which plays an important role in reducing poverty [15, 114]. While the importance of rainfed agriculture varies by region, it shares the substantial service of providing the majority of food for poor communities in developing countries. Almost all agricultural lands in sub-Saharan Africa are rain-fed, compared to 70% in the Middle East and North Africa [157]. Rainfed croplands are a future alternative arena for decision-makers and researchers to ensure food security by creating chances to boost productivity and crop intensification due to the current reported low yield levels and their variability [15].

According to the Fifth Assessment Report from the IPCC, the average combined land and ocean surface temperature has increased globally by 0.85 °C during the period 1880 to 2012 [66]. Due to more frequent extreme weather conditions, such as droughts and floods, crop production has been increasingly impacted, especially in rainfed environments, where crop production and irrigation water depend highly on rainfall [53, 122]. Drought is the consequence of a "deficiency of precipitation over an extended period of time resulting in water scarcity"; therefore, rainfed croplands are more vulnerable to drought in semi-arid and arid areas [67]. In addition, there is a cause-and-effect relationship between drought and land degradation, which are the primary drivers of poverty in rural areas. [114, 153]. The soil serves as a buffer in rainfed agriculture, storing water during a short drought period and making it available to plants. This highlights a narrow window of opportunity for increasing crop productivity and sustainability through effective strategies for managing soil and water in rainfed areas [15, 122]. The rainfed agricultural systems in the Mediterranean are among the most significant cases of rainfed agriculture [122]. Most of the Mediterranean region falls within the arid and semi-arid rainfall zones [37]. The agriculture in this area is regarded as the most water-stressed in the world with significant inter- and intra-annual variation in rainfall distribution, typically concentrated in the autumn and winter seasons, and dry and hot springs and summers [2].

## Rainfed agricultural production systems in Morocco: importance and constraints

Due to the geographic configuration of Morocco, agriculture areas are confined within the borders of the mountains and the seas and are highly influenced by climatic factors, mainly rainfall [9]. The area of Morocco is 710,850 km$^2$, most of which is in an arid to semi-arid climate (200 to 400 mm). Water supply in Morocco is entirely dependent on precipitation, unlike countries of the Middle East and Eastern and Central Africa. Moroccan agriculture is highly dependent on rainfall, with rainfed croplands accounting for 81% of the utilized agricultural area (UAA), or 7 million hectares [36, 88]. Consequently, crop productivity heavily depends

**Table 1** Land area and population distribution according to hydro-climatic zones and land-use

| Region | | Area (% of total world land area) | Population (% of total world population) |
|---|---|---|---|
| Hydroclimate | Arid | 23 | 7.2 |
| | Semi-arid | 18 | 16 |
| | Dry sub-humid | 9 | 13 |
| | Total | 50 | 36 |
| Cropland use | Rainfed agriculture | 11 | 28 |
| | Irrigated agriculture | 2.1 | 19 |
| | Total | 13.1 | 47 |

(Data source: Rosegrant et al. [116]; World Bank, [157]

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on the amount and distribution of rainfall. Any rainfall deficiency has an immediate detrimental effect on the nation's water supplies, agriculture, and the economy of the country. The frequency of dry agricultural seasons has increased fivefold in Morocco, going from one dry year out of 15 normal years during the 30 s, 40 s, 50 s, 60 s, and 70 s, to one dry year out of three during the last two decades (Fig. 1, Balaghi, unpublished). Depending on their nature and varied intensity, these droughts have had substantial effects on agriculture and on the economy of the nation. Moreover, Morocco is recognized as a "hotspot" for anticipated climate change scenarios, and is predicted to have 20% reduced rainfall as well as a temperature increase of 2 °C by 2050 [65, 123]. Consequently, Moroccan rainfed agriculture needs to be given more attention because of its greater vulnerability to climate change compared to irrigated agriculture.

Agriculture plays a vital role in Morocco's economy (12–14% of GDP between 2008 and 2018 and 38% of employment in 2018), and any temporal or seasonal variation of the climate will immediately affect agricultural production, particularly for crops that provide the foundation of the food supply [88]. The most important food resource is cereals, and wheat is the most commonly produced cereal in the nation [9, 93]. National wheat production has improved over the years. However, this improvement was insufficient to cover the fast-growing population's needs. Cereal imports have been consistent since 1980, by representing nearly 48.7% of the national annual produced amount, and most of the imported food products and import costs [9].

The Moroccan Ministry of Agriculture has divided the rainfed croplands into six agro-ecological zones according to their production potential: Favorable, Intermediate, Unfavorable South, Unfavorable East, Mountainous, and Pre-Saharan and Oasis areas (Table 2). Average cereal yields have increased from 0.5 to 1.5 t.ha$^{-1}$ in the last 20 years. The coefficient of variation in cereal yields over this period has been around 40%. As expected, most of the yield variation is in the less favorable growing areas. For example, the coefficient of variation of cereal yields is over 70% in the pre-Saharan and oasis zone and around 40–50% in the mountainous and unfavorable southern regions. In contrast, yield variation is only about 24% in the favorable region [130]. Overall, cereal

**Table 2** Agro-climates of Morocco [9]

| Agro-climate | Rainfall (mm) | % Surface | Cereal production (%) |
|---|---|---|---|
| Favorable | >400 | 30 | 31.1 |
| Intermediary | 300 to 400 | 24 | 16.8 |
| Unfavorable east | 200 to 300 | 12 | 25.5 |
| Unfavorable south | 200 to 300 | 12 | 9.8 |
| Mountain | 400 to 1000 | 15 | 10 |
| Pre-Saharan and Oasis | < 200 | 7 | 4.1 |

production increases are plagued by recurring drought and stymied by low inputs of fertilizers and machinery, as well as low control of diseases and crop pests. Consequently, cereal yields are still low and stagnant in Moroccan rainfed areas [93].

The implementation of improved varieties and effective agronomic management strategies has considerable potential to reduce the huge cereal yield gap in rainfed areas in Morocco [9, 103, 153], and thus sustainably enhance cereal productivity and approach the potential yield for those climatic conditions [125, 149].

## Wheat crop: development processes and abiotic stresses
### Wheat growth and development processes
Plant development is the sum of events, whereby tissues, organs, and the whole plant are produced [135]. It implies three main processes: growth (the effect of cell division and enlargement on cell size and plant organs), morphogenesis (the acquisition of form and structure), and differentiation (plant cells differentiate to perform specialized functions) [3, 30]. The interactions of the environment, the plant genotype, and crop management practices (i.e., G×E×M interactions) determine how the plant develops [86, 126, 155]. Overall, the term "development" refers to all the changes that a plant experiences, from seed germination to senescence. The net $CO_2$ assimilation (i.e. through photosynthesis) at the tissue level constitutes the basis for plant growth. Photosynthesis processes are affected by different factors that depend on the plant development phase as well as
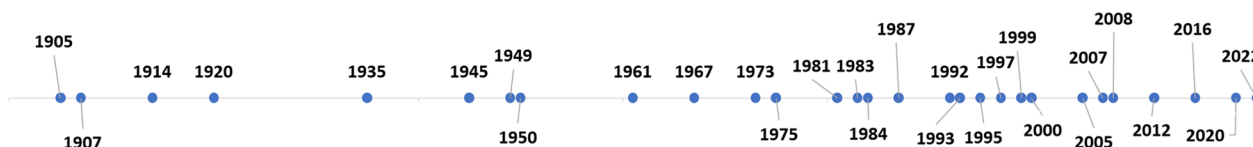


**Fig. 1** History of drought seasons in Morocco

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on environmental characteristics: sunlight and radiation, water, nutrients, temperature, and $CO_2$ [1].

Wheat growth and development processes are complex. During the life cycle of wheat plants, many of the development stages overlap, and while one part of the plant develops, another part dies [100, 127]. Organ differentiation during the cycle defines the wheat development stages [1, 127]. The following development stages for wheat can be identified based on physiological traits: germination, emergence, tillering, stem elongation, booting, heading, anthesis, grain filling, and maturity. The duration of each development stage depends on the $G \times E \times M$ interactions: genotype (species, cultivars), environment (temperature, day length, water, etc.), and management practices (sowing date, fertilization, etc.) [1, 100, 126, 155]. The most commonly used scale to define cereal growth stages, including wheat, is Zadoks Growth Stage Key [162]: the development of the cereal plant is divided into 10 general development phases covering 100 individual growth stages. Individual growth stages are indicated by the prefix Z (Fig. 2).

## Wheat development under abiotic stresses

For optimal crop growth and development, crops need adequate levels of moisture (i.e., accessible water), temperature, nutrients, and $CO_2$, with variations in crop interactions according to the progression of phenological growth phases [17, 64]. Abiotic stress is defined by Cramer et al. [29] as the reversible and irreversible impacts of environmental variables that cause crop growth and productivity to fall below optimal levels. As a result, abiotic stresses that affect plant growth and development include environmental factors, such as heat or cold stress, drought stress, light intensity, salinity, and nutrient insufficiency [3, 17]. The main abiotic stress threats to plant development and yield potentials in the Mediterranean-type environment are heat and water deficiency events, notably for grains [4, 161]. Overall, from germination to flowering, the various types of stress have a significant negative impact on plant growth [3]. In the next section, the effects of abiotic factors on different periods of wheat growth and development are described.

a. Focus on water

A water deficit occurs when water absorption by the crop is lower than water evapotranspiration, which reduces the plant water availability and affects the normal functioning of the plant–soil system [50]. Therefore, three processes determine the soil water status: (i) the amount of applied and available water (rainfall amounts in the case of rainfed areas), (ii) the water absorption level by the crop, which is related to the crop characteristics (species and genotype) and the soil physical proprieties, and (iii) the evapotranspiration process that depends on the atmospheric properties (temperature, radiation, vapor pressure, etc.), on crop characteristics (Kc, Kr, stomatal conductance, etc.) and on soil physical characteristics.
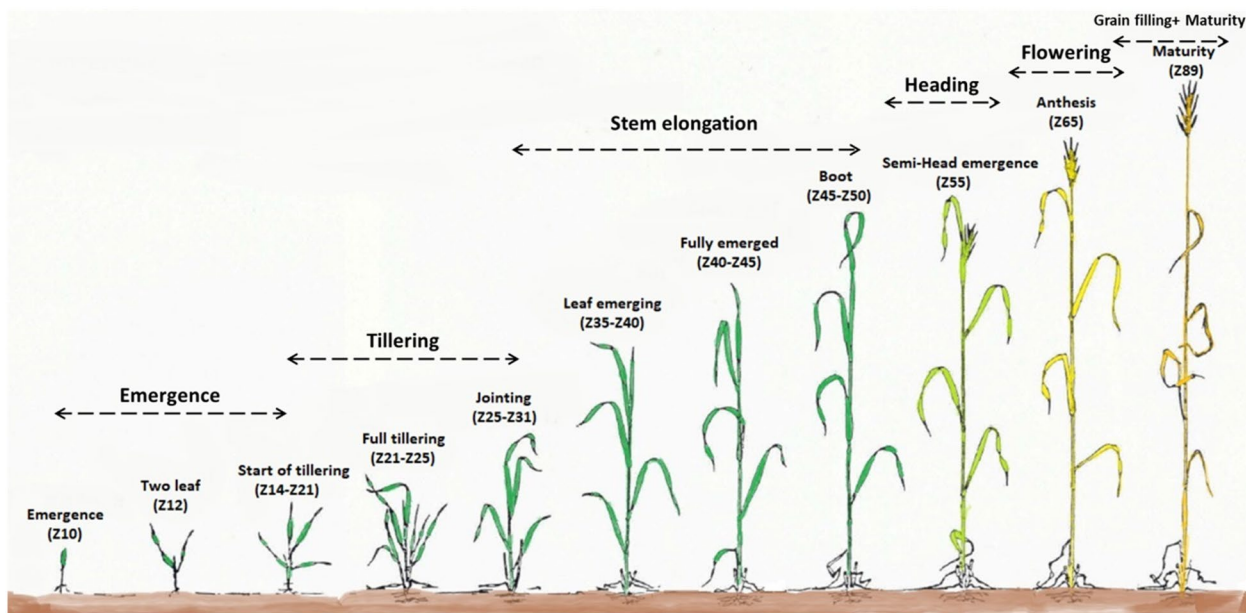


**Fig. 2** Zadoks Growth Stage Key of a wheat plant. Modified from Simmons et al. [127]

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Water stress strongly affects several aspects of plant growth and development: morphology, physiology, biochemistry, and crop productivity [69]. For cereals, a positive correlation exists between evapotranspiration and grain yield [1]. When a wheat plant experiences drought stress, various negative reactions are generated depending on which growth stage the plant is in [147]. Consequently, it is necessary to investigate wheat plant behavior under water stress at various developmental stages:

- Germination and emergence period: plant stability depends on drought resistance during this period. Water availability is a determining factor that prevents seed germination [100]. Early drought indices during the growing season affect wheat germination and crop establishment, influencing final germination rates [147]. Water stress during the germination period leads to a 12% decrease in grain yield [110]. Furthermore, water deficiency affects the emergence phase: hard soil, due to low moisture, inhibits the coleoptile vigor to grow and perforate the surface, especially for wheat varieties with short coleoptile characteristics [100].
- Vegetative growth period: water deficit during the crucial development phases, including the vegetative growth period, leads to a significant loss of wheat grain yield [79, 98]. Low soil moisture combined with heat stress is unfavorable during wheat vegetative growth due to their negative impact on transpiration and photosynthesis processes. Water stress slows photosynthesis and leaf area expansion, reducing dry matter production. It also limits root growth, thus reducing nutrient uptake [16, 62].
- Reproductive and grain development period: during this period, wheat is highly sensitive to environmental stresses, particularly nitrogen and water [160]. The occurrence of water stress and high temperatures during a critical period of 2–3 weeks before anthesis can significantly impact the floret production [55], reducing the number of grains per spikelet, thus affecting the final yield [100]. Wheat's booting and heading are important reproductive stages and are the most sensitive to drought, as heat and water stresses could lead to a drop of 30–90% in wheat grain yield [98, 124]. Similarly, the occurrence of water stress during wheat grain filling stages influences various yield components, mainly grain weight (Table 3) [55]. Moreover, wheat crop exposure to water stress during this period has a significant effect on the quality of wheat grain (i.e., starch and protein contents) [129].

**Table 3** Effect of water stress on wheat leaf area index (LAI), yield components, and water use efficiency (WUE) at various growth stages [55]

| Parameter | Timing of water stress | | | |
| --- | --- | --- | --- | --- |
| | Control | Pre-anthesis | Anthesis | Grain filling |
| LAI at booting | 5.00 | 3.30 | 5.00 | 5.00 |
| Fertile tillers.m$^{-2}$ | 513 | 658 | 434 | 435 |
| Grains/spike | 32.7 | 13 | 27.1 | 31.4 |
| 1000 grain weight (g) | 56.3 | 55.2 | 53.7 | 49.2 |
| Grain yield (g.m$^{-2}$) | 779 | 559 | 498 | 658 |
| Harvest index | 0.52 | 0.50 | 0.53 | 0.53 |
| WUE (kg grain/ha mmET) | 16.8 | 14.6 | 12.4 | 15.2 |

b. Focus on temperature

Temperature is a substantial meteorological factor considered in plant development processes. The computation of grain development rates and the illustration of transitions between development stages, which is typically expressed in terms of accumulated growth degree-days (GDD), revealed the significance of temperature variables (maximum, minimum, and mean temperatures). In addition, the plant responds negatively to excessive changes in temperature, i.e., extreme events (heat or cold), which influence the cereal dry matter accumulation rates and yield production. Porter and Gawith [108], reviewed the effects of climate variability and extreme temperature events that occurred during the different wheat growth and development periods:

- Germination and emergence period: the seed germination rate is dependent on temperature. The wheat genotype determines the response to temperature regimes during germination, and each variety has a maximum seed germination and vigor index under a specific temperature, with a required mean of 35 degree-days for visible germination to occur [25]. In addition, the temperature affects wheat emergence and establishment, in which high or low temperatures perturb the emergence of the coleoptile and cause seedling mortality [100].
- Vegetative growth period: wheat vegetative growth, specifically the tillering phase, is sensitive to heat stress. An obvious decrease in wheat growth state variables (LAI, plant height, number of tillers, etc.) is observed when plants are exposed to extreme temperatures during the vegetative period [1, 59]. Under the Mediterranean-type climate, temperature acts negatively in two different ways during the wheat vegetative period: i) heat stress impacts the plant

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water availability through intensifying the evaporation process, and ii) high temperatures accelerate the plant development stages by the accumulation of the growing degree-days (GDD), without allowing the plant to achieve the potential growth rates in each independent stage (e.g., tillering and stem elongation).

- Reproductive and grain development period: due to the direct impact on grain number and dry matter accumulation, wheat reproductive and grain filling stages are the development periods most affected by high temperatures. The main mechanisms of heat stress include tissue dryness, pollen sterility during floret development, decreased $CO_2$ assimilation, and higher photorespiration. These effects decrease photosynthesis and lower grain yield. High temperatures influence different components of grain yield: reducing the grain number per spike, grain dry weight, and grain protein content [49, 108].

c. Focus on macro-nutrients

Optimal crop nutrition is necessary for improved plant growth and development processes, high-yield production, and acceptable grain quality. Plant nutrient stress, specifically deficiency of the primary nutrients (nitrogen (N), phosphorus (P), and potassium (K)), is one of the major abiotic stresses that affect cereal growth and grain productivity potential, especially when rainfall amounts are adequate (i.e. in favorable rainfed areas). Moreover, the risks of plant nutrient imbalances are manifested not only in a negative impact on crop growth and yield patterns but also affect the notable role of those nutrients in the activation of several plant mechanisms to mitigate other biotic and abiotic stresses [52, 76].

- Germination and emergence period: wheat is very sensitive to insufficient nitrogen (N) and very responsive to nitrogen fertilization at sowing. Nitrogen has a significant impact on wheat vigor after sowing, helping to increase the final germination rates [154]. Phosphorus (P) is an essential element in seed germination and early root development. P-deficiency at this early development stage significantly reduces wheat growth potential later. In additon, P and K fertilizer has to be applied close to the seed during sowing and cannot be top-dressed due to the relative immobility of these nutrients in the soil (as opposed to N) [100].
- Vegetative growth period: during this period, scientists report the most critical wheat crop physiological responses to N- and P-deficiencies. Overall, N stress

during the vegetative period reduces plant growth, decreasing the tiller number and leads to yellowing of leaves [163]. However, the early detection of N stress and the delivery of essential N recovery dosages may reverse the effects on wheat development and productivity. On the other hand, while the P-deficiency symptoms could be detected mainly from perturbations of the root system development, it also appears as dark green spots in leaves, as well as regression of plant growth, reduced tiller emergence, and late plant maturity [41, 121, 163]. Potassium (K) also has a significant effect during the plant's vegetative period, specifically on plant height and the tiller number [8, 100].

- Reproductive and grain development period: the supply of N-fertilizer between stem elongation and the heading period amounts to 60% of the total N uptake and has a significant effect on increasing the number of spikelets and grains per ear, the grain protein content and grain weight, and causes an increase of 40% in grain yield [78, 100, 120]. In addition, an obvious evolution is seen in different components of grain yield and quality with appropriate P-fertilization [95]. K-application influences the grain yield and quality, resulting in an increase in dry matter and grain weight, also allowing the evolution of grain quality by increasing the amount of zinc, iron, and protein in the grain [8].

## Wheat genotype and yield potential

Yield potential is the maximum yield that a crop cultivar can achieve when cultivated in an ideal physical environment free of biotic and abiotic stress [46]. The evolution of potential yield in a specific environment depends on the enhancement of adaptive wheat genotypes (varieties) through breeding and aims to improve: (i) specific adapted plant growth and development characteristics, (ii) grain yield components and quality, and (iii) resistance to biotic and abiotic stresses.

In Morocco, the development of wheat varieties has traditionally been seen as a fast way to increase yields to meet the country's rising production shortfall. The Moroccan National Institute of Agronomic Research (INRA), in partnership with the International Maize and Wheat Improvement Center (CIMMYT), created various wheat genotypes that were well-adapted to the various agro-climates of Morocco in the early 1980s. However, these genotypes were sensitive to some pests, specifically Septoria fungus and Hessian fly. These wheat genotypes were exploited later in a breeding and varietal selection program. They were considered during the following breeding works: resistance to brown rust in 1980, to

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Septoria in 1987, to Hessian fly in 1989, and to heat and drought stress in 1992 and 1995. Table 4 presents a list of important soft wheat (*Triticum aestivum*) varieties developed between 1980 and 2010 in Morocco.

## Soil: a vital slowly renewable resource for long-term agricultural production systems
### Soil quality and degradation
Soil, as one of the most important natural resources, plays a vital role in the production of human food, the preservation of terrestrial ecosystems, the provision of an environment for plant growth, the storage of water and chemical elements, and the biological background for organic waste decomposition. Because soil is a slowly renewing resource, its loss of quality has a long-term impact on numerous soil processes.

The soil may reduce environmental swings and manage various biological processes that maintain water and air quality and ensure plant development by interacting intimately with water, air, and plants. Therefore, soil quality is defined as the ability of a specific type of soil to function, maintain, or improve the quality of water and air and support human health and housing [83]. The terms "health" and "quality" of soils are frequently used to define the same concept [128].

**Table 4** List of soft wheat varieties released between 1980 and 2010 [68] (Data source: http://wheatatlas.org/country/varieties/MAR/0?AspxAutoDetectCookieSupport=1)

| Name | Years | Selector | Description |
|---|---|---|---|
| MARCHOUCH | 1984 | Jliben, Bouchoutrouch and Ouassou (INRA, CIMMYT) | • Favorable RA and semi-arid<br>• Sensitive to Hessian fly |
| SAIS | 1985 | Jliben, Bouchoutrouch and Ouassou (INRA, CIMMYT) | • Favorable RA and semi-arid<br>• Sensitive to Septoria and Hessian fly |
| KANZ | 1987 | Jliben, Bouchoutrouch and Ouassou (INRA, CIMMYT) | • Favorable RA and semi-arid<br>• Sensitive to Septoria and Hessian fly |
| SABA | 1987 | Jliben, Bouchoutrouch and Ouassou (INRA, CIMMYT) | • Favorable RA<br>• Sensitive to Septoria and Hessian fly |
| ACHTAR | 1988 | Mergoum and Smith (INRA, CIMMYT) | • Favorable RA and irrigated cropland<br>• Favorable response to nutrients |
| KHAIR | 1988 | Mergoum and Smith (INRA, CIMMYT) | • Favorable RA and irrigated cropland<br>• Highly sensitive to Septoria and Hessian fly |
| BARAKA | 1988 | Mergoum and Smith (INRA, CIMMYT) | • Favorable RA and semi-arid<br>• Sensitive to Septoria and Hessian fly |
| TILILA | 1989 | Jliben, Mergoum and Smith (INRA, CIMMYT) | • Favorable RA, irrigated cropland, semi-arid and mountain<br>• Sensitive to Septoria and Hessian fly |
| MASSIRA | 1992 | Jliben (INRA) | • Favorable RA and irrigated cropland |
| AMAL | 1993 | Jliben (INRA) | • Sub-humid regions and irrigated cropland<br>• Highly productive |
| RAJAE | 1993 | Jliben (INRA) | • Sub-humid regions<br>• Favorable response and valorization of nutrients |
| MEHDIA | 1993 | Jliben (INRA) | • Favorable RA and irrigated cropland<br>• Sensitive to Septoria and Hessian fly |
| ARREHANE | 1997 | Jliben and abdella (INRA) | • All RA and irrigated cropland<br>• Sensitive to Septoria<br>• High resistance to Hessian fly<br>• late sowing |
| AGUILAL | 1997 | Jliben and Amri (INRA) | • Favorable RA and semi-arid<br>• Resistant to Hessian fly |
| WAFIA | 2005 | Florimond Desprez | • Favorable RA and irrigated cropland<br>• Resistant to brown rust and Septoria |
| RADIA | 2006 | Florimond Desprez | • All RA and irrigated cropland<br>• Resistant to brown rust and Septoria |
| BANDERA | 2010 | Florimond Desprez | • Favorable RA and irrigated cropland<br>• Resistant to brown rust and Septoria |
| FAIZA | 2010 | Florimond Desprez | • Favorable RA and irrigated cropland<br>• Resistant to brown rust and Septoria |

*RA* rainfed areas

Because soil health is still an intrinsic aspect of the notion of sustainable agriculture, soil may initially be deemed in poor health if it is not naturally capable of supporting intensive agriculture [111]. The most practical definitions of soil quality are those that are related to their functions. Agronomists often employ a definition that focuses on soil production, i.e., soil in "good health" produces abundant crops of high quality. Agriculture has been perceived differently in the last 10 years. It is no longer regarded as a closed-circuit activity, but rather as a component of a much broader ecological system that interacts with other components of the system. This has led to a new definition of soil quality that exceeds productivity and links with the environment. The National Research Council of Canada (NRC) also recognized the importance of including environmental perspectives in soil quality. The NRC ruled in 1993 that "[s]oil quality is the ability of a soil to promote plant growth, protect watersheds by regulating seepage and dividing precipitation, and preventing water and water pollution by cushioning potential pollutants such as agricultural or industrial chemicals or organic waste" [145].

On the other hand, land degradation refers to weakening soil quality and capacity through natural perturbations (e.g. extreme climatic events) or human activities [101, 156]. Likewise, soil degradation refers to a decline in the soil's current or potential performance to ensure livelihoods and the provision of other ecosystem goods and services, notably, food production [77].

In Morocco, as in other developing countries, the combination of poverty and population growth in fragile environments results in the degradation of non-renewable or slowly renewable resources, particularly forests, soils, and water. Overexploitation of soils through increasingly intensive crop rotations, unsustainable soil cultivation, and export of crop residues from farmed and grazed fields all contribute to carbon loss and aggregate instability [119].

Three main forms of soil degradation require attention [19, 77]:

- Biological degradation: loss of organic matter and reduction in the activity of microorganisms and species diversity;
- Physical degradation: soil erosion and sedimentation, decline in soil structure, crusting and compaction;
- Chemical degradation and nutrient depletion: prevalent nutrient depletion and salinization of agricultural soils are primary causes of decreasing yields, low on-site water productivity, and off-site water pollution.

## Nutrient depletion and yield reduction

Several decades of research into the cause–effect relationship between crop production and nutrient availability have revealed that, even in the driest parts of the world, nutrients are among the most limiting factors for crop growth, with the macro-elements (N, P, and K) being the primary limiting nutrients [31]. Worldwide, it was estimated that more than 50% of the increase in crop yields during the twentieth century was due to the adoption of chemical fertilizers [77, 85. As a result, without adequate replacement of nutrients extracted in agricultural products, as well as nutrient losses due to soil erosion and leaching of chemical or natural fertilizers [150], soil nutrients decrease—resulting in poorer crop yields, as proven in long-term tests [148].

Soil nutrient depletion refers to soil nutrient losses through natural and human-induced processes (Fig. 3). In other words, it is the process by which the soil nutrient stock is shrinking because of continuous nutrient mining in the absence of replenishment of the required nutrients. It can be attributed to the following factors: agriculture intensification, lack or insufficient replenishment of nutrients, accelerated soil erosion, inappropriate land uses, poor management practices, unbalanced fertilization, etc. (Fig. 3). Soil nutrient depletion is closely connected to food insecurity in emerging and least-developed nations due to the expansion of land usage for agriculture without sufficient application of external nutrients [54, 90]. Inadequate replenishment of nutrient-depleted soils exacerbates soil degradation and has an impact on agricultural sustainability and food security.
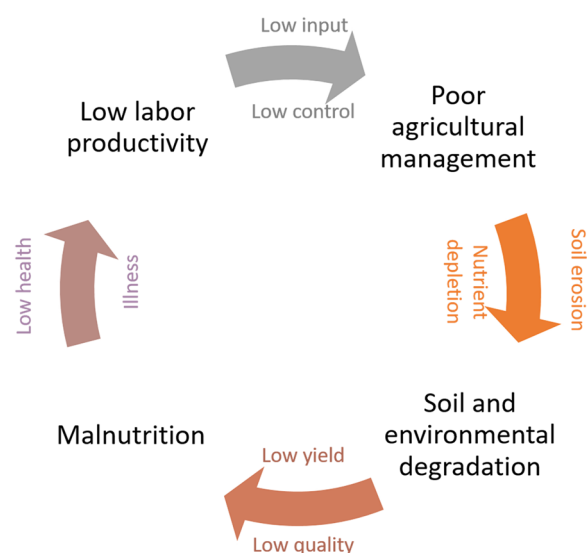
**Fig. 3** Soil nutrient depletion and its impacts on soil quality, crop production, and the environment. Modified from Deckelbaum et al. [35]
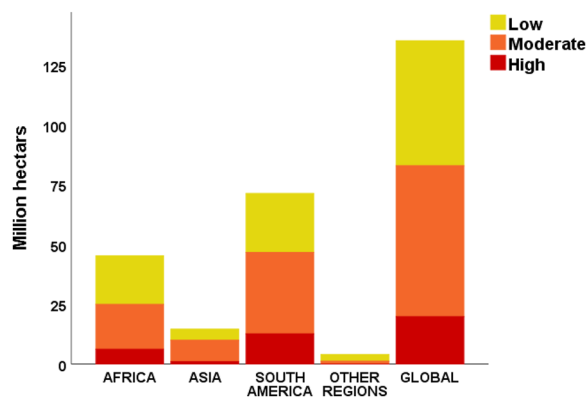
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**Fig. 4** World land area affected by nutrient depletion (Data source from Tan et al. [140]

**Table 5** Average level of NPK balance 1993–1995 [117]

| High (≥ 60) | Medium (− 60 to − 30) | Moderate/low (≤ 30) |
|---|---|---|
| Kg of N–P–K ha$^{-1}$ year$^{-1}$ | | |
| Burkina Faso | Cape Verde | Algeria |
| Burundi | Congo | Egypt |
| Cameroon | Chad | Morocco |
| Kenya | Sudan | Tunisia |
| Nigeria | Niger | South Africa |
| Senegal | | |
| Ivory Coast | | |

Low-input and inappropriate fertilization are a threat to food security in many regions of the world [140], both directly by lowering crop yields and crop nutritional values and indirectly by lowering resource use efficiency (i.e. land, water, fertilizer, etc.) and farmers' marginal revenues [77]. These effects are intensified under the climate change context and the recurrence of extreme events (e.g. drought), which exacerbates food insecurity. Overall, continuous nutrient depletion perturbs socio-economic security and degrades soil resource sustainability and environmental quality.

Around 135 million hectares of soil were considered to be prone to nutrient depletion worldwide at the turn of the twentieth century, with 97% occurring in developing and least-developed countries. In Africa, over-cultivation and insufficient replacement of nutrients and management techniques have impacted about 45 million hectares of soil (Fig. 4). Furthermore, nutrient depletion rates in Africa demonstrate a clear negative balance for the majority of countries [117] (Table 5).

In conclusion, adopting appropriate crop management practices, including adapted fertilizer strategies, will contribute to a substantial crop yield improvement.

Studies on soil degradation and soil fertility assessments conducted in different countries play a major role in improving crop production and optimizing fertilizer use efficiency, maximizing the farmers' revenues, specifically those with low incomes. For cereal crops, the main efforts should be focused on identifying nutrient constraints in the field, mainly nitrogen and phosphorus.

### Nitrogen and phosphorus fertilization

Nitrogen (N) is a critical element in worldwide food cropping systems due to its essential function as a cereal yield-determining nutrient. N-fertilizer inputs ensure food for half of the world's population [45, 80] through the reduction of staple crop yield gaps, specifically, where yields are less limited by water availability [122]. Prior to the 1960s, crop N-intake was mostly dependent on manure inputs, biological N-fixation, and indigenous N-supply through mineralization of soil organic matter [131]. Afterward, N-fertilizer consumption increased worldwide. Since the 1990s, N consumption has decreased in developed countries, whereas the increase continues for developing countries (Fig. 5). This new trend in N-fertilizer consumption was primarily caused by developing countries' high population growth rates in comparison with developed countries, as well as an increase in nitrogen use efficiency in developed countries due to the adoption of new technologies and insights into crop management practices [14]. Many studies in the literature have highlighted the influence of N-fertilizers on global food security [75, 80, 131].

Phosphorus is a significant nutrient for plant growth and production and has a limiting effect at different stages of wheat crop development (see Sect. Wheat development under abiotic stresses: focus on macronutrients). The agricultural practice of applying P-fertilizers has existed since the middle of the nineteenth century and developed in the twentieth century to exceed the amount of phosphorus applied as manure. Likewise, the consumption of P-fertilizers in developing countries has increased from less than 1 million tons of P per year (MT P.year$^{-1}$) during the 1960s to 13 MT of P.year$^{-1}$ in 2010 [118]. In parallel to this evolution, studies have stated a two to three-times increase in P-uptake in crops [28, 136]. Most of the phosphate rock mined (around 80%) is used in fertilizer production [136]. Syers et al. [139] reported critical challenges to the improvement of P-fertilizer use efficiency, and they justified its importance by two substantial reasons: (i) phosphate rock as the origin of phosphorus fertilizer is a non-renewable resource, and (ii) under a non-limiting N supply in terrestrial systems, P is usually the limiting nutrient for biomass development. As a result, enhancing the P status of many soils
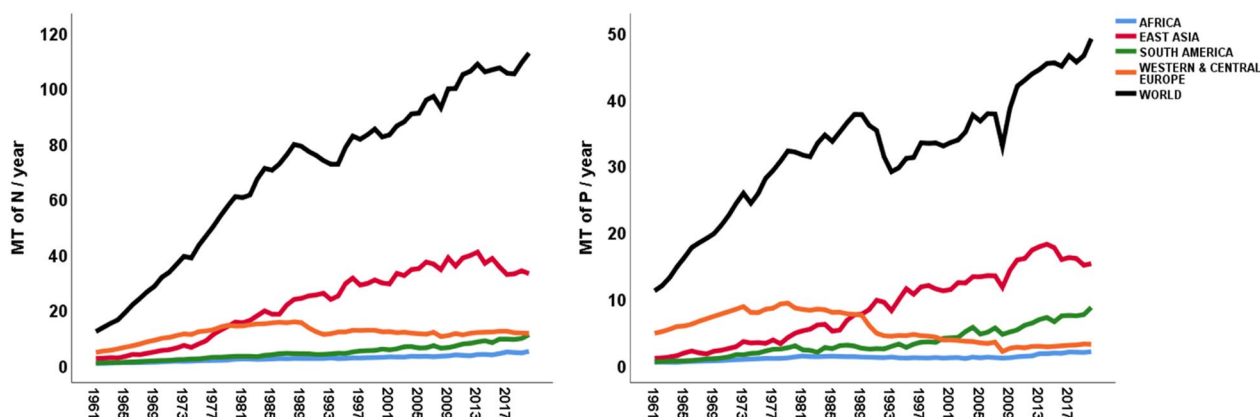
**Fig. 5** Developing and developed countries' total nitrogen (N) and phosphate (P) fertilizer consumption (by million tons per year) from 1960 to 2020. [63] (data source: https://www.ifastat.org/databases/plant-nutrition)

worldwide is critical to maintain optimal crop development and production, hence ensuring global food security [28].

In Morocco, N and P fertilizer recommendations are formulated to relevant farmers by agronomists and soil experts using two main conventional approaches: (i) based on the average crop yield response to fertilization data collected in the long-term over large geographic areas, or (ii) based on simple statistical equations (linear or multiple regression equations) relating the amount of applied fertilizer to soil fertility proprieties, yield, and crop type. In conventional N- and P-fertilizer timing advice for cereal crops, while P application is automatically added at sowing (P applied as deep fertilizer), N application is prescribed before sowing, with three conventional applications: at sowing as deep fertilizer, at tillering stage (Z20 to Z25), and the start of the heading stage (Z50) as N-recovery fertilizer. Originally, two factors explained those fertilizer application dates: (i) the farmers' usual calendar and (ii) the market availability of N-fertilizer, i.e., when appropriate amounts of conventional N-recovery fertilizer are available.

The conventional N- and P-fertilizer recommendations are designed to achieve a target yield defined before sowing and possibly based on actual soil conditions, average climate of the location, and on weather conditions of the current growing season. Thus, there is a large probability of applying excessive or too-low amounts of N- and P-fertilizer in several farmers' fields, specifically in rainfed croplands. This situation impacts not only crop production and fertilizer use efficiencies but also the farmers' incomes and increases the risk of environmental degradation through exaggerating greenhouse-gas emissions and groundwater pollution.

There is an apparent high interest in newly developed strategies and tools that aim to optimally formulate N- and P-fertilization for farmers by applying adequate N and P amounts at appropriate times during the growing seasons. Furthermore, using agro-meteorology to enhance fertilization recommendations in rainfed areas might be a valuable tool for adjusting fertilizing methods to climate change and reducing economic and food insecurity concerns in Mediterranean environments.

## Advances in modeling of wheat cropping system management

### Introduction

Cropping systems are unstable ecosystems, and their establishment and management are surrounded by uncertainty and gaps [89]. The complex interactions of agricultural systems, determined previously through the $G \times E \times M$ factors, impact crop growth, development, and productivity. Studies of the causal relationships between crop management and real crop production functions (i.e., measurements and observations) are conventionally conducted through experience-based agronomic research [40]. However, since the need for a more complex understanding of crop responses in field trials and environments has increased, such traditional approaches have shown many limitations [74, 102]. First, this type of research study provides information and results that not only are site-specific, and therefore, their re-exploitation depends on the environmental conditions of new sites, but also limited in time (season-specific or decade-specific) due to the severity of climate change effects [56]. Second, demand is rising for extensive data sets and

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databases to ensure reasonable and accurate guidance of sensitive decision-making and policy processes, such as the food security issue. Finally, these trials are intensively labor-, time-, and cost-consuming. Thus, a major difficulty is presented in conducting experiments across multiple years and sites during the season, as well as monitoring a large number of plant–soil state variables [27].

Over time, it became clear that farmers, specialists, and decision-makers urgently require tools and advisory systems for crop scenario assessments [74]. Worldwide, the newly discovered tools had to provide more simple, rapid, less expensive, and deeper research findings for an alternative exploration of the plant–soil–climate interaction effects on the environment and crop productivity. Mathematics may now be used to represent complicated biological processes due to technological breakthroughs [102]. The modeling process uses sets of equations to create representations of the behavior of real systems (whether they are complicated or simple), and then uses those representations to replicate the behavior of those systems [71, 97]. To combine the key processes involved in the understanding of crop growth and development, quantitative methodologies were created in crop modeling studies, taking into consideration the interconnections of several disciplines (plant physiology, agronomy, soil science, agro-meteorology, etc.) [94, 107]. Agricultural modeling has enabled crop research studies for various aims to be undertaken, imitated, and pre-evaluated in a few minutes of computer effort [70, 133, 134], such as for crop yield prediction, climate change, crop responses to different environmental and management factors, etc. However, it has been explicitly stated that the use of traditional field experiments in tandem with crop modeling studies is essential for calibrating and validating the model's effectiveness [115, 152].

To simulate crop growth, development, and production, two main crop modeling techniques have been proposed [73, 109]: (i) empirical models and (ii) mechanistic models. Empirical models are the first models used primarily for crop yield modeling; they are calibrated using historical data, and their structure requires few parameters. These models focus on data interactions and require less direct information from the plant [84]. Mechanistic models, on the other hand, are more complex and include a core framework of equations that reflect the physical and biological interactions of crop–soil–atmosphere systems to mechanistically mimic crop growth and development [5].

The two types of models are described individually in the following sections, and the pertinent uses of crop modeling to improve crop management strategies are investigated.

## Type of models

a. Empirical models

Also called "statistical" or "descriptive" models. Unlike mechanistic models, empirical models focus on describing and interpreting data, with a few assumptions specified to develop a knowledge-based model from the data set [6, 102]. Sample data of the studied population are used to build empirical models [11]. Thus, the accuracy of an empirical model is highly dependent on the quality of the sample data, the equations and parameters used in the model. For modelers, the preferred characteristics of empirical models are represented in their simple structure with limited requirements for input parameters and reduced time to run the models [104]. Therefore, statistical models were the first empirical models to be used, specifically on a large scale [138].

Statistical crop models are often based on machine learning techniques or simple or multiple regression models. Statistical crop models are often used in practice to explain the variation of a dependent variable, mostly crop yield, using a collection of predictors (independent variables), most commonly represented by meteorological parameters, satellite indices, soil, and crop management factors [84]. Consequently, those types of models are mainly used for crop yield forecasting and yield gap studies.

b. Mechanistic models

Mechanistic models, also known as biophysical, crop simulation, or process-based models, are computerized representations of crop growth, development, and productivity that use biophysical equations to provide an understanding of the biological, chemical, and physical processes that interact with the soil–plant–atmosphere continuum [58, 107]. There has been a lot of literature published on mechanistic models since the 1980s. Developments in computer science, as well as the increasing complexity of the challenges faced in agricultural systems, have resulted in the development of more complicated models [12]. Previous reviews have reported the creation and evolution of mechanistic crop models [71,

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106], while Wallach et al. [151] provided further data on crop model methodologies and applications.

These models compute the plant growth rates based on information about crop management and environmental factors (soil, weather), and they predict the biomass output from resources, such as carbon dioxide, water, solar radiation, and nutrients that are captured [7]. Hence, three types of process-based crop models were distinguished by Steduto [132]: (i) crop models based on carbon uptake through the photosynthetic process (De Wit school of models), an approach initially developed by de Wit et al. [33, 34] which includes the "WOFOST" model ("the WOrld FOod STudies") [18, 26, 39, 141], (ii) water-driven models based on the proportional linear relation of biomass accumulation rates to transpiration, through a water productivity parameter, included in this group are the two crop models "CropSyst" [137] and "AquaCrop" [133, 134]; and (iii) radiation-driven models that quantify the accumulation of biomass from intercepted solar radiation through a unique conversion coefficient called Radiation Use Efficiency (RUE) [91, 141], and the main examples of these models are APSIM [57] and DSSAT–CERES [112].

Mechanistic models have been developed for a wide range of crop species for many applications connected to the world's urgent problems, such as food security, climate change, crop management adaptations, and so on. The more complex the models, the better they will explain the soil–plant–climate systems, with a high demand for input parameters. Mechanistic models need a three-step approach to ensure better model design before applying such models to various goals:

- Parameterization: this process is a higher level adjustment of specific model parameters than calibration [48]. It refers to supplying the model with local and time-specific input parameters that were directly measured or recorded (climate input parameters, soil physical and chemical characteristics, management information, etc.).
- Calibration: while some model parameters, such as crop cultivars and soil coefficients, cannot be directly measured or have higher levels of uncertainty, iterative modification or calibration is highly recommended. Calibration is the process of adjusting particular model coefficients (parameters), so that the model simulates output, primarily crop growth and productivity outputs, in agreement with the observed values in a given environment. In case of discrepancies, the relevant parameters are revised within acceptable boundaries, and the procedure is repeated until the model accuracy is acceptable. In the literature, the terms parameteri-

zation and calibration are sometimes used interchangeably.
- Validation: the model's ability to model crop growth, development, and productivity outputs against independent measured or observed data sets is the ultimate test of the calibrated model's correctness (data sets of new experiments, locations, or years). This step is referred to as verifying the model's truthfulness following the calibration and parameterization processes. The validation process involves comparing independent field measurements to model results [96].

c. Model sensitivity and uncertainty

Input parameters, calibration coefficients, and model structure (or equations) are all prone to variation or uncertainty. A quantitative examination of the uncertainty and variability of a model's various parts is known as an uncertainty analysis, and it enables the determination of a range of uncertainty for each output variable as opposed to a single misleading estimate [152]. Sensitivity analysis, on the other hand, is used to assess how sensitive the output of a crop model is to model components that are unknown or variable. These studies help researchers to understand the model's behavior during crop growth, development, and yield simulations [72].

## Major insights on crop modeling applications for food security and crop management adaptations

a. Crop growth monitoring and yield forecasting

Sustainable crop intensification and effective natural resource use are major challenges for ensuring food security. Crop forecasting models are key instruments for farmers, agronomists, and policymakers addressing food security concerns in the context of climate change. Model forecasting has been developed to anticipate crop yield as early as possible, based on a conceptual logical relationship between crop yield and within-season external factors (environmental conditions and management techniques), internal factors (crop genotype), or environmental indices (ex: NDVI).

Empirical or mechanistic models are two of the most used yield prediction techniques in literature; both are integrated with agricultural yield forecasting models.

Pre-harvest opportunities (pre-harvest crop production forecasts) are provided by global or national systems of crop growth monitoring and yield forecasting to plan for any potential shortages in crop production. In other words, it enables the planning of preventative

interventions (such as farmer assistance and cereal imports) by estimating the consequences of severe events on crop output, hence reducing climate risk sensitivity.

Morocco has experienced a significant decrease in terms of water availability (from 1016 m$^3$ per capita in 2000 to 799 m$^3$ per capita in 2019) [157] because of the increasing pressure on water demand and rainfall fluctuations caused by climate change, which has had a negative impact on the agriculture sector and, consequently, on the country's food security [9], [158]). Water scarcity, inter- and intra-annual variance in rainfall, and the recurrence of drought episodes all contribute as abiotic stressors and to disruptions in agricultural production, particularly for wheat crops in Moroccan rainfed regions **(See** Sect. "Introduction"). Hence, in the framework of an institutional consortium between the National Institute of Agronomic Research (INRA-Morocco), Agronomic and Veterinary Institute Hassan II (IAV Hassan II), the National Weather Service (DMN), and the Strategy and Statistical Service (DSS) of the Ministry of Agriculture, and using a combined agrometeorological modeling approach, a national system for cereal crop growth monitoring and agrometeorological prediction of yields was developed: The Crop Growth Monitoring System of Morocco "CGMS-Maroc" [9, 32]. CGMS-Maroc is a national system that allows in-season monitoring of cereal crops and agrometeorological prediction of cereal yields using climatic variables (ex: temperatures and rainfall) and remote sensing vegetation indices (ex: NDVI).

In Table 6, we detail the main characteristics of CGMS-Maroc. Moreover, we compared the Moroccan system with well-known agricultural monitoring and yield forecasting systems currently in operation: (i) China's global crop-monitoring system (CropWatch) [159], (ii) Forecasting Agricultural output using Space, Agro-meteorological and Land-based observations (FASAL) [105], and (iii) the Crop Explorer service of The Foreign Agricultural Service of the United State Department of Agriculture (USDA–FSA) [146]. The comparison of the systems' yield prediction performances is not considered due to differences in climatic parameters, temporal and geographical scales, and crop species importance for the countries' food security (staple foods). Instead, the comparison was centered on the systems' key components, which may provide insight when considering adaptations to the systems' structure for possible improvement of robustness. When CGMS-Maroc was compared to the other three systems, two significant differences were identified. First, CGMS-Maroc is based on empirical models and machine learning algorithms, whereas other systems use empirical and mechanistic models. Second, the other systems integrate soil data sets and crop management information

(for parameterization of mechanistic models), whereas CGMS-Maroc does not consider those variables.

Aside from the Moroccan system (CGMS-Maroc), additional recent investigations modeling agricultural production predictions for Moroccan rainfed areas have been conducted using other methodologies and under varied climate conditions. Epule et al. [44] cited some of those research studies in their literature review and gave insights on the following modeling approaches, model structure, required input data set, and their performances in estimating crop yield.

b. Between broad adaptations and within-season crop management advice, the transition from crop modelling to crop management

Agricultural modeling studies have made a significant contribution to food security worldwide by evaluating the productivity of national or global crop systems (see Sect. "Nitrogen and phosphorus fertilization"), as well as local assessments of various crop management techniques in current and future climatic conditions. By suggesting optimal and sustainable management techniques and assisting adjustments to the variations in market inputs, model-assisted decision-making in the local agricultural sector might reduce farmers' vulnerability to climatic and economic hazards.

Crop simulation models (mechanistic models) play important roles as decision support systems because of their complex structure that integrates plant–soil–climate system interactions. They help to identify the best adaptation strategies for farmers to combat and control the impact of climate fluctuations and global warming on crop growth and production [94, 107]. As a result, by modeling crop responses to various management techniques for local environmental circumstances, such models may provide a better understanding of the interconnections between the key systems of the soil–plant–climate continuum and its worldwide functioning at a daily time step.

Using empirical models for this purpose, on the other hand, is based on linking crop biomass or yield (dependent variable) to agronomic and environmental parameters. Through regressions and correlation analyses, the statistical technique facilitates a straightforward qualitative understanding of the relationships between biomass or grain production measurements and environmental factors (see Sect. "Nutrient depletion and yield reduction"a). As a result, it might be challenging to draw agronomic conclusions from a model of this kind that, on one hand, ignores the biological, physical, and chemical processes of the system, and crop functioning under management approaches on the other. Using

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**Table 6** Comparison between four crop yield forecasting systems: CGMS-Maroc, CropWatch, USDA–FAS, and FASAL systems

| | | CGMS-Maroc | CropWatch | USDA-FAS (Crop explorer) | FASAL |
|---|---|---|---|---|---|
| References | | [9] | [159] | [146] | [105] |
| Modeling approach | | Empirical models (multiple regression, machine learning and similarity analysis) | Empirical models (multiple regression and similarity analysis) | Empirical and mechanistic models | |
| Crop | | Cereal crops | Cereal crops and soybean | Cereal crops, soybean, cotton, etc | Cereal crops, cotton, sugarcane, rapeseed, mustard, etc |
| Mission | | - Yield forecasting<br>- Monitoring crop growth and climate indicators | - Monitoring agro-climatic indicators,<br>- Crop mapping<br>- Yield forecasting,<br>- Analysis of phyto-sanitary conditions | - Monitoring crop, soil, and climate indicators,<br>- Crop mapping,<br>- Yield forecasting,<br>- Drought risk assessment | Monitoring crop growth and development indicators,<br>- Crop mapping,<br>- Yield forecasting,<br>-Water balance |
| Yield predictors | Meteorological input parameters | -Gridded data sets from ground stations: temperatures, rainfall, evapo-transpiration | Satellite-based: temperatures, rainfall, photosynthetically active radiation, and land surface temperature + Snow coverage in Crop Explorer | Satellite-based: temperatures and rainfall, photosynthetically active radiation, DEM, etc | -Station-based: temperatures and rainfall<br>-Satellite-based: insolation and land surface temperature |
| | Other remote sensing products | Vegetation indices (NDVI, LAI, FAPAR, FCOVER), rainfall estimates | Vegetation indices (NDVI, LAI etc.) + Soil moisture | | |
| | Auxiliary parameters | Land cover map, crop calendar | Systems use some common auxiliary parameters: crop type (or land cover maps), crop calendar, crop development scales, soil information, DEM, etc | | |
| Systems' scales | | - Administrative level,<br>- National level | - Administrative level,<br>- National level,<br>- Global level | - Administrative level,<br>- National level,<br>- Global level | - Administrative level,<br>- National level |
| Schedule to release system findings | | Every 10 days, during the growing season | Quarterly (every 4 months) and annually | Monthly and numerous parameter maps and charts updated every 10 days | Depends on crop species. Overall, in early season, mid-season, and pre-harvest |
| Area covered by the system | | Morocco | - Global for Agro-climatology,<br>- Crop production and yield estimation for 31 countries | Global | India |

*FPAR* fraction of photosynthetically active radiation, *DEM* digital elevation model

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remote sensing-based variables (such as crop growth and vegetation indices, soil moisture and organic matter indices, and plant stress indices) as well as combining soil, climate, and crop management information are practical aspects of implementing empirical methodologies [11, 61]. Furthermore, complex empirical models (machine learning techniques) may be preferable for managing and analyzing a huge collection of variables (large data set) during model extraction [81].

Hundreds of crop modeling studies have recently been conducted to address climatic and economic risks by recommending general adaptation strategies to be followed in cropping systems under various environmental conditions, such as: evaluating the effects of adopting the three axes of conservation agriculture, improving plant breeding works, assessing general adaptive management practices (in irrigation, weed control, or fertilization), etc. Crop modeling methodologies, however, have rarely been incorporated into decision support systems to offer optimal within-season and on-farm tactics for farmers, such as the Yield Prophet tool [60] (https://www.yieldprophet.com.au/yp/Home.aspx) that provides advice to farmers on nitrogen and irrigation applications, sowing dates, crop varieties, etc., to match crop management practices with the fields' crop yield potential.

Various mechanistic and empirical models have been used in Morocco to analyze general adaptation techniques for soil degradation and climate change, as well as to provide recommendations for optimal within-season cropping management guidelines. In this latter context, a number of mostly unreported contributions were implemented as part of agronomic advice and development initiatives for small farmers (e.g. the OCP-AL Moutmir program) or for commercial gain. One of the famous, older Moroccan realizations is the Fertimap project. The OCP group in collaboration with the Moroccan Ministry of Agriculture and Maritime Fisheries and Moroccan institutes of agronomic research (INRA, IAV, ENA, etc.) developed the Moroccan soil fertility map "Fertimap", which was constructed from more than 32,000 soil samples collected from different agro-climatic zones during the last decade and analyzed for different soil fertility parameters. Afterward, a decision support tool for recommending N–P–K fertilization at the field level was derived from regression relations between the created Fertimap soil fertility database, within-season applied fertilizer rates, and recorded yield in farmers' fields. The Fertimap tool is available on an open access platform (http://www.fertimap.ma/map.html), and fertilization recommendations can be extracted by directly selecting the retained fields on the map (or inserting the field coordinates) and defining a target yield value to extract the fertilization recommendations. Other unpublished

contributions for developing crop decision support tools have been developed, such as the OCP-Al Moutmir "NPK Engine", which is a soil-based method for defining fertilization recommendations based on empirical models that include actual soil analyses, previous field history, current cereal species, and an expected yield value determined based on the agricultural potential of each area. In addition, many crop management decision-making services and tools are being developed by the AgriEdge program (an innovation structure at the Mohamed VI Polytechnic University UM6P), in which researchers propose within-season and field-level optimal and sustainable crop management tools: FertiEdge, AquaEdge, PhytoEdge, YieldEdge, etc. Overall, those described decision support tools share the main characteristic of utilizing empirical modelling approaches (multiple regression or machine learning). In addition, when the tool is recent, it substantially integrates more remote sensing-based indices, independently or in combination with the actual environmental conditions. The absence of mechanistic models in such contributions, on the other hand, could be attributed primarily to: (i) the nature of some business research projects that require commercial licenses to use the majority of crop simulation models, (ii) the high requirement for field input parameters to run those models in a large number of farmers' fields (i.e. labor-, time-, and cost-consuming), and (iii) the need for expert knowledge to combine agronomic and modeling to exploit such models.

Recently, in the only published review article (a systematic review) about crop modeling studies under specific Moroccan conditions, Epule et al. [44] collected the major crop modeling achievements over the last two decades that concern the evaluation of yield gaps under Moroccan cropping systems. However, during this literature review, they concentrated on crop modeling methodologies, specifically the type, methods, and structure of the applied crop models, as well as the input variables used, without any focus on the contribution of the type of studies (yield forecasting, general adaptation strategies, or within-season management tools), the concerned management practices (fertilization, irrigation, weed control, etc.), cropping systems (rainfed or irrigated), and the agro-climatic conditions. Consequently, and to provide more extensive information, we tried to highlight various peer-reviewed crop modeling studies for wheat cropping systems in Morocco, based on those ignored neglected characteristics (Table 7).

## Conclusions

In Morocco, a number of constraints and limitations encourage policymakers, agronomists, and scientists to closely monitor in-season and post-season wheat

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**Table 7** Crop modeling studies on wheat cropping systems under Moroccan conditions

| Objective of crop modeling study (contribution) | References | Title of publication | Type of model | Type of cropping system | Concerned crop management practice | Contribution's primary scale | Concerned Agro-climatic zone |
|---|---|---|---|---|---|---|---|
| Model calibration and evaluation independent studies: - Crop growth, development, and yield prediction | [22] | New multi-model approach gives good estimations of wheat yield under semi-arid climate in Morocco | WOFOST and CROPSYST | Irrigated and rainfed systems | Monitoring crop growth and final yield prediction | 25 km × 25 km elementary simulation unit | Unfavorable, intermediate, and favorable areas |
| - Estimation of soil–water and soil-fertility variables | [10] | Empirical regression models using NDVI, rainfall and temperature data for the early prediction of wheat grain yields in Morocco | Regression models | Rainfed systems | Final yield prediction | Administrative level (provinces) and national level | All Moroccan agro-climatic areas |
| | [21] | Cereal yield forecasting with satellite drought-based indices, weather data and regional climate indices using machine learning in Morocco | Machine learning | Rainfed systems | Final yield prediction | Agricultural province unit | Unfavorable, intermediate, and favorable areas |
| | [87] | Relevance of soil fertility spatial databases for parameterizing APSIM-wheat crop model in Moroccan rainfed areas | APSIM | Rainfed systems | Monitoring crop growth and final yield, and assessment of soil fertility | Field level | Unfavorable, intermediate, and favorable areas |
| | [82] | GEPIC—modelling wheat yield and crop water productivity with high resolution on a global scale | EPIC | Rainfed and irrigated systems | Final yield prediction and assessment of crop water productivity | 50 km × 50 km elementary simulation unit | Unfavorable, intermediate, and favorable areas |

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**Table 7** (continued)

| Objective of crop modeling study (contribution) | References | Title of publication | Type of model | Type of cropping system | Concerned crop management practice | Contribution's primary scale | Concerned Agro-climatic zone |
|---|---|---|---|---|---|---|---|
| General strategies of crop management adaptation | [38] | Explaining yield and gross margin gaps for sustainable intensification of the wheat-based systems in a Mediterranean climate | Regression model | Irrigated and rainfed systems | Assessment of different factors responsible for yield gaps | Field level | Unfavorable, intermediate, and favorable areas |
| | [99] | Adaptation of Moroccan durum wheat varieties from different breeding eras | Regression model and the additive main effects and multiplicative interaction model (AMMI) | Irrigated and rainfed systems | Cultivar choice and breeding recommendations | Field level | Unfavorable, intermediate, and favorable areas |
| | [92] | Modeling the impact of conservation agriculture on crop production and soil properties in Mediterranean climate | APSIM | Rainfed system | Evaluation of conservation agriculture practices | Field level | Favorable area |
| | [42] | Towards precision agriculture in Morocco: a machine learning approach for recommending crops and forecasting weather | Machine learning | Irrigated and rainfed systems | Recommending optimal crop species to grow and forecasting of the hourly average air temperature | - | Unfavorable, intermediate, and favorable areas |
| | [24] | Modeling sustainable adaptation strategies toward a climate-smart agriculture in a Mediterranean watershed under projected climate change scenarios | Soil and Water Assessment Tool (SWAT) model | Rainfed system | Improve crops' water productivities using sowing dates and no-tillage adaptations | Watershed level | Favorable area |
| | [23] | Wheat (*Triticum aestivum*) adaptability evaluation in a semi-arid region of Central Morocco using APSIM model | APSIM | Rainfed system | Sowing date adaptations and cultivar choice | Field level | Unfavorable area |

**Table 7** (continued)

| Objective of crop modeling study (contribution) | References | Title of publication | Type of model | Type of cropping system | Concerned crop management practice | Contribution's primary scale | Concerned Agro-climatic zone |
|---|---|---|---|---|---|---|---|
| Crop modeling for within-season management advice | [43] | Weather-based predictive modeling of wheat stripe rust infection in Morocco | Threshold-based weather model | Rainfed system | Disease control | Field level | Favorable area |
| | [142] | Performance assessment of AquaCrop model for estimating evapotranspiration, soil water content and grain yield of winter wheat in Tensift Al Haouz (Morocco): application to irrigation management | AQUACROP | Irrigated system | Sowing date adaptations and irrigation scheduling | Field level | Favorable area |
| | [13] | Assessment of vegetation water content in wheat using near and shortwave infrared SPOT-5 data in an irrigated area | Regression models (satellite-based indices) | Irrigated system | Irrigation scheduling | Field level | Intermediate area |
| | [20] | Linkages between rainfed cereal production and agricultural drought through remote sensing indices and a land data assimilation system: a case study in Morocco | Regression models | Rainfed system | Monitoring and assessment of drought events | Agricultural province unit | Unfavorable, intermediate, and favorable areas |
| | [51] | Calibration and validation of the STICS crop model for managing wheat irrigation in the semi-arid Marrakech/Al Haouz plain | STICS | Irrigated system | Irrigation scheduling | Field level | Unfavorable area |

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cropping systems in rainfed circumstances. Among these are: (i) the importance of wheat for the country's food security, (ii) the aridity of the climate, (iii) the impacts of inter- and intra-annual variability of rainfall and increased recurrence of extreme events, particularly drought, and (iv) the adoption of inefficient crop management strategies due to a shortage of knowledge provision to Moroccan small farmers, or their indigent economic situation. Hence, critical efforts were established in development programs and scientific research to deal with the relevant constraints and limited conditions of Moroccan rainfed areas, such as increasing the reliance on efficient and sustainable adaptive strategies for cereal system management, such as the three axes of conservation agriculture, rational fertilization, and precision agriculture, among others. During the present work, we have highlighted the effectiveness of applying crop models for the assessment and enhancement of wheat cropping systems under Moroccan rainfed conditions. As described in the previous section, various types of models were adopted in past research studies and integrated into sophisticated systems to support the country's food security through monitoring wheat growth and yield forecasting. Moreover, several crop modeling works have contributed to increase understanding and address the climate change effects on wheat productivity. Their aims were mainly the evaluation of new crop management strategies, and recommending general adaptations to be applied in a wide spatiotemporal scale (e.g. agro-climatic unit). On the other hand, the use of crop modeling tools for within-season and on-farm specific crop management is very rare in Morocco. The few modeling studies conducted have focused mainly on water management (irrigation scheduling), and another on controlling crop diseases (Table 7). While other applications of models as decision support tools to manage soil and fertilization advice were unpublished contributions or conducted for commercial profit, i.e., with restricted access.

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