# 23

# Potential of Crop Simulation Models to Increase Food and Nutrition Security Under a Changing Climate in Nepal

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## Abstract

With current trends of increasing population, decreasing arable land, and a low yearly increment rate of cereal productivity, Nepal has an annual deficit of >1.3 million tons of edible rice, wheat, and maize. This indicates the urgent need for demand-led agricultural interventions for improving cereals productivity for food security. Crop simulation models and DSS tools have potential to predict potential yields, identify yield gaps, and help make decisions for improved crop, nutrient, water and pest management. Models can assess the impact of climate change, and help develop adaptation and mitigation measures to lesses the impact of climate change. To date, no review work has been conducted on the potential applications of crop simulation models and their relevance in Nepal. The objective of this chapter is to review and synthesize the relevant studies on the development and application of crop simulation models for major cereal crops: rice, wheat, and maize. We reviewed around 95 published papers and reports from South Asia and Nepal available in Scopus, SpringerLink, and ScienceDirect using the Google search engine. Analysis revealed that yield gaps (potential minus farmers' field yields) of 4.9–9.0, 3.1–6.9, and 4.5–12.5 t $ha^{-1}$ exist in rice, wheat, and maize crops, respectively. For achieving self-sufficiency in cereal grains, the average national productivity of rice, wheat, and maize needs to be increased to 5.7, 3.9, and 4.9 t $ha^{-1}$, respectively by 2030. Based on the review, climate change has both positive and negative consequences on cereal production across all agro-ecological zones. Crop simulation models have been applied for enhancing crop productivity and exploring adaptation strategies for climate change resilience. Models can generate various recommendations related to biophysical factors: crop, water, tillage, nutrient, and pest management, crop yield, and weather forecasting. Furthermore,

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J. Timsina et al. (eds.), *Agriculture, Natural Resources and Food Security*,
Sustainable Development Goals Series, https://doi.org/10.1007/978-3-031-09555-9_23

models have shown the potential to determine the effects of climate change on crop productivity across a range of environments in Nepal. In conclusion, crop simulation models could be useful decision support tools for policy planning and implementation, increasing efficiency in research, prioritizing research and extension interventions for increasing crop yields, and the way forward to achieve food and nutritional security and some of the Sustainable Development Goals (particularly #1, #2 and #13).

**Keywords**

Model application · Food security · Climate change · Yield gap · Decision support

## 23.1 Introduction

Rice, wheat, and maize are the main staple crops, which contribute more than 72% of the total calorie intake in the Nepalese diet (Kumar et al. 2020). The food security situation in Nepal has been challenged with the increasing annual population growth rate (+4.61% in urban and +1.19% in rural areas), declining arable land (−0.33%), and low cereal crops productivity growth rate (+1.98%) (Fig. 23.1; FAOSTAT 2021). The analysis of long-term FAOSTAT data compared to the initial (2000–2004) and final 5 years (2011–2016) revealed an increase in reliance of food security on import by almost 3-folds (289%; yearly increment by 14.58%). This trend is likely to increase in the upcoming years unless drastic measures are adopted (Fig. 23.1). Intergovernmental Panel on Climate Change (IPCC) food security projections for Nepal revealed that climate change is already affecting the food security situation and the effect will be much higher in the future, especially in the lower altitude regions. However, the higher altitude regions will see yield increment of the major cereal crops (Mbow et al. 2019).

The prevalence of high variability in soil, climate, and geographic conditions in the country require varying site-specific research recommendations. However, conducting intensive field research for generating site-specific recommendations under

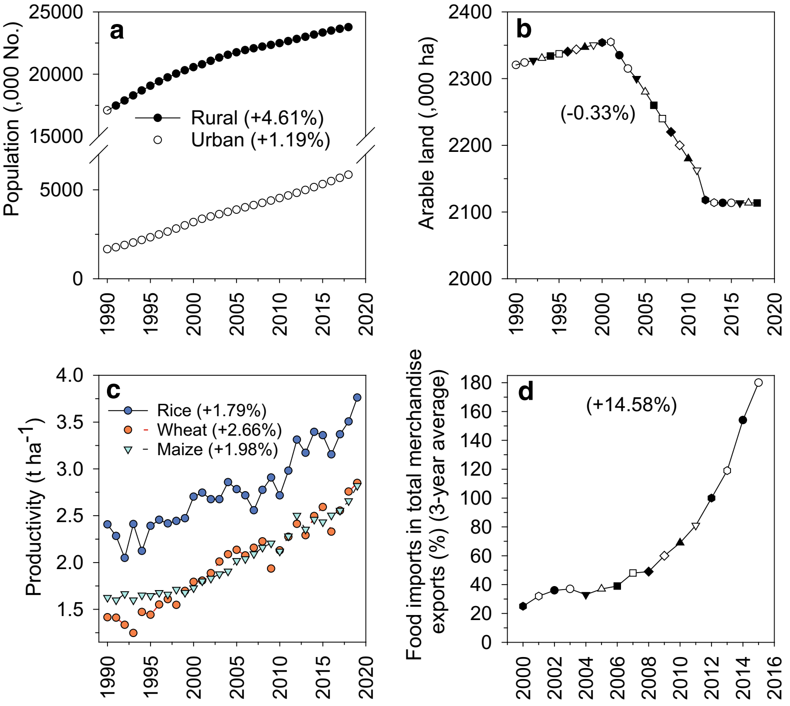

**Fig. 23.1** Trends of yearly rural and urban population growth **a**, arable land area **b**, averaged rice, wheat and maize productivity **c**, and value of food imports in total merchandise exports **d**. *Data source* FAOSTAT (2021). Figures in parenthesis yearly growth rate

diverse growing environments is resource-intensive. Furthermore, field experiments are time-consuming. Therefore, extrapolation of field studies using simulation models over different locations and time could help in scaling-out the recommendations, policy formulation, and adaptation to climate change. Simulation models are knowledge-based decision support systems (DSS) used to translate research results for the extension. Models help answer questions in research, provide pre-season and in-season management decisions in cultural practices, fertilization, irrigation, develop alternative crop management practices, and assist in the formulation of policy strategies and development (Penning de Vries et al. 1989; Boote et al. 1996). Models help improve understanding of the broader perspective of biophysical and socio-economic potential to enhance cereal crops' productivity and profitability to improve food and nutrition security. In this context, the application of crop, cropping or farming systems, and the landscape-scale simulation models are an alternative approach to achieve the intended goal of food and nutritional security with improved resilience to climate change.

Long-term trends (1991–2019) and projections for the next 10 years for cereal yield, population growth, and cereal crops deficits showed that the total deficit of these crops will decrease, with a recent annual deficit of >1.3 million tons (Fig. 23.2). The current trends of yield increments by 73,000 t year$^{-1}$ in rice, 46,000 t year$^{-1}$ in wheat, and 49,000 t year$^{-1}$ in raw maize show that the country still needs to either import a hefty amount of food or needs to launch a rapid productivity enhancement strategy.

This study involves the analysis of around 95 peer-reviewed published papers and reports from South Asia (60) and Nepal (35) available in Scopus, SpringerLink, and ScienceDirect using Google search engine using keywords 'food security, simulation model, climate change, yield gap, model application, agronomic management, and climate change adaptation' in the title, abstract, and entire text of the manuscript. Papers on: the application of simulation models for improving yield, closing yield gaps, and importance of agronomic management practices and crop varieties for improving food and nutritional security, and climate change impact and adaptation strategies in Nepal and South Asia were reviewed. Also, from the long-term historical data from FAOSTAT, additional productivity requirement for self-sufficiency was projected for the three major cereal crops of Nepal.

## 23.2 Simulation Model Application Framework

Smallholder farming systems are practiced in diverse biophysical, socio-economic, and policy environments in Nepal and South Asia. It is commonly observed that the biophysical conditions and improved technologies for obtaining desired crop yields do not satisfy sufficient incentives for the adoption of technologies by farmers. Hence, it is important to understand the socio-economic conditions under different scenarios, such as climate change and variability, changes in farmers' management practices ranging from crop to cropping or farming system to landscape level. Simulation modeling is an approach that describes processes of crop growth and development and yield formation as a function of biophysical (weather, soil, water, nutrients, and crop management) and socio-economic conditions using mechanistic and process-based computer models (Jones et al. 2003; Keating et al. 2003; Penning de Vries et al. 1989). Crop simulation models are useful DSS tools as they can generate relevant outputs ranging from crop yield and management recommendations, climate change mitigation and adaptation, ecosystem services, and institutional and policy reform (Fig. 23.3). Such models have the potential to quantify the magnitude of and identify factors responsible for crop yield gaps; they also suggest technological interventions considering the socio-economic and policy environments to help close those gaps. A robust analysis of yield gaps can help increase food production, meet food demand, reduce food import, and achieve food and nutritional security (Guilpart et al. 2016; Timsina et al. 2018). The application of crop simulation models, incorporating socio-economic and climate processes can contribute to

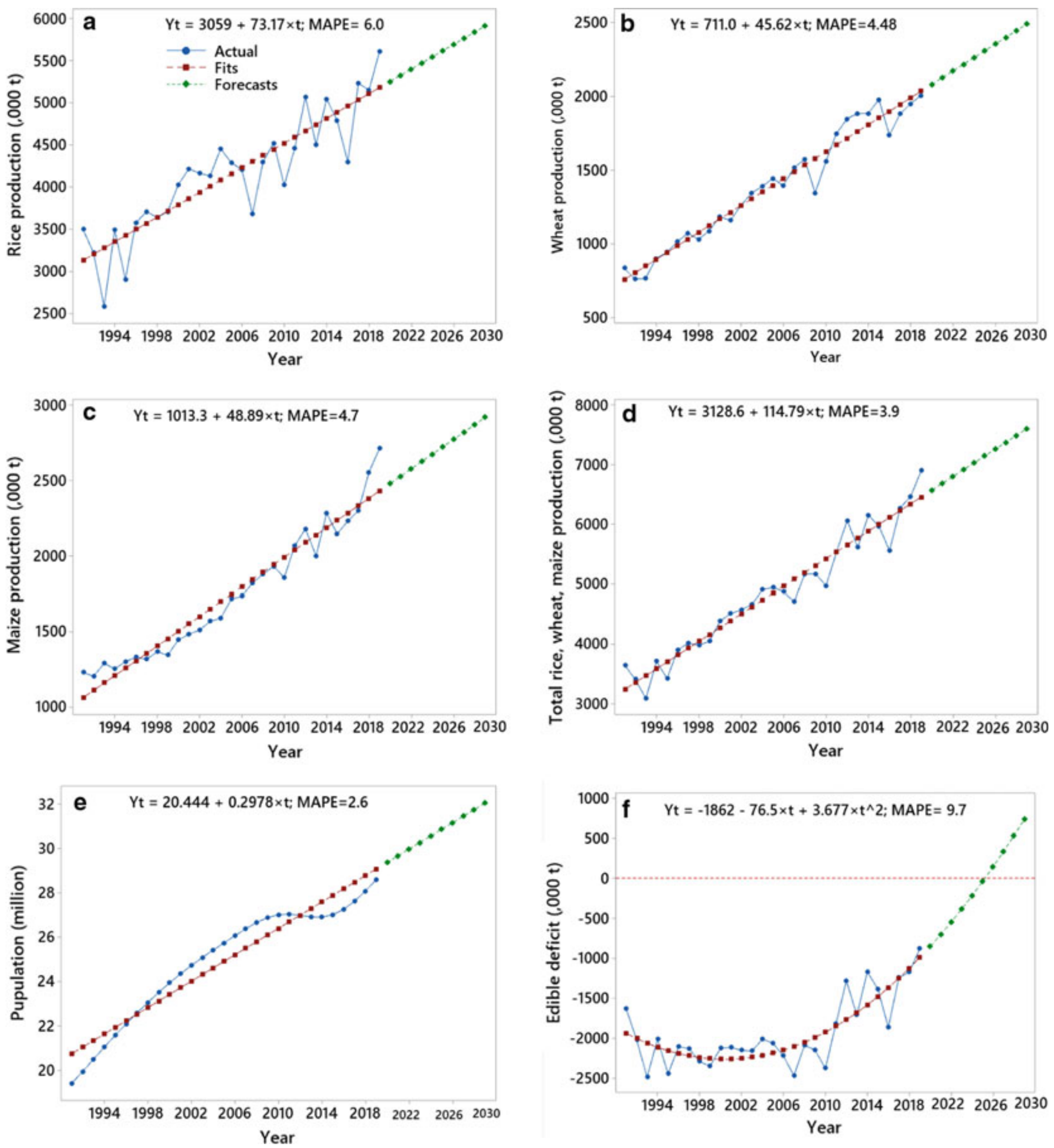

**Fig. 23.2** Yearly and projected (for next 10 years; green dotted lines in all six figures between 2020 and 2030) trends of production of rice (**a**), wheat (**b**), maize (**c**), total rice, wheat and maize in terms of edible production (**d**), population growth (**e**), and deficit in food supply from these three crops for the current and future population. Figs. A, B, and C are harvested grain yields; D is the total edible product from rice, wheat, and maize. Edible yield is derived by converting 60% milling recovery from rice, and 75% each for wheat and maize after reducing the losses during processing. F = deficit in terms of edible rice, wheat, and maize. Deficit computed subtracting demand from the supply (total edible rice, wheat, and maize). Demand was computed by multiplying each individual person by 272 kg for one year as suggested by Gauchan et al. (2021). MAPE = measure of the absolute percentage error in the model. *Data source* Recalculated and drawn from CBS (2019)

sustainable development goals (SDGs): poverty reduction (No. 1), zero hunger (No. 2), and climate action (No. 13). Since the three major staple cereals—rice, wheat, and maize—are vital for providing calorie and protein to the majority of smallholders and the urban population (Kumar et al. 2020), this chapter focuses on the application of simulation models for improving food and nutritional security in South Asia and in Nepal in particular.

Many of the crop simulation, econometric, and climate change models operate dynamically (Fig. 23.3). The biophysical information required for most of the simulation models is climate, soil, inputs used, and crop management practices. Such datasets can be derived from different sources, such as field experiments, household surveys, web-based data sources, remote sensing, and published literature. Besides simulating yields and other input use dynamics, most crop and cropping system models have the option of simulating economic profitability and trade-offs using the per-unit cost of production of input and output variables. With such models, information about the impact of climate change and the alternative management practices (adaptation and mitigation strategies) for changing climatic conditions are generated. Such models are used to predict the impact of alternative soil, climate, genotype, management conditions, profitability, soil organic carbon sequestration, enhancement of biodiversity and ecosystem services, institutional pathway, and policy and subsidy from local to global scale.

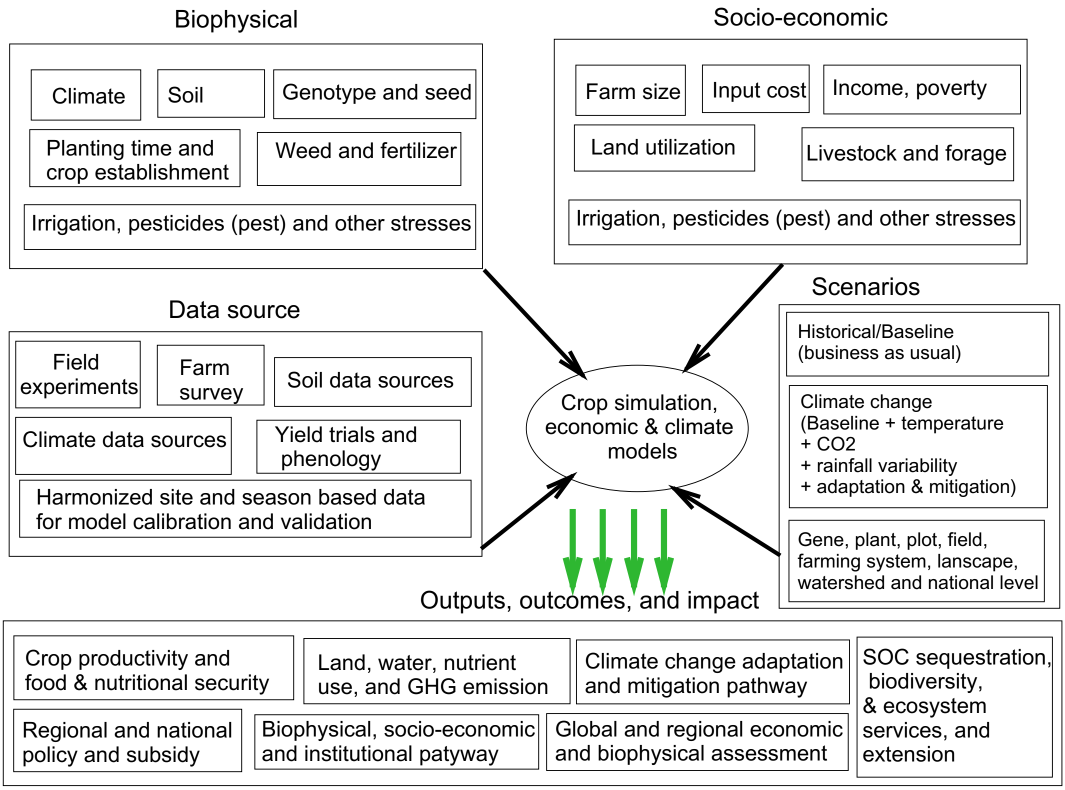

**Fig. 23.3** Processes and application of simulation models (*Source* authors' own work). SOC = Soil organic carbon; GHG = greenhouse gas emission

## 23.3 Evaluations and Applications of Crop Simulation Models

### 23.3.1 Evaluations and Applications in South Asia and Nepal

Several aspects of cereal production have been simulated using cereal crop growth models for improved understanding of research and policy issues related to increase in productivity and combat the effects of climate change (Timsina and Humphreys 2006a; Maraseni et al. 2021). Cereal crop growth models such as CERES-Rice, CERES-Wheat, and CERES-Maize embedded within DSS for Agro-technology Transfer (DSSAT) (Jones et al. 2003), Cool-Farm Tools (Hillier et al. 2011), ORYZA2000 for rice (Bouman et al. 2001), model embedded within Agriculture Production Systems Simulator (APSIM) (Keating et al. 2003). Similarly, other popular models include Hybrid-Maize (Yang et al. 2006), Quantitative Evaluation of Fertility of Tropical Soils (QUEFTS) (Janssen et al. 1990), FAO developed soil, water and plant management model AQUACROP (Foster et al. 2017), IWMI developed CRAFT (Shelia et al. 2019), CROPSYST (Stöckle et al. 2003), EPIC (Izaurralde et al. 2017), CROPWAT (Smith 1992), FARMSIM (van Wijk et al. 2009), World Food Studies (WOFOST) (van Diepen et al. 1989), Nutrient Expert (Pampolino et al. 2012), Rice Crop Manager (RCM) (Buresh et al. 2019), InfoCrop (Aggarwal et al. 2006), etc. for various purposes globally and in South Asia.

Several of these models are validated and applied in South Asia (Table 23.1), including Nepal (Table 23.2). Hence, they can be confidently applied in different agro-ecological zones (AEZs) for policy decisions in Nepal. Matthews et al. (2002), Reynolds et al. (2018), and Timsina and Humphreys (2006a) reviewed the application of CERES rice and wheat models for rice and wheat crops in Asia. These models have been applied mainly for crop genotype improvement, identification of desirable plant traits, environmental characterization, genotype x environment interaction, yield gap and yield trend analysis, and optimization of tactical crop management practices. Moreover, these models are applied in selecting appropriate establishment methods, planting and harvesting time, water and nutrient management, and pest and disease management, designing new cropping systems, evaluating sustainability, improving farming systems and rural livelihoods, land use and irrigation planning, strategic decision-making, and aiding government policies (Tables 23.1 and 23.2). In addition, they are also applied to predict the effects of climate change on crop yields, greenhouse gas emissions from agriculture, and short- and long-term climate and crop yield forecasting (Jha et al. 2019a, b; Table 23.2).

### 23.3.2 Increasing Cereal Yields and Improving Food Security in Nepal

Most globally used crop simulation models are for strategic and tactical decision-making, and for yield forecasting purposes with the goal of maximizing crop productivity and profitability with reduced environmental footprints. Crop, soil, water, and climate simulation models have the ability to integrate the results of research from many different disciplines and locations and offer a new way of improving efficiency by reducing research costs (Stephens 2002). In Nepal and largely in South Asia, much of the modeling work has focused on understanding the interactions between the various factors of production influencing crop growth and development, such as climate, water, nutrient supply, crop management practices, biotic and abiotic stresses, optimizing crop calendar and management practices for maximizing yields with sustainability, and improving resilience to climate change (Tables 23.1 and 23.2).

**Table 23.1** Summary of validations and applications of simulation models for cereal crops in South Asia

| Model used | Crops | Validation and application country/regions | Validation and application | References |
|---|---|---|---|---|
| CERES rice and CERES wheat | Rice and wheat | India and Pakistan | Climatic potential yield, yield gap, sensitivity analysis, temporal and spatial simulated yield trend | Pathak et al. (2003) |
| CERES-rice | Rice | Bangladesh, India, China | Strategic decision-making and planning | Singh and Thornton 1992), Timsina et al. (1997) |
| CERES models | Rice, wheat, maize | Punjab, India, Nepal, Bangladesh | Tactical management strategies | Singh and Thornton (1992), Timsina et al. (1997) |
| CERES-rice | Rice | South Asia | Prediction of greenhouse gas emission | Matthews et al. (2000) |
| CERES models | Rice, wheat, maize, and other cereals | Nepal, India, Bangladesh, Thailand, Philippines, Japan, China, Pakistan, Indonesia, Taiwan, Vietnam | Phenology, biomass and grain yield trends, growth, nitrogen (N) and water balance, strategic decision, tactical management, climate change study, predicting greenhouse gas, pest and disease management, policy formulation | Timsina and Humphreys (2006a, b) |
| CERES rice and CERES wheat | Rice and wheat | Punjab, India | Phenology, water and nitrogen management, climate change | Amgain et al. (2004, 2008) |
| APSIM and DSSAT models intercomparison | Rice and wheat | Pakistan | Climate change projections, trade-off analysis for multidimensional impact assessment, adaptation strategies of climate change on sowing density, improved cultivars, increase in N use, and fertigation | Khalid Anser et al. (2020) |
| APSIM | Rice, wheat, maize, cotton, soybean, mustard | Philippines, Indonesia, India, Bangladesh, Sri Lanka, Nepal, Bhutan, Pakistan, Japan, China, Cambodia, Laos | Crop phenology, yield trends, water-use efficiency and balance, soil dynamics (water, organic carbon, N), crop $CO_2$ response, soil salinity, sowing date, photoperiod | Gaydon et al. (2017), Timsina et al. (2021), Devkota et al. (2016) |
| INFOCROP, and STICS | Rice, wheat, maize, peanut | South Asia | Yield, impact of climate change | AgMIP (2012), Kaur and Singh (2020) |

(continued)

**Table 23.1** (continued)

| Model used | Crops | Validation and application country/regions | Validation and application | References |
|---|---|---|---|---|
| InfoCrop | Rice, wheat, pearl millet, maize, potato, cotton, and mustard | Several locations of India | Crop yields, pests, and environmental impacts in tropical environments (location, seasons, varieties, nitrogen management, organic matter, irrigation, and multiple pest incidences) | Aggarwal et al. (2006) |
| ORYZA | Rice | Several Asian countries | Growth, development, potential yield, water- and nitrogen-limited yield | Devkota et al. (2021), Li et al. (2017), Sudhir-Yadav et al. (2011) |
| Rice crop manager (RCM) | Rice | India, Bangladesh | Field-specific nutrient management in rice | Sharma et al. (2019) |
| Cool farm tool | Rice, wheat | South Asia | Precision nutrient management, nutrient use efficiency, and environmental footprint | Sapkota et al. (2014) |
| QUEFTS | Wheat | South Asia | Site-specific fertilizer recommendation | Maiti et al. (2006) |
| Hybrid-maize | Maize | South Asia | Growth, phenology, yield, irrigation management, yield forecasting | Timsina et al. (2010) |
| Oryza-2000 and hybrid maize | Rice–maize system | Bangladesh | Yield potential and yield gaps in rice–maize system | Guilpart et al. (2016) |
| CERES wheat within DSSAT | Wheat | Punjab, India | Yield, phenology, water management, and water productivity | Timsina et al. (2008) |
| CERES rice and CERES wheat; sucrose rice–wheat rotation model | Rice–wheat system | Pantnagar, India | System productivity, long-term yield, nutrients and soil organic carbon trends | Timsina et al. (1994, 1995, 1996) |
| CERES rice and CERES wheat | Rice–wheat system | Dinajpur, Bangladesh | Phenology, system productivity, Long-term yield and nutrients trends | Timsina et al. (1997) |
| Oryza 2000, hybrid maize, CERES wheat | Rice, wheat, and maize | Bangladesh | Estimation of yield potential and yield gap analysis, projection of food demand and food security | Timsina et al. (2018) |
| CRAFT | Cereal crops | South Asia | Forecasting crop production, risk analysis, and climate change impact studies | Shelia et al. (2019) |

*Note* These are just examples of some cereal crop models validated and applied in South Asia and is not the complete list of all models used

**Table 23.2** Summary of validations and applications of simulation models for cereal crops in Nepal

| Model used | Crops | Validation and application regions | Validation and application | References |
|---|---|---|---|---|
| CERES rice, CERES wheat, and CERES maize | Rice, wheat, and maize | Nepal | Phenology, yield, climate change effects; CA and N management in mid-hills | Amgain et al. (2019), Laborde et al. (2019), Timsina et al. (1997) |
| CERES rice | Rice | Nepal Terai | Crop yield forecasting | Jha et al. (2019a) |
| CERES maize | Maize | Chitwan, Palpa, Dailekh, Illam, Nuwakot, Kaski, Salyan, Surkhet, Tananun, Bhojpur, Okhaldhunga, Doti districts | Yearly variability and impact of climate change in maize, maize yield gap, planting time, variety, N and phosphorus (P) fertilizers rate, growth and yield | Bhusal and Timsina (2010), Devkota et al. (2015), Devkota et al. (2016), Sapkota et al. (2008) |
| APSIM model and ground and satellite-based approaches | Wheat | Nepal Terai | Yield, soil-dependent crop yield outcomes | Campolo et al. (2021) |
| Nutrient expert | Rice, wheat, maize | Nepal Terai | Optimization of fertilizer recommendation using 4R stewardship | Amgain et al. (2021), Bhatta et al. (2020), Thapa et al. (2020), Timsina et al. (2021, 2022) |
| AquaCrop | Rice, wheat, maize | Chitwan district | Irrigation water and fertilizer management, yield response, closing yield gap | Shrestha et al. (2013a, b) |
| Poly-crop | Rice, wheat, maize | Solukhumbu and and Kotang districts | Food security, climate change, crop yield, land use | Bocchiola et al. (2019) |
| DEED | Cereal crops and cropping systems | Nepal | Forecasting soil organic carbon and cereal crop yields | Adhikari et al. (2019), Acharya et al. (2019) |
| Climate forecasting | Cereal crops | Nepal Terai | Daily, monthly, and seasonal forecasting of temperatures, solar radiation and rainfall | Jha et al. (2019b) |

*Note* These are few examples of some cereal crop models validated and applied in Nepal and is not the complete list of all models used

### 23.3.3 Estimating and Understanding Yield Potential and Yield Gaps

In irrigated system, yield potential (Yp) is defined as the yield of a crop cultivar grown under non-limiting water and nutrient and crop free of biotic stresses, where crop growth is determined by solar radiation, temperature, atmospheric $CO_2$ concentration, and genetic characteristics (Evans 1996). Yp varies across genotypes and locations due to differences in climate, but not due to soil characteristics or any stresses such as nutrients, pests, and diseases.

Thus, Yp (i.e., climatic potential yield) serves as the benchmark for yield gap analysis. In the rainfed system, water-limited yield potential (Yw), the most relevant benchmark, is determined by rainfall events, soil water availability based on soil and terrain properties, and crop free of biotic and abiotic stresses.

The nutrient-limited yield gap is computed based on the economic sufficiency and deficiency of nutrients obtained from the farmers' practice (Devkota et al. 2018; Dobermann et al. 2004). The concept of yield gap (Yg) is rooted in the production ecology and is defined as the difference between Yp or Yw and actual farm yield. Yg provides a framework for contextualizing current farmer yields against Yp in different production environments, including at the cropping systems level (Guilpart et al. 2016; Lobell et al. 2009; van Ittersum et al. 2013). Nevertheless, Yg analysis will be of limited use for intervention prioritization in the context of agricultural development if the multiple causes of lower productivity at the farmer's level are not identified; i.e., Yg must be 'decomposed' by their constituent factors (Devkota et al. 2015, 2016, 2021; Lobell et al. 2009).

The prediction made by Amgain and Timsina (2004) and Krupnik et al. (2021) from several districts of Nepal showed that large Yg existed between simulated climatic potential yield, on-station yield, farmers' yield, and national statistics. The potential yield was exceptionally high, ranging from 8 to 13 t $ha^{-1}$ for rice, 6–15 t $ha^{-1}$ for maize, and 5–8 t $ha^{-1}$ for wheat (Fig. 23.4, Table 23.3; Devkota et al. 2021; Timsina et al. 2021; Amgain and Timsina 2004), while remarkably low national average yields of 3.76, 2.85, and 2.82 t $ha^{-1}$ existed respectively for rice, wheat, and maize (FAOSTAT 2021). Considering farmers' field yields of these crops, yield gaps ranged from 4.9 t $ha^{-1}$ for rice, 4.5-12.5 t $ha^{-1}$ for maize, and 3.1-6.9 t $ha^{-1}$ for wheat (Table 23.3). These data indicate the existence of huge yield gaps between climatically potential

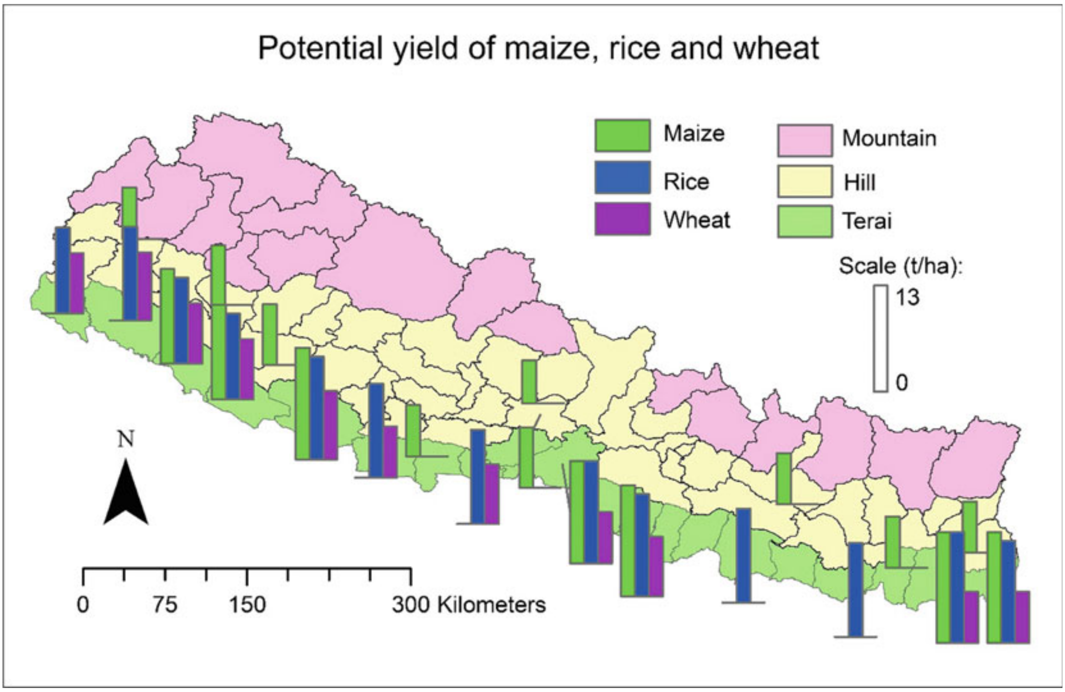

**Fig. 23.4** Climatic potential yield of rice, wheat, and maize across Terai, hill and mountain agro-ecological zones (AEZ) in Nepal. Black arcs/lines represent district boundaries. *Data source* Devkota et al. (2016, 2021); Timsina et al. (1997, 2021)

**Table 23.3** Yields and yield gaps (t $ha^{-1}$) of rice, maize, and wheat crops in three agro-ecological zones of Nepal

| Crop | Agro-ecological zones | Potential yield (A) | Research station yield (B) | Farmers' yield (C) | Yg1[a] (A–B) | Yg2 (B–C) | Yg3 (A–C) | References |
|---|---|---|---|---|---|---|---|---|
| Rice | Terai | 8.7 | 5.06 | 3.78 | 3.64 | 1.28 | 4.92 | Timsina et al. (2021) |
| | Terai | 8.1 | 3.40 | 2.74 | 4.10 | 0.66 | 5.36 | Krupnik et al. (2021) |
| | Nepal | 10–13 | 5.0 | 3.76 | 5–8 | 1–2 | 6–9 | Fig. 23.4 |
| | Terai¶ | 12 | 5.06 | 3.5 | 6.9 | 1.56 | 8.5 | – |
| | Mid-hill | 11 | 5.0 | 3.12 | 6.0 | 1.88 | 7.88 | – |
| | High-hill | 10 | 4.0 | 2.34 | 6.0 | 1.66 | 7.66 | – |
| Wheat | Terai | 5.5 | 3.06 | 2.39 | 2.44 | 0.67 | 3.11 | Timsina et al. (2021) |
| | Terai | 5.03 | 3.50 | 1.88 | 1.53 | 1.62 | 3.15 | Krupnik et al. (2021) |
| | Nepal | 6–8 | 4.0 | 2.82 | 2–4 | 1–2 | 3–5 | Fig. 23.4 |
| | Terai | 8 | 3.06 | 2.61 | 4.9 | 0.45 | 5.39 | – |
| | Mid-hill | 8 | 3.5 | 1.07 | 4.5 | 2.43 | 6.93 | – |
| | High-hill | 7 | 3.0 | 1.64 | 4.0 | 1.36 | 5.36 | – |
| Maize | Terai | 13.4 | 10.11 | 5.76 | 3.29 | 4.35 | 7.64 | Timsina et al. (2021) |
| | Terai | 6.3 | 3.30 | 1.82 | 3.0 | 1.48 | 4.48 | Krupnik et al. (2021) |
| | Nepal | 11–13 | 8.0 | 2.85 | 3–5 | 4–5 | 8–10 | Fig. 23.4 |
| | Terai | 13 | 10.11 | 4.15 | 2.9 | 5.96 | 8.85 | – |
| | Mid-hill | 15 | 11 | 2.53 | 4.0 | 8.47 | 12.47 | – |
| | High-hill | 11 | 7 | 1.94 | 4.0 | 5.06 | 9.06 | – |

[a] Yg1 = Yield gap 1; Yg2 = Yield gap 2; Yg3 = Yield gap 3

and farmer's field yields. They reveal an urgent need for the implementation of the science-led approach to maximize cereal productivity for food self-sufficiency. This also suggests that Yg 1 (gaps between Yp and those typically obtained on research stations) was larger for rice than that for open-pollinated variety (OPV) maize and wheat, suggesting that the use of high-yielding rice varieties, good integrated soil and agronomic practices required to reduce these gaps. A recent study by Devkota et al. (2021) has shown rice Yg in the Terai region can be closed by 1.85 t $ha^{-1}$ (48%) through the use of integrated agronomic management packages. Yg 2 (between research stations and yields obtained by farmers) was larger for wheat than the other two crops, suggesting that farmers' management for wheat was poor; thus, the extension of recommended technologies to farmers and their adoption will help increase wheat yields and reduce Yg. The large Yg in maize can be closed through improved varieties (1.4 t $ha^{-1}$), fertilizer (1.75 t $ha^{-1}$), optimal plant population (0.9 t $ha^{-1}$), integrated weed management (0.87 t $ha^{-1}$), and with the package of best agronomic management practices from 2 t $ha^{-1}$ (under farmers' practice) to 4.5 t $ha^{-1}$ in the rainfed mid-hill region of Nepal (Devkota et al. 2016; Table 23.3).

Timsina et al. (1997, 2010, 2011) reported that the long-term mean Yp of rice (12 t $ha^{-1}$), maize hybrid (15 t $ha^{-1}$), and wheat (7 t $ha^{-1}$) estimated by ORYZA 2000, Hybrid-Maize and CERES models in Chitwan, Central Terai under optimal crop planting, suitable varieties, non-limiting water and nutrient, and control pests and disease conditions. Sustainable intensification of crop production is required to feed the growing population. Sustainable intensification is associated with growing two or more crops with optimal inputs and management practices using short- or medium-duration high-yielding varieties, which can minimize the yield gaps (Devkota et al. 2021; Timsina et al. 2021; Amgain and Timsina 2004).

Farmers' decisions on resource allocation, prioritization, and crop management practices for closing the Yg depend on objectives, resource constraints, synergies, and trade-offs between different components/activities, thus requiring an in-depth analysis at the farm level (Silva, 2017). In this context, other methods of analyzing Yg, for instance, crop yields and resource-use efficiencies using stochastic frontier analysis (SFA) and determining technically efficient Yg (Dossou-Yovo et al., 2020; Silva, 2017). Similarly, Devkota et al. (2018, 2021) determined Yg using machine learning and categorizing farmers into different Yg groups.

### 23.3.4 Simulating the Impact of Climate Change on Cereal Productivity

The IPCC Third Assessment Report (IPCC 2001) projected that from 1990 to 2100, the average global temperature is likely to increase by 1.4–5.8 °C, with a substantial rise in intensity and frequency of rainfall and extreme events (floods, drought, cyclones, wildfire). The climate change scenarios for Nepal show an increase in the average annual mean temperature and rainfall; where temperature will increase by 0.9–1.1 °C in medium-term (2016–2045), 1.3–1.8 °C in the long-term (2036–2065), and 1.7–3.6 °C in 2100. Similarly, there will be an increase in rainfall by 2–6% in the medium-term, 8–12% in the long-term, and 11–23% in 2100 (MoFE 2019). The recent IPCC 6th report (Shukla et al. 2019), which consists of improved methodologies compared to the earlier reports, has projected an even higher (at least by 0.1 °C) increase in temperature. Furthermore, the projected effect of climate change shows there might be a shift in bioclimatic conditions, which will affect the crop calendar, rainfall and temperature patterns, and glacial melting in Himalayan countries of South Asia including Nepal. Zomer et al. (2014) predicted that by 2050 over 76% of the total area may shift to a different stratum, 55% to a different bioclimatic zone, and 37% to a different ecoregion, with an upward shift in elevation of bioclimate (357 m) and ecoregions (371 m). Due to changes in those climatic factors, there will be a significant and substantial impact on the country's agricultural production, food security, and socio-economic conditions across the three AEZs (mountain, hill, and terai). Table 23.4 summarizes major projections related to climate change and its impact on food production in Nepal.

Besides the effect on grain yield, in all three AEZs, climate change impacts crop growth duration (APN 2005), planting time, and seasonal and spatial soil water balance. Such impacts result in increased disease and insect pressure and abiotic stresses, and increased demand for alternative crops and varieties (Krupnik et al. 2021). Because of the fragility, marginality, and small scale (~0.7 ha) nature of subsistence farming in Nepal, coping strategies and capacity for adaptation to climate change are also low (Bocchiola et al. 2019). Such conditions demand for the development of smart and climate-resilient agricultural practices for smallholders.

### 23.3.5 Simulation Models as DSS Tools for Adaptation Strategies and Input Optimization

With the current and predicted climate change conditions (IPCC 2013), an absence of appropriate adaptation strategies will exert further negative impacts on the livelihood and food security situation of the smallholder farming communities. Knowledge-driven field and landscape-scale DSS tools can provide guidance for developing adaptive crop production practices through the better choice of crops, varieties

**Table 23.4** Projected climate change and its impact on cereal crops production in Nepal

| Methodology/Study | Climate change scenario | Impact on cereal crops yield | References |
|---|---|---|---|
| 13 general circulation models (GCM) from 67 meteorological stations in Nepal by Asia Pacific-network (APN) | Temperature increase of 2.89 °C in winter and 2.09 °C in summer in 2050 and 4.96 °C in winter and 3.67 °C in summer in 2080 compared to base year 1971–2005 | Both positive and negative consequences across all three AEZs of the country | APN (2005) |
| Simulation using 13 GCMs by APN using DSSAT-CERES models | +250 ppm $CO_2$ concentration | Rice yield: +9.5% in Terai, +5.9% in hills and +16.6% in mountains;<br>Wheat yield: +41.5% in Terai, +24.4% in hills and +21.2% in mountains;<br>Maize yield: +9.0% in Terai, +4.9% in hills and +15.5% in mountains | APN (2005) |
|  | +250 ppm $CO_2$ + 4 °C increase in mean temperature | Rice yield: −3.4% yield Terai, +17.9% in hills and +36.1% in mountains;<br>Wheat yield: −1.8% Terai, +5.3% hills and +33.3% in mountains;<br>Maize yield: −26.4% in Terai, −9.3% in hills and +26.8% in mountains |  |
|  | +250 ppm $CO_2$ +4 °C temperature +20% rainfall | Rice yield: −0.8% in Terai, −14.6% in hills, and +39.1% in mountains |  |
| Using stochastic production functional model | Effect of climate change (rainfall and minimum, maximum and average temperature) | Rainfall variability worsen the effect of climate change. Decrease summer maize while increase rice and wheat yield | Poudel et al. (2014) |
| Climate–crop yield relationship and impact of climate change on rice, maize, and wheat yields in Koshi River Basin in eastern Nepal | Increased effect of temperature (disregarding $CO_2$ fertilization) | In altitude <1100 m for rice, <1350 m for wheat and <1700 m for maize, crops suffer from high temperature. Flowering and yield formation processes affected. Rice, wheat, and maize yields decreased by −6 to 16%, −4 to 11%, and −12 to 3%, respectively | Bhatt et al. (2014) |
|  | +1 °C increase in maximum temperature | −23.6 kg $ha^{-1}$ $year^{-1}$ maize yield;<br>+44.9 kg $ha^{-1}$ $year^{-1}$ wheat yield;<br>No effect on rice yield |  |
|  | +1 °C increase in minimum temperature | +68, +7, and +56 kg $ha^{-1}$ $year^{-1}$ increase rice, maize, and wheat yields, respectively |  |

(continued)

**Table 23.4** (continued)

| Methodology/Study | Climate change scenario | Impact on cereal crops yield | References |
|---|---|---|---|
| Poly-crop model using daily rainfall, maximum and minimum temperature, and solar radiation in Dudh Koshi river basin in eastern Nepal | Under three climate change scenarios provided by IPCC (2013) (RCP 2.6, 4.5, 8.5) during 2040–2050 and 2090–2100 | Maize area increases at higher altitudes (1500–2500 m); wheat area increases between 500 and 1500 m altitudes; rice area decreases at the intermediate altitudes (250–1500 m), with some increases at 1500–1800 m altitude | Bocchiola et al. (2019) |
| The impact of climate change on rice production in Nepal using stochastic frontier model in 28 districts | +1 °C increase in average summer temperature | −0.48% (−4183 kg ha$^{-1}$ season$^{-1}$) reduction in rice production | Rayamajhee et al. (2021) |

and cropping systems, management practices, and inputs optimization for improved food and nutrition security.

#### 23.3.5.1 Fertilizer Application and Site-Specific Nutrient Management

Crop simulation models can be used to optimize fertilizer and nutrient management in cereal crops and estimate their yields in cropping systems. Such models and the DSS tools and Nutrient-Expert (NE) for rice, wheat, and maize have been used for site-specific and crop demand-based fertilizer recommendations in cereal crops in Nepal. Balanced application of organic and inorganic fertilizers increases cereal yields in farmers' fields through improved soil quality and fertility and develops plants' resistance to insects and diseases. In addition, the application also improves soil nutrient balance, optimizes water application, and consequently improves the long-term sustainability of the cropping system (Devkota et al. 2016, 2018; Krupnik et al. 2021; Timsina 2018). In the recent studies by Amgain et al. (2021), Bhatta et al. (2020), Thapa et al. (2020), and Timsina et al. (2021, 2022), NE-based nutrient recommendations indicate that cereal yields, profits and energy- and water-use efficiency can be increased, energy use and GHG emissions can be reduced, and crop yield gaps can be narrowed in Terai and western mid-hills regions. A high disparity in Yp and district-specific attainable yield exists, requiring domain-specific recommendations of N fertilizer rates varying between 65 and 208 kg N ha$^{-1}$ (Devkota et al. 2016).

The optimal seeding date of maize is important but may vary in different locations. Seeding beyond optimal date causes prolonged growth and develops a high risk of crop failure due to temperature (hot or cold) (Devkota et al. 2015). Devkota et al. (2016) observed that the response of maize hybrids was significantly higher than OPVs to fertilizer and seeding date. In a western mid-hill district (Palpa), under rainfed conditions hybrids responded up to 180:60:60 kg N:P:K ha$^{-1}$ while the plateaus were between 120–180 kg ha$^{-1}$ for N and 30–60 kg ha$^{-1}$ for P and K nutrients for OPV. Optimal fertilizer rates for both maize varieties differed based on seeding date (Devkota et al. 2016). Considering small-scale spatial soil and climatic variability, especially in hill ecology, improved understanding of farm-level nutrient management recommendations using the Nutrient Expert (NE) tool helps to make informed farmers and extensionists.

#### 23.3.5.2 Irrigation Scheduling, Water Management, and Water and N Interaction in Cereals

Crop simulation models can also be used to optimize water management in cereals and estimate their yields under different soil and crop management practices. Application of supplementary irrigation through improved agricultural water management, for example, water harvesting, crop demand-based irrigation scheduling, or efficient irrigation techniques helps improve and stabilize yields under the prevailing rainfall variability. In the context of Nepal, more than 65% of rice production is under the rainfed system; the application of supplementary irrigation might improve the sustainability of rice production. In a long-term simulation with ORYZA3 using historical rainfall data (where rainfall amount declined over time) in eight Terai districts of Nepal, Krupnik et al. (2021) showed that rice yield decreased by 21% under rainfed conditions, while it increased by 2% with supplementary irrigation. It indicates that with increasing rainfall variability (>27%) during the rice-growing season, the availability of irrigation facilities is the assured way for improving resilience and yield stability in the Terai region of Nepal. In the Terai region, it is possible to increase the availability of supplementary irrigation through: (i) increasing irrigated area either by building new irrigation structures and rehabilitation of old structures; (ii) constructing appropriate excess water harvesting small reservoirs for supplementary irrigation; (iii) improving on-farm agricultural water management practices; and (iv) reducing unproductive water losses through the adoption of crop demand-based irrigation scheduling and efficient application techniques (drip, sub-surface drip, sprinkler, furrow irrigation, etc.). It is envisioned that irrigation will remain a key policy and development intervention for the next few decades for the Nepal government.

From the experimental and simulation study using the AquaCrop model, Shrestha et al. (2013a, b) reported that for wet (monsoon) season, soil nutrient management is more important than water management, while for dry season (winter and spring) water management coupled with nutrient needs to be considered in central Terai region (Chitwan). They found that during the summer season, with improved nutrient management rice and maize yields could be increased by 65 and 58%, respectively; while in the dry season, with improved water and nutrient management, wheat and spring maize yields can be increased by 197% and 100%, respectively.

#### 23.3.5.3 Effects of Crop Varieties and Time of Planting on Simulated Yields

Maize yields in the mid- and high-hills regions of Nepal are judged to be intractably low, and few efforts have systematically assessed either the water-limited productivity potential or identified sensible entry points toward sustainable intensification that can be matched to the needs and constraints faced by farmers. Devkota et al. (2015) from the long-term simulation using CERES Maize found long maturity does not always mean high yield. The OPV maize had the lowest and the long-duration hybrids had the highest yield, with short-duration hybrids having the intermediate yield (Fig. 23.5). Devkota et al. (2017), with a rice simulation model, reported that across the AEZs of Nepal, rice can be planted starting from February up to the end of July based on the availability of irrigation water. Rice transplanting in June requires the lowest irrigation amount as it can utilize the rainfall effectively (Fig. 23.5). Varietal response, as well as the variety and seeding date interaction in yield differs significantly in rice as well. Under late planting, yield declined earliest for a long-duration variety (Swarna) but was the slowest for the short duration variety (Radha-4).

The long-term (1987–2013) simulation using CERES Maize (yearly simulation at every 10 days interval) was used to explore the opportunities for closing maize yield gaps with optimal seeding date and suitable variety for the mid-hill ecology of Nepal (Devkota et al. 2015). Authors reported that planting either before 25 April or after 20 May could reduce Yp by 19% in short-duration hybrid and by 11% in long-duration hybrid and OPV (Fig. 23.5). Fortunately, these optimum planting windows have the lowest level of intra-annual variability in Yp and the lowest risk of crop mortality before physiological maturity. In contrast, there was a sharp drop in Yp and a high risk of crop mortality with planting before mid-April due to

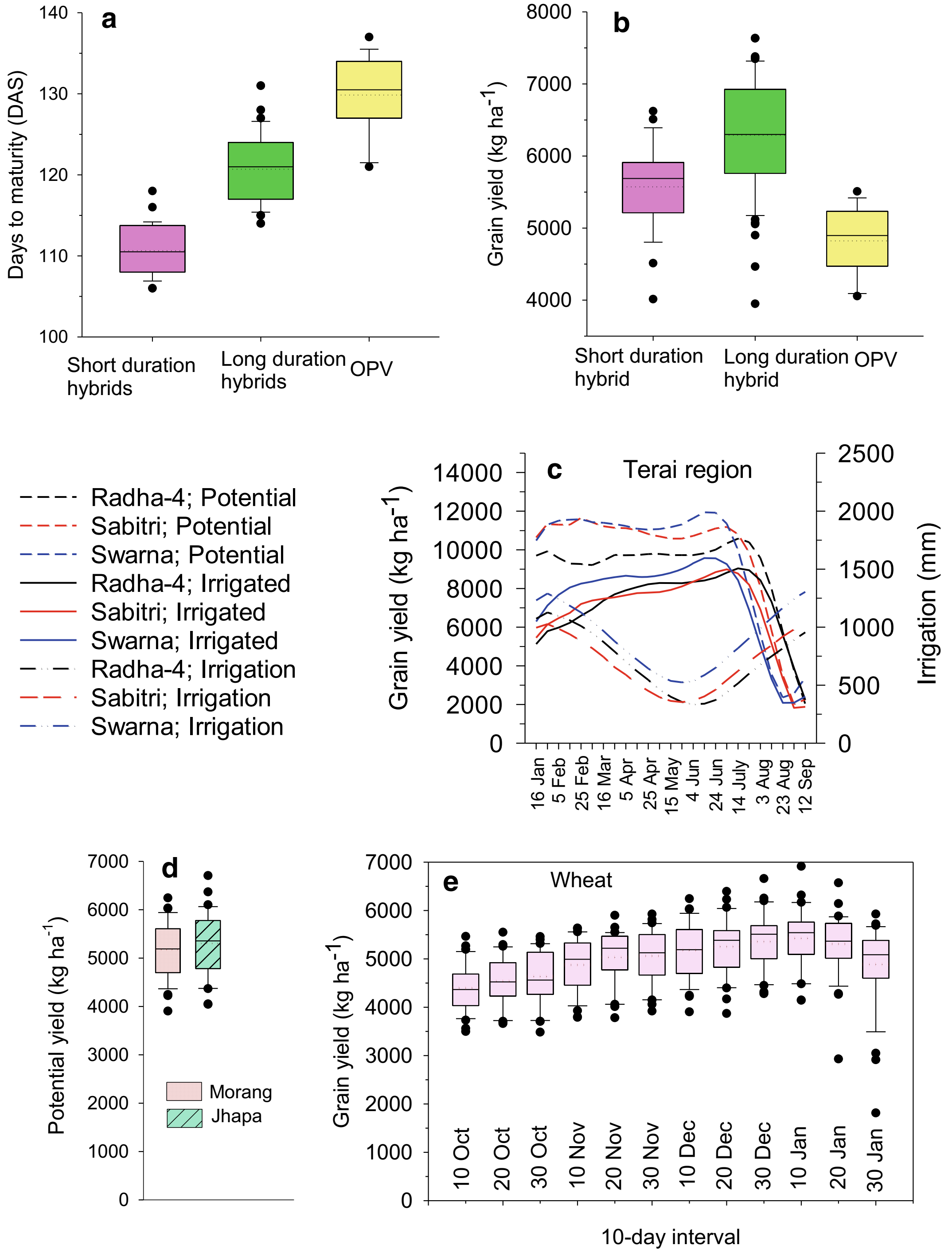

**Fig. 23.5** Simulated maturity days (**a**) and grain yield (**b**) of three category maize varieties, and simulated potential and irrigated yields of three rice varieties for 13 seeding dates (spring and monsoon season rice) and the irrigation requirement (excluding rainfall) in Terai region (results from simulation for 8 Terai districts, **c** and simulated potential yield for 10 January planting **d** and for 12 seeding dates at 10 days interval (**e**) for Jhapa and Morang districts. *Source* Devkota et al. (2015) for Figs. a and b, Devkota et al. (2017) for Fig. c and Timsina et al. 2021 for Figs. d and e. OPV = open-pollinated variety

moisture limitations. The implications of late planting (e. g., beyond 10 June; DOY 160) are less severe for maize Yp but come at the additional cost of delaying the establishment of the second crop in the rotation (Fig. 23.5). For wheat, Timsina et al. (2021) reported that its Yp across years ranged from 3.5 to 5.5 t $ha^{-1}$ (mean: 4.4 t $ha^{-1}$) for 10 October and from 4 to 7 t $ha^{-1}$ (mean: 5.5 t $ha^{-1}$) for 10 January planting. Further, Yp was lower, ranging from 4.0 to 6.5 t $ha^{-1}$ and from 4.0 to 7.0 t $ha^{-1}$ with a mean yield of 5.5 t $ha^{-1}$ in the two sites (Group 1: Babiya Birta and Itahara in Morang, and group 2: Damak and Gauradaha in Jhapa), respectively when planted on December 10th.

### 23.3.6 Matching Productivity Required for Self-Sufficiency

Our long-term analysis (1991–2019) using a regression model, considering the amount of imported, current production, and actual area under respective crops revealed a deficit of 0.4, 0.23, and 0.42 t $ha^{-1}$ of rice, wheat, and maize grains in 2019, respectively. This deficit is equivalent to the deficit of 11, 8, and 15% respectively for these crops; in terms of edible products, it is a total of 1.3 million tons (Fig. 23.2). Currently, Nepal is meeting this deficit from import (Fig. 23.6). The regression models ($R^2$ = >0.65 in all cases) showed that this gap will be much higher in 2030, where for attaining self-sufficiency, the productivity of rice, wheat, and maize needs to be increased to 5.7, 3.9, and 4.9 t $ha^{-1}$ to sustain the current rate of population growth (Fig. 23.2; Fig. 23.6). If the productivity remained constant (as current; 4.4, 3.3, and 3.7 t $ha^{-1}$ for rice, wheat, and maize, respectively) by 10 years the deficit will be 38, 25, and 25% than the required. In this scenario, the import value will be three times higher than the current amount in 2030. This analysis has clearly shown that the current effort in agronomy, breeding, and other required sciences to increase cereal productivity for achieving self-sufficiency is largely inadequate and greater efforts will be required. As shown by the various simulation results earlier, additional gains in cereal production should come from science-led and demand-driven knowledge and technologies.

## 23.4 Policy Implications and Recommendations, and Limitations in Use of Simulation Models

The findings of this review conveyed the role of crop simulation models in crop yield predictions and yield gap analysis, understanding the climate change effects on crop production, and addressing food and nutrition security which would help achieve SDGs 1, 2, and 13 in Nepal. The review identified the following limitations of model use and some suggestions for policy implications in South Asia in general and Nepal in particular.

### 23.4.1 Limitations in Model Use

Following are the major limitations for effective use of the simulation models for answering the questions related to research, crop management, and policy implications.

- **Inadequacy of quality input data**: Input data, for example, climate, soil profile characterization, crop management, and cultivar characteristics are generally incomplete, poor in quality, and not easily accessible for immediate use of crop modeling. Also, the field experiments focus more on yield and profits and less attention is paid to collecting data that are vital for simulation modeling (especially on seeding date, dates on phenological stages, biomass yield, etc.). Most of the data found on reports are available on a percentage of phenological stages and such data do not fit well into any model as they do not meet the requirement for the model input data format.
- **Poor in communicating the model application**: The uptake of the model outputs in research and policy is low due to limited

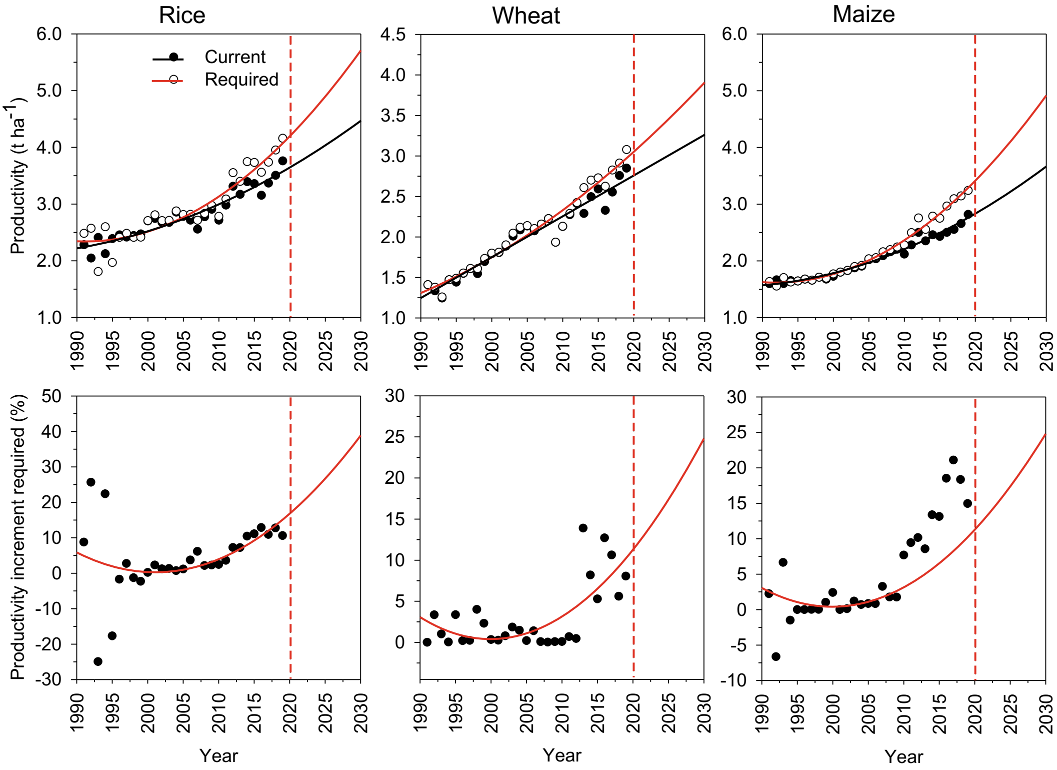

**Fig. 23.6** Current and the required productivity (upper) and the percentage productivity (lower) to eliminate import and self-sufficiency in rice, wheat, and maize in 2030 in Nepal. The required productivity and percentage are computed considering the current yearly import, the total area under crops, and yearly productivity. The lines after the vertical red dotted line are the predicted trends for 2030. *Data source* FAOSTAT (2021)

exposure of model application, and insufficient appreciation and recognition by policymakers.

- **Limited availability of automated devices for continuous data**: Very limited numbers of automated devices (sensor-based soil and weather monitoring devices) are available to generate quality data required for crop modeling.
- **Lack of uniformities in the storage of weather and soil data**: There is a lack of uniformity in data management and storage. If data are available, there are tedious and bureaucratic steps to access/download and insufficient download tips and steps available publicly in an understandable way. The cloud-based secondary and remote sensing data are mostly provided as a link to big data and only a handful of researchers are familiar with such tools.
- **Poor or no capacity development for validation and applications of simulation models**: Low-capacity development for engagement and co-generation of scenarios and poor collaboration for sharing knowledge and outputs among stakeholders at different levels.
- Location-wise validation of the model demands costs and human resources.

## 23.4.2 Policy Implications and Recommendations

- In the context of Nepal, not much work on modeling is done so far while in the global context, simulation modeling has been used as a decision support tool, technology transfer, and policy planning strategies. Those works have shown models have immense potential and more research work needs to be conducted on model validation and application to increase crop productivity, profitability, and achieve food and nutrition security under current and future climate change conditions.

- Development of storylines and exploration of intervention priorities at national, regional/province, and local levels for the sustainable development of the crop, livestock, economics, climate, and land surfaces.
- Sensitivity of current agricultural production systems to climate change, the impact of climate change on future agricultural production systems, and the benefits of climate change adaptation can be better understood through risk and vulnerability assessment, and economic feasibility of adaptation strategies using simulation modeling.
- The earlier studies have indicated that except for hybrid maize, crop yields are low, and a large yield gap exists between potential and farmers' field yields. In this context, models can be a DSS tool for breeding climate resilient varieties, improved resistance against biotic and abiotic stresses, and agronomic research for improving resilience to stresses for all cereals.
- Site- and soil-specific technology development by conducting experimental and simulation studies across three AEZs to develop and evaluate smart-agricultural practices for staple cereal crops.
- Simulation models need to be applied to provide an evidence-based comprehensive methodology to support the adaptation plans at the country, regional, and local levels.
- Many models have been validated in South Asia and Nepal in different aspects. However, as of now, only a few model outputs have been utilized for the improvement of the economic, environmental, and resilience of cereal production systems.
- Most models consider only the climatic and other biophysical aspects. Future modeling works would also require combining the socio-economic and farming systems perspective with biophysical aspects. Addressing bio-physical and socio-economic aspects would help address food and nutrition security under varying socio-economic environments.
- The application of simulation results can achieve self-sufficiency in rice, wheat, and maize to achieve the productivity target of 5.7, 3.9, and 4.9 t $ha^{-1}$, respectively for 2030.

## 23.5 Conclusions

Models are powerful, quick, and less expensive tools for quantification of yield gaps, a better understanding of integrated soil and crop management and crop diversification, and designing climate-smart agronomic practices considering climate, soil, and socio-economic interactions. These can serve as alternative and more efficient DSS tools for research and extension and in providing reliable guidance to policymakers in policy assessment and design. This review showed the potential application of crop models for improving the food and nutrition security of the country by closing the cereal deficits and improving self-sufficiency in Nepal. Models helped in recommending site- and crop-specific fertilizer rates, optimizing crop yields, developing sustainable crop and soil management practices to quantify and close yield gap, and understanding the effects of climate on cereal yields. However, potential applications of crop models addressing socio-economic issues or interactions for better policy formulation and application are lacking in Nepal and South Asia in general. Rigorously calibrated and validated crop models have great potential to improve decision-making, assist policy, reduce imports, and achieve the food and nutrition security of the country. The future of crop modeling relies on the availability of quality input data, the strength of modelers to synthesize and standardize the data, and potential user groups' ability to communicate and implement the modeling results at different levels. Though this study focuses on the applications of simulation models in Nepal, the lessons learned here could equally be useful in other South Asian countries facing similar socio-economic and environmental challenges.

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