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Bridging the Yield Gaps of Major Cereals through Agronomic Interventions in Nepal

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ABSTRACT

Agricultural production is due to the exploitation of soil, water and energy. The objective of this review work was to identify the yield gap of major crops viz. rice, maize, wheat, and finger millet and their causes. An attempt has been made to suggest the potential agronomical interventions that reduce the yield gaps. Rice, wheat, and finger millet yields in all agro-ecological zones are declining, although yield trends of maize were reported to have increased in the Terai due to the increased use of hybrids. The yield gap can be minimized with assured irrigation and appropriate agronomic practices such as the use of the quality seed, timely planting with appropriate establishment methods, timely intercultural operations, soil fertility, moisture, weeds, diseases, insect pests and post-harvest management along with growing high-yielding and stable genotypes resilient to climate change. It is obvious that there must be a strong interaction between plant breeding and agronomy for enhanced crop production. Therefore, some of the potential agronomical technologies that contribute to increase the crop yields thereby reduce the yield gaps have been discussed in this article.

Keywords: Agronomic practices, constraints, genotypes, yield gap.

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INTRODUCTION

In Nepal, the area of maize, wheat, and finger millet from 1977 to 2017 was not increased substantially although the rice area increased by 23%. Similarly, the average yield of wheat increased by more than 100% (1.04 to 2.55 Mt ha^{-1}) and rice yield by 87% (1.8 to 3.37 Mt ha^{-1}) during this period. A gain of 54% in maize yield (1.66–2.55 Mt ha^{-1}) was also found (FAOSTAT 2019) due to hybrids (Devkota et al 2016). Only about 70% of rice area is either partially or fully irrigated in the country. Likewise, 66% of all wheat area is partially or fully irrigated with 81, 46, and 46% of the areas respectively in the Terai, hills, and mountains (MoALD 2018). Decline in rice and wheat yields in all agro-ecological zones but yield trends of maize were reported to have increased in the Terai due to increased use of hybrids (FAOSTAT 2019). However, the yield of maize was found to be stable in the hills and mountains (CBS 2019), it might be due to the use of open-pollinated varieties and limited access to inputs such as chemical fertilizers and pesticides (Devkota et al 2016). Improved varieties of rice, wheat and maize are more common among farmers (MoALD 2018). In the Terai and Inner Terai improved varieties of crops are more common than in the hills. In maize, improved OPVs are used in the hills, but both open-pollinated varieties (OPVs) and hybrids are grown in the Terai and Inner Terai (MoALD 2018). Analysis of long-term yield and area expansion data shows the millet yield has been nearly stagnant since 1961, with a yield increment of 1.3 kg ha^{-1} year $^{-1}$ (FAOSTAT 2019).

Differences in average yields of these cereals in the three agroecological zones have been found substantial and are heavily influenced by water availability and irrigation regimes (MoALD 2018). Average yields of rice, maize, wheat, and millet, respectively ranged from 2.47, 2.23, 1.40, and 1.14 Mt ha^{-1} in the mountains, to 3.49, 2.87, 2.94 and 1.07 Mt ha^{-1}, in Terai in 2018, with intermediate yield levels in mid-hills. Due to cooler temperatures and longer growing seasons, higher wheat yields were recorded in the hills than in Terai. Average yields of rice and wheat have been found to increase substantially under irrigated conditions (3.74 and 2.72 Mt ha^{-1}, respectively) than under rainfed conditions (2.49 and 1.75 Mt ha^{-1}), respectively (MoALD 2018). Yields of the improved OPVs of maize range from 2.31 Mt ha^{-1} in the mountains to 2.87 Mt ha^{-1} in the Terai, while that of local varieties ranges from 1.26 Mt ha^{-1} in the hills to 1.40 Mt ha^{-1} in the mountains (CBS 2019; MoALD 2018). Both open-pollinated and local varieties require fewer external inputs (mainly fertilizers) than hybrids and produce moderate but stable yields. OPVs are also less expensive and more affordable for resource-poor farmers, especially in the mid-and high hills (Thapa et al 2019). A study on the adoption of OPVs showed that 83.3% of farmers saved their seeds or obtained seeds from fellow farmers, whereas only 16.7% obtained OPVs from governmental organizations. The Government of Nepal has adopted agricultural development policies aimed at the development of both locally-adapted hybrids and OPVs, with measures to increase the availability of maize seeds to resource-poor farmers (Gauchan 2019; Thapa et al 2019). The seed sector development strategy has targeted to release of 423 open-pollinated and 60 new hybrid varieties by 2025 (MoAD 2013). Yields of maize in experimental stations as well as farmers' fields under relatively non-limited input conditions in the Terai, to limited input conditions in the Terai, were reported to be as high as 12 Mt ha^{-1} (Pandey and Koirala 2017). Therefore, there is a challenge to narrow down the yield gap of major cereals mainly through agronomic interventions. Hence, the review article aims to suggest potential agronomic interventions to reduce the yield gaps of major cereal crops.

Potential Yield and Yield Gaps of Major Crops

The yield potential (Yp) of a crop cultivar or variety (v) is defined as the yield of the cultivar grown without the limitation of water and plant nutrients and free of biotic stresses (Penning de Vries et al 1989). An illustrative figure has been presented below to reveal the reasons and limitations of the yield gap (Fig 1). Irrigated farming systems with appropriate agronomic practices are more likely to reach Yp. Abiotic stresses should not be limited to achieving Yp in a rainfed system. The water-limited yield potential (Yw) is determined by soil water availability for crop growth, which in turn depends on soil properties. The yield gap (Yg) is defined as the difference between Yp and Yw or between Yp and the actual yield obtained by farmers (Penning de Vries et al 1989; Timsina et al 2018b). There is a large gap between Yp and on-stations (Yg 1), between on-stations and on-farm (Yg 2) and also between Yp and on-farm (Yg 3) in Central Terai of Nepal. Amgain and Timsina (2004) reported a larger Yg 3 was found than Yg 1 or Yg 2 for cereals, pulses, tubers and oilseeds. For rice, Yg 1 was larger than that for OPV maize, and also for wheat. It suggests that the use of high-yielding varieties and improved crop and soil management practices are likely to be required to reduce this gap. Yg 2 was larger for wheat than for the other two crops, suggesting that there is a limitation in farmers' current management of wheat. The larger Yg 3 for soybean, lentil, and potato suggests that there is considerable scope for yield increment in farmers' fields through the use of improved varieties and crop management practices, while a smaller gap for rapeseed and mustard suggests less scope for improvement. These data reveal that the Yp of all crops except wheat was smaller in Nepal than expected for sub-tropical regions of Asia (FAOSTAT 2019). Studies using Nutrient Expert (NE) for maize, a decision support tool developed based on the principles of site-specific nutrient management (SSNM), have shown that maize yields in the Terai and Western mid-hills can be increased by reducing the discrepancy between yields estimated by NE and either farmer' practice or recommended fertilizer rates by using SSNM recommendations (Bhatta et al 2020; Devkota et al 2015, 2016, 2018). Using the ORYZA 2000, Hybrid Maize, and CERES Wheat models, Timsina et al (2010, 2011) estimated climatic Yp as high as 12 Mt ha^{-1}, 15 Mt $ha^{-1,}$ and Mt ha^{-1} for rice, maize, and wheat, respectively, in Chitwan. It was reported that the mean Yp of the rice varieties ranged from 7.5 to 8.8 Mt ha^{-1} and that of maize ranged from 5.0 to 7.5 Mt ha^{-1} (Devkota et al 2016).

Based on recent wheat crop cut data with over 5000 observations of farmer's crop management practices across several Terai districts from four provinces in Nepal, CSISA (2019) found that the use of improved agronomic practices has the potential to enhance wheat yield if the 80% of farmers observed employ similar management practices to those being used by the top 10%. In particular, surveys indicated that current application levels of nitrogen (N) @ 88 kg ha^{-1} and potassium (K) @11 kg ha^{-1}respectively were below the rates for optimum response (150 kg N ha^{-1} and 50 kg K_2O ha^{-1}). Whereas the data from similar crop cut surveys in rice indicated only 3.5 kg K_2O ha^{-1} application and that higher rice yields could be obtained with 110, 70, and 40 kg N, P_2O_5, and K_2O ha^{-1} respectively in the western Terai region (CSISA 2019). Devkota et al (2018) also found that the yields of both crops could be increased and yield gaps reduced by the application of balanced nutrients and the use of precise crop management practices.

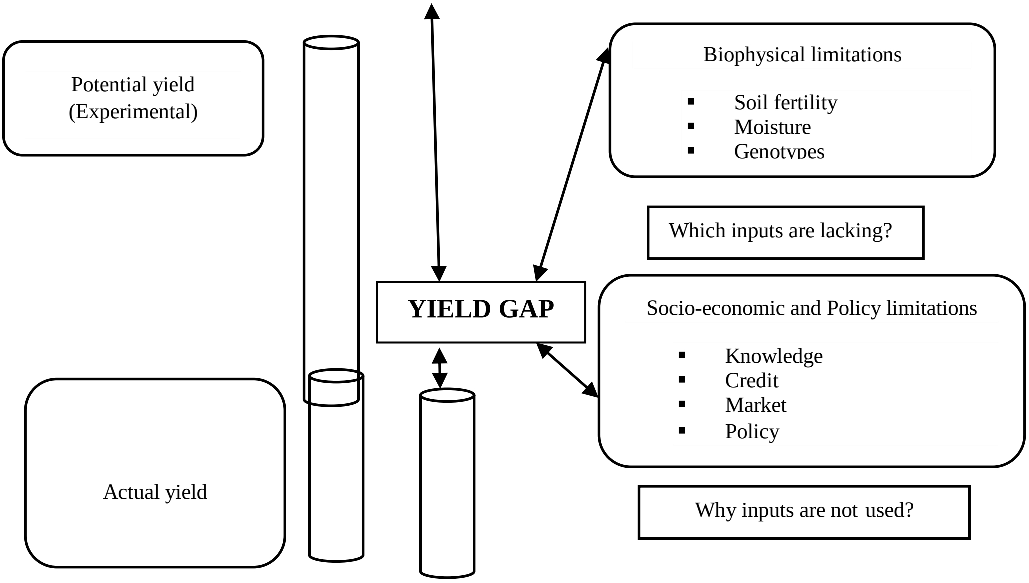

Figure 1. The yield gap of crops and its limitations

Bridging the Yield Gap through Alternative Crop Management Practices

Timothy et al (2021) revealed that farmers manage their agroecosystems through indigenous knowledge, particularly in the hills and mountains of Nepal, where access to extension services and markets for agricultural inputs are limited. Unsustainable agricultural practices increase soil, water and nutrient losses through soil erosion. Therefore, systematic research to develop appropriate crop and soil management practices is a must. Some potential agronomical technologies for major crops in Nepal have been discussed in this article.

1. Conservation agriculture (CA)

Conservation agriculture where the soil is less or no-tilled, retained the crop residues on the soil surface, and adopts crop rotations has been practiced to increase crop productivity, reduce labor use and farm inputs, and increase resource-use efficiencies and farmers' income globally (Jat et al 2014; Kassam et al 2019).

In South Asia, sufficient work has been done the positive effects of CA and zero-tillage has been found compared to conventional practices (Dixon et al 2019, 2020; Islam et al 2019). However, farmers' adoption has been found to be slow (Keil et al 2017). In Nepal, research on CA and resource-conserving technologies (RCTs) like reduced tillage, residue retention or mulching, direct-seeded rice with a seed drill, zero till wheat, mechanical transplanting of rice, laser land leveling etc particularly in rice-wheat systems was started in the early 1980s by the Rice-Wheat Consortium (Harrington and Hobbs 2009). Similar works were done by the Cereal System Initiatives for South Asia (CSISA) and Sustainable and Resilient Farming Systems Intensification (SRFSI) projects mainly in Terai, in addition to related initiatives (Dixon et al 2019, 2020). However, there are few published studies comparing CA with conventional agriculture in the hills and mountains of Nepal (Karki et al 2014a; Karki 2014b). Some of the improved agronomic practices could address soil and nutrient losses, as well as low crop yields in the hills and Terai.

2. Soil tillage, and water management

Minimum tillage (MT) could be a potential option to reduce soil and nutrient losses in the hills. Brown and Shrestha (2000) and Pratap and Watson (1994) reported losses of soil organic matter (SOM), N, P, and K up to 150–600, 7.5–30, 5–25, and 10–40 kg ha^{-1} yr^{-1} respectively, from terraced but poorly maintained lands with conventional tillage (CT). Tiwari et al (2009a) suggested that minimum tillage with residue retention in maize-cowpea rotations was more effective in maintaining soil fertility and increasing farm income compared to the predominant cropping system of maize-millet rotation. Atreya et al (2008) found significantly lower soil and nutrient losses with Mt and mulching with rice straw compared to CT. Tiwari et al (2008) reported that Mt decreased runoff by 7–11% and soil loss by 18–28% compared to CT in a mid-hill watershed in the central region of Nepal. In contrast, commercial vegetable production had greater soil disturbance due to repeated tillage and a lower amount of residues retention on the soil surface, causing increased runoff and decreased infiltration. Minimum tillage in a combination with mulching would reduce the early impact of the rainstorm. McDonald et al (2006a, b) compared the effect of six rice tillage and crop establishment practices on soil physical properties and wheat following rice over two cycles in a rotation on a silt loam soil in the central mid-hills at Khumaltar in the Kathmandu valley. During the rice season, Saturated hydraulic conductivity was higher in plots under direct-seeded rice (DSR) than transplanted rice. Bulk density (BD) measured after the harvest of each crop was also higher after transplanted rice than DSR. In wheat, there was no effect on BD, soil moisture retention characteristics, root development patterns or yield. Acharya (2017) observed that the yield of rice under DSR was reduced when established using zero tillage (ZT) compared to CT, though production cost in all crops was consistently lower in the former than in the latter. An experiment on various nutrient levels and crop establishment methods carried out by the author in 2016 (unpublished work) in Rampur showed that the interaction between various nutrient levels and establishment methods were significant, having the highest grain yield of rice in CA (Direct Seeded Rice) with recommended doses of nutrients over ConA ie puddled transplanted rice) (Fig. 2).

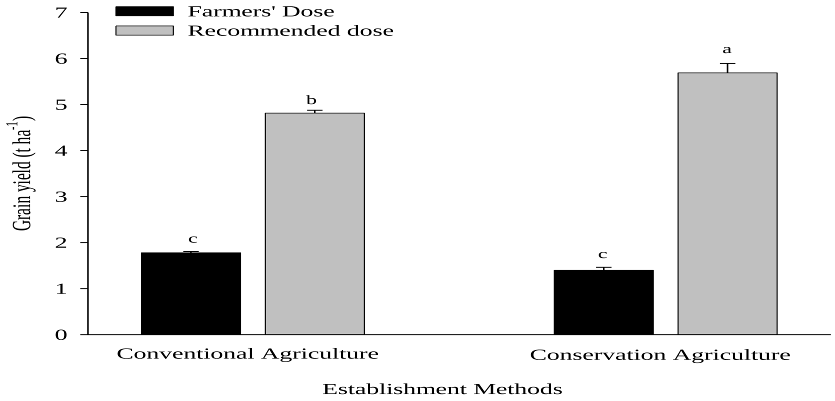

Figure 2. Interaction between establishment methods and nutrient levels on rice yield, 2016

Karki et al (2014b) concluded that a significant reduction in production cost and increase in income could result without any yield penalty from CA compared to conventional practices in a maize-rapeseed rotation in both the mid-hills and Terai. Laborde and McDonald (2019) reported that after 2 years of conversion from conventional tillage (CT) to CA in maize-rapeseed and maize-wheat rotational systems, the mean weight diameter of dry aggregates (0–5 and 5–10 cm depths) was greater by 45%, and 24%, respectively, soil sorptivity lower, and BD measured at the 0–15 cm soil depth greater in CA than the CT. Similar or lower maize yields were recorded in NT than CT practices, but effects were not significant for rapeseed and wheat. These findings demonstrate that during the initial years of transition from conventional to a CA-based crop management system, soil physical properties may improve but crop yield could either decrease or remain stable in the mid-hills of Nepal. As such, the benefits of CA appear to be largely oriented towards improving environmental outcomes and the profitability of crop cultivation. In the Terai, Ghimire et al (2011) reported that the addition of crop residues to no-tillage plots resulted in improved organic carbon sequestration, but there was no effect of N management on soil carbon. Acharya (2017) reported that the grain yields of wheat and rice in Terai were found to be inconsistent under RT and CT. Production cost was nonetheless consistently lower and the benefit-cost ratio was consistently higher, under MT than under CT. Devkota et al (2019) found that both DSR and zero-tilled wheat produced similar or higher grain yields with lower production costs, higher water productivity, and higher net profit than conventionally tilled wheat in the Western Terai. Karki et al (2014a) also concluded that, compared to CT, CA could significantly reduce production cost and increase income without any yield penalty in a maize-wheat rotation. Islam et al (2019) suggested that there was a significant yield gain of around 5% in wheat, maize or lentil under rice-wheat, rice-maize and rice-lentil cropping systems in central and Eastern Terai of Nepal, respectively.

CA contributed to reducing water requirements for the cultivation of wheat and maize crops. Increased infiltration rate in CA than conventional agriculture (ConA) under rice-maize cropping system in sandy-loam soil of Rampur, Chitwan was depicted in Fig 3 after the elapsing of time for 10 minutes. Up to 20 minutes both have cumulative infiltration of 25 mm but after that CA exceeded with a higher infiltration rate of 84 mm ha^{-1} in 20 minutes and 78 mm ha^{-1} in 30 minutes' period.

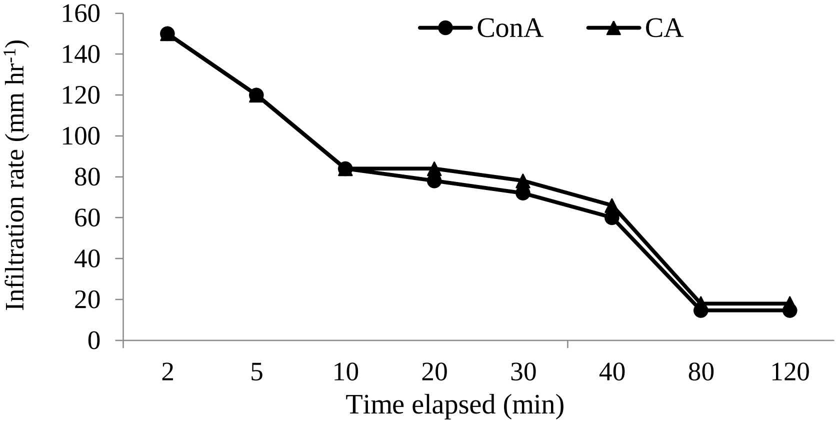

Figure 3. Infiltration rate of soil as affected by crop establishment methods, 2012

The soil moisture content (% by volume) after the fourth season of maize harvest at Rampur, Chitwan, depicted that it was statistically significant for establishment methods during the crop period (Figure 3). CA had significantly higher soil moisture content across all-time series starting from 30 days after planting (DAP) to 130 DAP compared to ConA. Dixon et al (2020) concluded that CA can improve food production and increase energy and water use efficiencies.

3. Nutrient management

In the low-input, rice-wheat and rice-maize rotations systems of the Terai, the nutrition of all crops is largely based on indigenous N supply (Timsina and Connor 2001; Timsina et al 2010). During the transition from dry to the wet season, a period of 6 to 10 weeks, large amounts of nitrate can accumulate in the soil and is subject to potential losses and nitrous oxide emissions upon soil saturation (Becker et al 2007). Therefore, management options during this period should aim to avoid losses of water and N from native soil. The combined application of manure in combination with inorganic fertilizers resulted in higher productivity and larger economic benefits than the application of either one alone under three rotational (rice-wheat, maize-millet, and upland rice-black gram) experiments across six sites of Eastern and Western mid-hills of Nepal (Pilbeam et al 1999). It shows the importance of integrated soil fertility management approaches in Nepal. In another maize-millet rotation at two mid-hill locations in eastern and western Nepal, Pilbeam et al (2002) found less than 25% of the applied fertilizer was recovered by the maize crop, and the subsequent millet crop recovered just 3% more. On average, 58% of the applied fertilizer was found in the 0 to 60 cm soil layer at maize harvest, mainly in non-mineral N pools. In contrast, rainfed sites had large surpluses of N, P and K with significant increases in soil K, base saturation, and available soil P. These results demonstrate the need to develop sustainable strategies to increase K and reduce P for irrigated systems and reduce N, P and K for rainfed systems to maintain nutrient balances in the mid-hills of Nepal. Ladha et al (2003) from the long-term soil fertility trial reported that depletion of soil C, N, Zn and P, delayed planting and decreased solar radiation and increased minimum temperatures, were among the major causes of yield decline for both crops in this region. In a long-term trial established on silty loam to silty clay loam soils at Bhairahawa, in the western Terai, both rice and wheat yields were lower than their attainable yields due to lower nutrient (especially K) availability (Regmi et al 2002b). Both crops responded to P and K addition, but the wheat response to the latter was substantially higher, indicating that native K availability was lower for the wheat crop. Wheat yield declined in all treatments except when farmyard manure was applied, indicating the role of organic matter additions in sustaining yield. In another long-term rice-wheat rotation trial at the same site, Regmi et al (2002a) reported that soil K depletion and inadequate K fertilization were primary reasons for declining crop yields and nutrient balances. This indicates that other than N, soil supplies of these nutrients were non-limiting. Across crops, apparent N and P balances were positive in treatments with N, P, and K, as well as farmyard manure, but the observed K balance was negative in all plots except those in which farmyard manure was applied to both rice and wheat. Negative K balances and K deficiencies in rice-wheat and rice-maize rotations however appear to be widespread throughout the Indo-Gangetic plains, due to the lack of consistent K application by farmers (Ladha et al 2003; Panaullah et al 2006; Singh et al 2018; Timsina et al 2013). Declining yield trends in rice-wheat rotations suggest scope for yield improvement through continued monitoring and the revision of nutrient management recommendations for component crops and systems.

Park et al (2018) demonstrated that the use of a simple, low-cost, chest-mounted seed and fertilizer drill resulted in significant N and P use efficiencies in wheat in Nepal and in Bihar India. Improved understanding of farm and watershed-level nutrient balances is likely to be more useful than plot or field-level assessments and if clearly articulated, could aid in land use planning and policy-making decisions. In a series of on-farm experimental and long-term simulation experiments using Decision Support System for Agrotechnology Transfer (DSSAT) in maize in the mid-hill district of Palpa, Devkota et al (2016) showed that (a) degraded soils in the mid-hills of Nepal respond favorably to macronutrient fertilizers even at high rates, (b) balanced fertilization is necessary to optimize returns on N investments, but these must be weighed against additional costs, (c) OPVs of maize can benefit from investments in fertilizer, albeit at partial factor productivity of N that is 36–47% lower than for hybrids and consequently (d), where farmers can afford investments in seed, hybrids can be an effective mechanism to achieve a higher return on fertilizer, even when modest rates are applied.

Soil organic matter in both the conventional and conservation agriculture in the rice-maize system for four seasons in sandy-loam soil of Rampur, Chitwan, was not affected during the first and second seasons, however was significantly higher in the third and fourth seasons of experimentation (Fig 4).

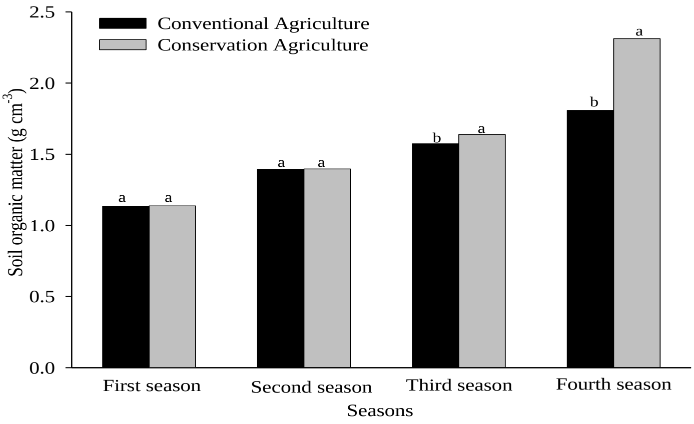

Figure 4. Soil organic matter (%) as affected by crop establishment methods, Rampur, 2012

4. Management of soil acidity

Many of the soils in both the hills and Terai are acidic. Soil acidity can also increase when nitrogenous fertilizers are applied in excess without associated SOM management (Tripathi 1999a, b). Tripathi (1999a, b) reported the existence of acid soil tolerant local and improved varieties of maize, wheat, soybean, and upland rice varieties in Nepal. Agriculture lime if applied in acidic soil only 40–45% of it is utilized by the first crop and the remaining 55–60% is utilized by succeeding crops. In a study in central Nepal, the application of $CaCO_3$ at 2–3 Mt ha^{-1} to maize increased soil pH and maize yield, and also had a residual effect on the succeeding wheat crop in a maize-wheat rotation in the first year of application. Further residual effects were also found for both crops in the second year of rotation (Tripathi 1999a). The author concluded that in Nepal, $CaCO_3$ should be applied and incorporated into the soil every 3–4 years. In addition to $CaCO_3$, research has also sought to identify alternative mechanisms to reduce soil acidity. Studies in the Philippines (Tripathi and Dacayo 1988) showed that the application of rice hull ash at 10 Mt ha^{-1} increased the pH of acid soils by releasing fixed P from

Fe and Al. Rice hull application also increased dry matter of *Sesbania rostrata* grown after rice, as well as the yield of the ensuing rice crop.

5. Supplementary irrigation management

Due to Nepal's erratic rainfall patterns, supplementary irrigation helps in timely crop establishment and in overcoming moisture stress during water-sensitive crop growth stages (Devkota et al 2019; McDonald et al 2006a, b). The importance of supplementary irrigation will be increasing due to the increasing trend of droughts for example farmers in the Terai are already adapting to these changes by investing increasingly in groundwater irrigation (Paudel et al 2020c; Urfels et al 2020, 2021). Non-linear yield response to the timing of rice establishment in the neighboring Indian state of Bihar was observed, where yield levels dropped by 70% if a critical threshold of timely crop establishment is passed (Singh et al 2019). It highlights that supplementary irrigation is critical when the onset of monsoon is late. As most canal irrigation schemes rely on the monsoon onset to increase stream water flows, the use of submersible pumps that do not have a suction depth limit, directly sown rice, or shorter duration rice varieties present potential options for overcoming this barrier. Furthermore, McDonald (2006a, b) found that dry season crops tend to significantly benefited from irrigation during planting.

In a meta-analysis, Carrijo et al (2017) consider alternate wetting and drying (AWD) practices in rice and show that supplementary irrigation in rice can achieve yield levels comparable to continuously flooded irrigation. Alternate Wetting and Drying (AWD) irrigation techniques can reduce the total water inputs ranging from 25–70% (Muhammad et al 2020). Howell et al (2015) showed a non-significant difference in yield between treatment plots, although AWD plots received 57% less water requirement than conventional plots on dry season rice in central Terai of Nepal. The figure below (Figure 5) shows how water pipe is used for AWD in the paddy field.

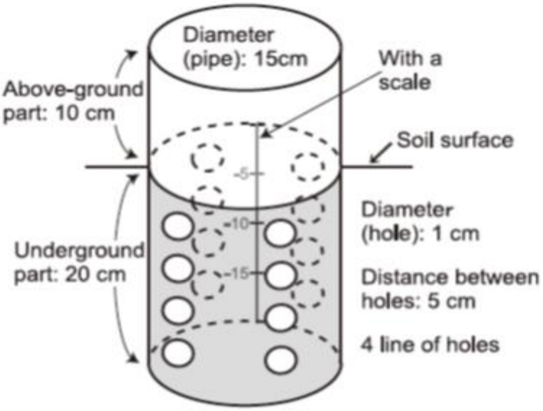

Figure 5. Installation of Pani pipe (Water pipe) in paddy field.

Under the situation of severe water stress due to precipitation deficit and high rental rates for pumping equipment, late scheduling, and insufficient infrastructure tend to limit timely irrigation (Foster et al 2019; Urfels et al 2020, 2021) in Nepal. For this, the attainable yield of rice was simulated with 150 kg N ha^{-1} under rainfed and partially irrigated (with 50 mm at 10 k Pa) in eight locations of Terai using the ORYZA3 rice growth model developed by Bouman et al (2001). Between 1970 and 2015, analysis indicated that the attainable rice yield increased by 2% when irrigated, but decreased by 21% under rainfed conditions. This suggests that unreliable irrigation not only increases climate risk but also prevents farmers from benefitting from CO_2 enrichment under climatic change. Dry winter season wheat cultivation can largely benefit from increased irrigation rates (Shrestha et al 2013). Shrestha et al (2013) using the AquaCrop model reported that for rice and maize during the summer monsoon season in Chitwan, central Terai improved soil fertility management was more important than water management for obtaining higher levels of system yields. Conversely, for the winter and spring seasons of wheat and maize, partial or full irrigation together with fertilizer application was more important. In the summer monsoon season, rice and maize yields could be increased by up to 65% and 58%, respectively, with improved fertilizer management. Conversely, considering wheat and spring maize, yields could respectively be increased by up to 197% and 100%, respectively, with improved irrigation management. In wheat, a single irrigation application (equivalent to roughly a quarter of net irrigation requirement) increased yield by 28–86%, while two irrigation applications (a third of net irrigation requirement) increased by 39–105%. In spring maize, application of deficit irrigation of 1/4th of net irrigation requirement increased yield by 15–77% across different fertilizer application levels and soil types. Since rainfall was almost negligible in the growing season of spring maize, the differences in maize yield for various soil types were less pronounced than for wheat. Findings of these studies suggested that for fertilizer application below 50% of the nationally recommended fertilizer rate, deficit irrigation application of a quarter of net irrigation requirement was sufficient, but for application above 50% of recommended fertilizer rates, irrigation water equal to or higher than a third net irrigation requirement would be necessary to achieve stable yields.

6. Manipulating the cropping geometries and time of planting

The result of the survey in Parbat and Baglung revealed that farmers harvest only about 36,000 maize plants ha^{-1} as against recommended density of 53333 plants ha^{-1} (Karki et al 2014). It is mainly due to repeated thinning of the maize for animal feed (Fig 6). The higher initial maize population increased the system's productivity by approximately 150%. It shows how faulty agricultural practices adopted by farmers affect cropping geometries thereby crop yields.

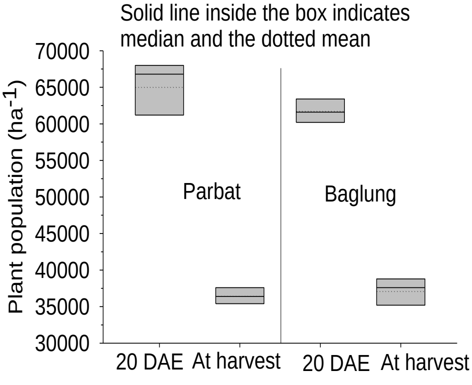

Figure 6. The maize density at 20 DAP and at harvest in Parbat and Baglung districts (Karki et al 2014).

Nepalese maize hybrids produced the highest grain yield of maize in planting geometries of 60 cm between rows and 25 cm between plants having a population of 66,666 plants ha^{-1} compared to the previously recommended spacing of 75 cm between rows and 25 cm between plants

(53,333 plants ha^{-1}) (NMRP 2015). Similarly, to enhance the profitability of maize-based intercropping systems planting three rows of soybean in between two rows of maize (100 cm between rows and 50 cm between plants with two plants per hill giving 40, 000 maize plants ha^{-1}) proved beneficial over sole planting of maize 53, 333 ha^{-1} (NMRP 2015). The last fortnight of September was the best planting time for winter maize and for spring it was mid-February in the uplands of Terai (NMRP 2015).

Pariyar et al (2019) recommended that rice variety Khumal-10 can be transplanted at a spacing of 15 cm between rows and 15 cm between plants for mid-western mid-hills of Nepal with a grain yield gain of 71.9% high over farmers´ practice. Transplanting of 2-3 seedlings per hill at a spacing of 20 x 10- 15 cm (row spacing) at 2-3 cm depth is recommended for rainy season rice cultivation (June-July) in Terai. Seedling numbers per hill increased when using old seedlings (Bhattarai 2017). Wheat is generally sown by machine in the Terai where row to row spacing of 25 cm and continuous sowing of seeds in arrow is done and later thinning is done adjusted to around 10 cm between plants. In the hills, the seed is generally broadcasted. Stress-tolerant and early maturing genotypes must be planted in the normal time of planting ie second week to the last week of October to the first week of November in the high hill, the second week to the last week of November in the mid-hill, and the first to the second week of November in Terai.

7. Pest management

Green Revolution has significantly increased crop yields and land use efficiency in developing countries (Davis 2003). Pingali (2012) mentioned that it also exacerbated the problems of weeds, pests, and disease. In Nepal, pesticide application has begun to become more common after the green revolution, with more than 2200 pesticides (inclusive of insecticides, fungicides, herbicides, and rodenticides) now registered (Adhikari 2017). In a long-term trial of a rice-wheat rotation at Bhairahawa in Western Nepal Terai, the interaction of increasing K deficiency with *Helminthosporium spp*. leaf blight was previously considered one of the key factors limiting wheat yields (Regmi et al 2002b). However, leaf rust (*Puccinia triticina*) is also now common in wheat grown in the hills and Terai, with concentrations in eastern Nepal. Observations by CIMMYT and NARC have also indicated that stripe rusts (*Puccinia graminis*) are increasingly found in the mid-hills, with *Puccinia graminis* also appearing to move into the eastern Terai (CIMMYT 2020). Turcicum leaf blight (*Exserohilum turcicum*) has become highly problematic in intensified maize production systems in the cooler mid-hills of Nepal, while insect pests are more of a challenge in the lowland Terai than in the hills (Paudyal et al 2001). It might be due to the less biodiverse landscapes with refugia for predators and parasitosis, and the higher temperatures of the Terai favoring the rapid development of overlapping arthropod generations. The growing of monsoon season maize followed by winter season maize also appears to favor gray leaf spots (*Cercospora zeamaydis*), causing significant yield losses (Manandhar et al 2011). A one-year rotation without maize, followed by tillage, has been recommended to prevent disease development in the subsequent maize crop in the United States (Wise 2010); similar tactics may be applied in Nepal where double cropping of maize is practiced. In addition to these issues, cereal-based agroecosystems in Nepal also face threats from new and emerging pests. Fall Armyworm (FAW), (*Spodoptera frugiperda* J. E. Smith), a polyphagous pest with a strong preference for maize is one of them. FAW was first officially documented in Nepal in 2019 following its migration from Southern India, where it was observed for the first time in Asia in 2018 (Bajracharya et al 2021). Since then, it has been observed as a pest of maize and to a lesser extent other plant species in Nepal. It is urgently needed to develop integrated pest management techniques to manage this pest (Bhusal and

Bhattarai 2019). GC et al (2019) for example noted that given Nepal's relatively unique range of elevation and differing temperature and precipitation patterns in which maize is grown, a wide geographic range of studies will be needed to identify context-specific management techniques in response to the observed population dynamics of this pest.

There are at least 219 alien species of flowering plants (Siwakoti 2012) that are naturalized in Nepal. Among 25 invasive and alien plant species (IAPS), four species (*Chromolaena odorata, Eichhornia crassipes, Lantana camara, and Mikania micrantha*) are included in the world's 100 worst invasive species (Lowe et al 2000). The weed *Parthenium hysterophorus* L. is highly competitive and has a wide association with cereals, including rice, wheat, and maize. It can generate more than 5000 seeds m^{-2} and has become a serious problem in Nepal (Adkins and Shabbir 2014). In the wheat under rice-wheat rotations, *Phalaris minor* has been a severe problem in Nepal (Lamsal and Khadka 2019; Ranjit et al 2009). The use of zero tillage and alternative herbicides significantly reduced its effects (Malik et al 2000). These examples point to the importance of integrated weed management techniques that combine cultural practices with competitive cultivars, with the inclusion of chemical control when and where necessary.

8. Integration of crop-agroforestry and livestock systems

The integration of trees mainly fodders and livestock system is common in the hills of Nepal and is not scientific manner. Sloping Agricultural Land Technology (SALT) having dense contour planting of fast-growing nitrogen-fixing hedgerow species has been recommended by ICIMOD in sloppy lands to control soil erosion. The growing of cash crops like Cardamom is common under trees. Growing short-duration leguminous crops with fruit trees is also common in Nepal. Cereals are being grown in contour terraces along with fodder trees in bunds and raisers in Nepal for a long back. Further research in species selection, planting geometries, methods, and time of planting must be done to scale out it.

9. Integration of stress-tolerant crops/genotypes

In the area where there is excess rainfall, preventing logging and leaching of nutrients by erosion, using weather forecast information to reduce the risk of climate events different water management practices i.e. improving water-holding capacity of the soil, making physical soil and water conservation structures, collecting water to conserve the moisture of the soil, and changing the amount and timing of irrigation. Drought, submergence and other stresses tolerant genotypes of rice, maize, wheat, legumes, and other crops have been recommended by NARC.

CONCLUSIONS

A yield increase is the only option to bridge the yield gaps of major cereals in Nepal. It can be done only by breaking the major yield barriers. Improved crop management practices like improved soil fertility, minimum tillage, efficient irrigation management and integrated pest management in combination with stress-tolerant high-yielding crops and genotypes are the means to narrow down the yield gaps.

In-depth studies must be done in identifying the key barriers to the yield gaps in Nepal. Policy interventions are needed that influence investments in agriculture research, assure the availability of inputs, credits and crop insurance. In order to develop, verify, and scale-out agronomical technologies that are sustainable and economically profitable there must be close collaboration among the CGIAR centers, national agriculture research system, extension and farmers.

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AUTHORS' CONTRIBUTION

TB Karki conceptualized the topic of the review paper and prepared the manuscript jointly with the co-authors namely Reshama Neupane, Rajendra Kumar Bhattarai, Bhimsen Chaulagain, Sangita Kaduwal, Pankaj Gyawaly, Soni Kumari Das and Jiban Shrestha.

CONFLICTS OF INTEREST

The authors have no any conflict of interest to disclose.

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