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Decomposing maize yield gaps differentiates entry points for intensification in the rainfed mid-hills of Nepal

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ABSTRACT

The central mid-hills region of Nepal is characterized by rainfed production systems where maize (*Zea mays*) is the principal crop during the monsoon (*kharif*) season. In general, maize yields in the hills 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 selectively matched to the needs and constraints faced by different types of farmers. This study combines field surveys, on-farm field experiments, and simulation modeling (DSSAT) to explore opportunities for closing maize yield gaps in these ecologies. Among surveyed households, the mean grain yield of maize under current farmer practice was 2.0 t ha^{-1} whereas good agronomic practices increased maize yields up to 6.5 t ha^{-1} (i.e. exploitable yield gap of 4.5 t ha^{-1}). Recognizing that farmers rarely adopt full technology packages, the value of single agronomic interventions was also explored with all other management factors maintained as per prevailing farmer practice. Averaged across sites and two seasons, non-limiting fertilizer rates (175:60:60 kg NPK ha^{-1}) increased grain yields by 1.8 t ha^{-1} followed by the use of hybrids (1.4 t ha^{-1}), higher plant population (0.9 t ha^{-1}), and improved weed control (0.9 t ha^{-1}). These results were also reflected in changes to the economic performance of the system with gross margins increasing from a ‘farmer practice’ base of \$202 ha^{-1} (B:C = 1.86) to \$339 ha^{-1} (B:C = 2.14) with hybrid adoption, \$454 ha^{-1} (B:C = 2.88) with higher plant population, \$646 ha^{-1} (B:C = 2.52) with non-limiting fertilizer, and \$611 ha^{-1} (B:C = 3.37) with careful weed control. Further gains in profitability were achieved with layered agronomic interventions, which increased gross margins to \$857 and \$763 ha^{-1} (B:C = 2.95 in both) in conventional tillage (CT) and minimum (strip tillage; ST) systems, respectively. Divergence between grain yield gains and economic performance criteria highlights the importance of considering both perspectives. For resource-poor households, maintaining optimal plant population can increase B:C by more than 50% with small investments (\$7 ha^{-1}). Simulation results also suggest that additional potential productivity advantages are achievable with timely planting (e.g. 19% higher mean yield for short duration hybrid with less inter-annual variability). Cultivation of longer duration hybrids can also increase yield potential over their shorter duration alternatives, although trade-offs with yield potential of the second crop in the rotation must be considered. These results highlight several pathways toward intensification in the hills of Nepal that have varying investment requirements, inferred risks, and implications for the different dimensions of sustainability and food security.

1. Introduction

Maize (*Zea mays*) is the principal staple food and fodder crop of small-scale farmers in the mid-hill region of Nepal. Out of the 0.87 million ha maize area in Nepal, 69% area falls in hills (600–1800 m altitude), where 70% of total national production is grown (CBS, 2013). The hill region of Nepal is mostly characterized by bunded terraces and unbunded broad slopes, often found in upper landscape positions (Tiwari et al., 2004). Rainfed systems, often synonymous with stagnant and low crop productivity (Rockstrom et al., 2010), are common in the hill and plateau ecologies of South Asia, and cropping intensity (crops per year) and productivity are low in the regional context (Jat et al., 2012).

In rainfed (‘bari’) areas in the Nepal hills, maize is grown during the summer-monsoon season followed by mustard or other low-input/low-output crops planted after maize harvest during a three to four months period in the winter, and during spring fields

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generally remains fallow (Adhikari, 2000; Atreya et al., 2006). At present, Nepal imports more than 20,000 t of maize annually (FAOSTAT, 2015), suggesting considerable demand-led incentives for enhancing current domestic production. Due to population increase and rising demand for livestock and poultry feed, South Asia maize production has been growing at a rate of more than 5% per annum (FAOSTAT, 2015), a sustained rate of increase that presents an opportunity for enhanced market integration and income generation among hill farmers who, at present, produce maize for household uses. Given the degraded and vulnerable status of soil and other natural resources in the hills of Nepal and generally low level of social and capital assets among most farming communities, it is imperative to identify intensification opportunities that can be sustainably adopted while preserving or enhancing production capacity and ecosystem services.

Under current methods of crop management and input use, average maize productivity in farmers field is very low (2.0 t ha^{-1} in 2013) with negligible levels of increase over the past three decades (FAOSTAT, 2015). The so-called exploitable 'yield gap' concept quantifies the difference between what farmers achieve and what levels of productivity are currently attainable with 'best-bet' technologies and management practices in different production environments. Recently, considerable progress has been made characterizing yield gaps in both irrigated and water-limited environments (Grassini and Cassman, 2012; Pasuquin et al., 2014), but efforts to identify the root causes of these gaps are either lacking or incomplete for most regions. Decomposing yield gaps into their constituents is essential for two interlinked reasons. First, it has long been recognized that farmers rarely adopt full technology packages (Leathers and Smale, 1991). Second, entry points for sustainable intensification have different investment costs, expected benefits, levels of risk, and enabling conditions that facilitate adoption such as level of market integration (Shiferaw et al., 2009). These factors are all influenced by the biophysical and socio-economic heterogeneity associated with different production ecologies (Tittonell and Giller, 2013). By taking a targeted approach to matching technological entry points to the circumstances of different farmers, theory and experience suggests that technology adoption processes can be accelerated (Conroy and Sutherland, 2004).

Evidence from other rainfed production areas in developing regions in Africa and elsewhere in Asia suggests that crop production can be doubled or even tripled with integrated crop management through improved germplasm, soil fertility management, early and appropriate weed control, and efficient capture and utilization of water resources (Fermont et al., 2009; Wang et al., 2014). In hills of Nepal, farmers are generally not aware of existing technologies or have limited understanding about their benefits and costs even for the most basic management interventions; in part this is caused by an evidence-based knowledge gaps that remain to be addressed through strategic and on-farm research. As a consequence, there is low and unbalanced (<20:5:0 kg NPK ha^{-1}) use of fertilizers (Adhikari, 2000; Shrestha et al., 2013; Tiwari et al., 2004) and very limited adoption of hybrid maize (Tiwari et al., 2009).

Beyond measures to introduce better seeds and improve soil fertility, a host of other technologies and innovative management practices such as minimum tillage may have strong relevance in the rainfed maize systems in the Nepal hills. Most farmers employ intensive soil tillage and intercultural operations that cause soil erosion while increasing runoff and evaporative water losses (Alijani et al., 2012; Hobbs and Gupta, 2003). Minimum tillage and, where possible, conservation agriculture-based management ('CA' = minimum soil tillage, residue retention and proper crop rotation) approaches can provide pathways for sustainable intensification toward the goal of producing more food with less environmental impact (Derpsch, 2011). In other production environments, minimum tillage has been shown to improve soil quality and reduce soil erosion (Govaerts et al., 2007), enhance rainfall infiltration and reduce evaporative losses (Verhulst et al., 2009), enhance timely field operations and crop establishment (Sidhu et al., 2007), reduce production costs and labor requirements (Erenstein and Laxmi, 2008), may provide higher and stable crop yields in rainfed conditions (Govaerts et al., 2005). Evidence for the performance of minimum tillage in the hill regions of Nepal is lacking at present.

Other components of the yield gap for maize in the hill ecologies of Nepal such as timely planting are strongly influenced by seasonal weather factors such as the onset and uniformity of monsoon rains and hence difficult to determine with short-term experiments. Dynamic modeling provides a useful complement to field trials because it allows the assessment of the interactive impacts of climate, cultivar and crop management practices on crop growth and development (Wang et al., 2014). Crop simulation models are widely used to quantify the climate-defined yield potential under rainfed and irrigated conditions (Liu et al., 2012; Meng et al., 2013).

In addition to characterizing the yield gap in maize production systems in the central hill region of Nepal, the present study was designed to explore the contribution of single versus layered agronomic interventions for closing yield gaps along with the investment cost and economic benefits of different intensification options. As part of these on-farm evaluations, the performance of minimum tillage and maize hybrids of different growth durations was also assessed. The climate-driven components of yield gap analysis were assessed with the CERES-Maize model run within the Decision Support System for Agrotechnology Transfer (DSSAT Version 4.5) simulation framework.

2. Materials and methods

2.1. Site description

On-farm experiments were conducted in Palpa District of Nepal (approximately 27°50′ latitude and 83°30′ longitude—Fig. 1) and spread across three locations (i.e., Chhandibhanjang, Harthog, and Laguwa) during the monsoon ('*kharif*') 2012 and 2013 seasons. Farmers in this area dominantly plant maize followed by a short-duration rapeseed crop; from December to March most fields remain fallow. The soils of the experimental sites are dominantly haplaquept, ustochrepts and paralithic with varying textures (see Table 1). The climate in the experimental site is warm-temperate and the site receives average annual rainfall of 1531 mm $year^{-1}$ (Fig. 2), which is concentrated in the summer months during the monsoon period. The average daily maximum and minimum temperatures are 25.7 and 15.4 °C, respectively and the average solar radiation is about 18.1 MJ m^{-2} d^{-1}.

2.2. Household survey and crop yield measurement

For the characterization of maize production systems, input use and current farmer practices, a household survey of 72 households was conducted in 2012 with a structured questionnaire. In addition to the survey, plant population and grain yield of maize under farmers' management were measured from a 36 m^2 area for 30 surveyed farmer's fields in 2012 and from 17 farmer's fields in 2013.

2.3. On-farm experiments

2.3.1. Experiment I. Single vs. layered interventions for closing yield gaps

Seven experimental treatments composed of single or layered combinations of five (i.e. hybrid, plant population, fertilizer rate,