THESIS

FACTORS CONTRIBUTING TO MAIZE AND BEAN YIELD GAPS IN CENTRAL AMERICA VARY WITH SITE AND AGROECOLOGICAL CONTEXT

Submitted by

Lisa Eash

Department of Soil and Crop Sciences

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Master's Committee:

Advisor: Steven J. Fonte

Raj Khosla
Jessica G. Davis

ABSTRACT

FACTORS CONTRIBUTING TO MAIZE AND BEAN YIELD GAPS IN CENTRAL AMERICA VARY WITH SITE AND AGROECOLOGICAL CONTEXT

In Central America, the population and associated food demands are rising rapidly, while yields of their staple crops, maize and beans, remain low in a global context. To identify the main limiting factors to crop production in the region, field trials were established in six priority maize- and bean-producing regions in Guatemala, Honduras and El Salvador. Potential yield-limiting factors were evaluated in the 2017 growing season and included: nutrient management, irrigation, planting arrangement, and/or pest and disease control. When considering all sites, improved fertilization and pest and disease control significantly improved yields in maize by 11% and 16% respectively, but did not have a significant overall effect in beans. Irrigation had no effect in the year studied, due to sufficient and evenly distributed rainfall over the growing season. Optimized planting arrangement resulted in an average 18% increase in maize yield overall, making it the most promising factor evaluated in this study. However, the effectiveness of each factor varied across sites and no factor was effective at increasing yield consistently across all sites. Increased production was not always associated with net economic gains due to the relatively high costs of inputs and technology in the region. The study demonstrated that production constraints are highly dependent on local management practices and agroecological context. Therefore, public and private development efforts that seek to increase production should seek to identify site-specific limitations pertinent to each area in question.

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INTRODUCTION

As the world population rises to an estimated 9 billion by mid-century, demand for maize and other staple crops is expected to increase substantially (Foresight, 2011). Given the limited potential to expand agricultural lands, there is a great need to sustainably increase grain production around the globe, particularly in under-yielding nations (Baldos & Hertel, 2014).

Yield gap analysis represents a common approach to address this issue and identify intensification prospects. Yield gap is defined as the difference between actual yield and potential yield and is considered at the soil, field and crop level (van Ittersum & Rabbinge, 1997). Numerous approaches exist to estimate yield gaps. Farmer surveys can compare average yield with the best yield achieved in similar environmental conditions. Additionally, yield gaps can be evaluated through field experimentation, where farmer-level yield data is generated by replicating farmer management practices, and attainable yield is estimated by minimizing plant stress to the extent possible via the use of improved technologies and agrochemical inputs. Field experimentation can help to identify site-specific combinations of management practices that are conducive to high yields and low-risk input recommendations (Grassini et al., 2015).

While yield gap analysis is not a new concept in applied agronomy, it has not been adequately applied in many regions of the world, including Central America. Yield gap analysis in Central America is often grouped with the rest of Latin America, making region-specific recommendations difficult (Fischer et al., 2009; Hengsdijk, 2009; Licker et al., 2010). Understanding and addressing limitations to crop production in the region could have a large positive impact on production and food security, given the dietary reliance on maize (*Zea mays* L.) and particularly low yields in the region. Farmers in the Central American countries of El

Salvador, Guatemala, Honduras, and Nicaragua produce maize on a cumulative 2.4 million hectares. Yields average around 2.28 Mg ha^{-1} and are low in a global context, while modelled theoretical yield is estimated to be as high as 10 Mg ha^{-1} (Hengsdijk & Langeveld, 2009). This suggests great potential to improve production and overall food security in the region.

Factors contributing to low maize yields can include water shortage, inadequate nutrient management, insufficient or improper application of labor or mechanization, lack of technical expertise, and damage due to pests, weeds and disease. Limiting factors to production are region-specific and depend on socioeconomic and agroecological context. For example, in arid environments or regions with large year-to-year variation in rainfall, farmers often use risk management tactics, such as low plant density, and limit investments in inputs that may be unprofitable in the event of a drought (Lobell et al., 2009). Furthermore, subsistence-oriented systems are often less-intensively managed, as profits are lower and farmers often cannot afford the best available technologies that allow them to reach yield potential (Affholder et al., 2013). Understanding the primary causes of yield gaps allows for more effective research and policy efforts aimed at improving grain production and regional food security.

This research aims to understand factors contributing to yield gaps, defined as differences between attainable and actual yield, in six priority agroecological regions in Central America, specifically located within Guatemala, Honduras and El Salvador. Yield gap was estimated in maize and bean production through field experimentation at each site. The technologies implemented to address yield limitations included the following factors: planting arrangement (e.g., geometry, density) nutrient management, irrigation, and/or pest and disease control. We hypothesized that nutrient management and supplemental irrigation would have the greatest effect on maize and bean yields, but not necessarily profits due to the relatively high cost of inputs in the region.

MATERIALS AND METHODS

Site selection

Study sites were selected to represent distinct agroecological zones in Guatemala, El Salvador, and Honduras (Fig. 1). Agroecological zones were characterized by long-term annual rainfall and altitude, sourced from WorldClim Global Climate Data from NASA's Shuttle Radar Topography Mission, and were prioritized according to area (total ha) of maize and bean production (You et al., 2016). In each of six prioritized agroecological zones, potential collaborating institutions were visited to assess willingness of the collaborating institution to participate, technical capacity, and land availability. One research farm in each of the six regions was selected to host a trial (Table 1). Economic activity in all regions is heavily focused on agriculture, specifically maize production.

Climate and soil characteristics

Altitude across sites ranges from 315 to 2390 masl, and annual rainfall ranges from 800 to 3500 mm yr^{-1} (Table 1). All sites experience a distinct dry season from late November to April and a rainy season from May to early November. Rainfall is bimodal, with a short dry period in early August, referred to as the *canicula* or mid-summer drought. Topography also varies among sites. While Suchitepéquez is located on a coastal plain and La Libertad, El Salvador, and El Paraíso, Honduras are located in valleys, farmers in Quetzaltenango and Chimaltenango, Guatemala and Lempira, Honduras are faced with the challenge of steep, mountainous terrain that is highly susceptible to erosion. Soils range between clay loams and sandy loams, with a slightly acidic pH (Table 1).

Characterization of local management practices through semi-structured interviews

Semi-structured interviews were conducted in communities neighboring each site to characterize local management practices of maize and beans. The survey had three sections: general characteristics of the farm (including farm size, crop type and quantity produced, and income sources), management practices (seed varieties, land preparation, fertilization plan, pest and weed control, and planting and harvest dates), and farmer-perceived limitations to maize and bean production. Community leaders from the six sites were asked to select between five and ten maize farmers from their community, who represented high, low, and average production. Survey findings were verified by local agronomists and practitioners in each region.

Experimental design

The six field trials were implemented during the 2017 growing season, which generally spans from March to December. Protocols for each trial were designed based on common management practices in surrounding communities and the most pertinent limitations to maize and bean production, as determined by local agronomists and farmers. Therefore, treatments varied slightly among sites (Table 2) and evaluated the following factors: 1) supplemental irrigation, 2) fertilizer management, 3) pest and disease control, and/or 4) planting arrangement. While all treatment designs included supplemental irrigation and fertilizer management, pest and disease control and planting arrangement were only evaluated in sites where these factors were considered to be suboptimal by local farmers and agronomists. The effect of improved varieties on yield was anticipated to be an important limitation that would be evaluated in sites, but after extensive discussion with local farmers and agronomists, it appeared that improved genotype was either already adopted by farmers or not accessible in the region. Seed type used at each site therefore represented the most widely used in each region and was kept consistent among all treatments within each site.

Each experiment consisted of a full-factorial, randomized complete block design with split-split plot treatment arrangement and three replicates per treatment. Whole plots contained different irrigation treatments (drip irrigation vs. rain-fed), with sub-plots representing pest and disease control treatments, and sub-sub plots, ranging from 40 to 135 m^2 in size, which represented a factorial combination of fertilization and planting arrangement (where applicable).

Each factor evaluated included a ‘control’ level that represented the common management practices near the site, as well as an optimized treatment level. The control level was based on results of the semi-structured interviews, while the optimized level was determined through discussions with local agronomists and expert farmers. As a result, local and optimized plans for fertilization, pest and disease control, and planting arrangement differed among sites. Fertilization plans were adjusted in terms of the timing, rate, and method of application and optimized according to soil analyses and recommendations from local government extension services (Table 3). Planting arrangements were optimized in terms of spacing between rows and planting holes, as well as number of seeds per planting hole (Table 4). In the case of pest and disease control, preventative pesticide applications were scheduled to combat common pests and disease, but plots under optimized management were monitored and, if necessary, extra applications were realized to minimize plant stress (Table 5). It should be noted that optimized factor levels are based on previous experimentation and observation in the region and may not always represent optimal management interventions for eliminating stress associated with nutrient, water, pests, and/or other limitations.

In irrigated treatments, water was applied before planting to achieve field capacity. Every three days, the difference between crop demands (estimated to be 5 mm per day) and rainfall since last irrigation was calculated. If the rainfall received did not meet estimated crop demands, that quantity of water was supplemented in irrigated treatments.

Depending on typical maize systems in each region, maize (*Zea mays* L.) was relay cropped or cultivated in association with beans (*Phaseolus vulgaris* L.). In Quetzaltenango, Guatemala, maize and climbing beans are planted in association. In Chimaltenango, La Libertad, and El Paraíso, maize and beans are relay cropped. In Lempira and Suchitepéquez, only maize was planted. Similarly, land preparation, sowing and harvest dates, planting method, seed varieties, and herbicide management mirrored common management practices in each region and therefore were distinct across sites (Table 6).

Data Collection

Climate data

Climate data were obtained from weather stations at each experimental site. In Chimaltenango and Quetzaltenango, Guatemala, weather stations from the National Institute of Seismology, Volcanology, Meteorology and Hydrology (INSIVUMEH) were used. For the remaining sites, a Vantage Vue (Davis Instruments, 2017) weather station was installed. All weather stations captured minimum and maximum temperature, rainfall, relative humidity, and hours of sunlight at daily intervals.

Plant and yield measurements

Plants survival and density were assessed for both maize and beans in two subsamples of eight planting holes per plot after the population had stabilized, approximately two weeks after planting. Prior to harvest or folding over of maize plants (for drying), ear height (defined as distance from the soil surface to the base of the lowest ear) and plant height (distance from the soil surface to the base of the tassel) were measured on six randomly selected plants in each plot. These measurements were used to interpret yield data, but were not considered primary variables of interest in the statistical analyses.

At harvest, the central area (excluding the two outer rows on each side of the plot) was harvested manually. Cobs were separated into healthy cobs and cobs with more than 50% of the kernels affected by ear rot, and then each group was counted and weighed. Grain-to-cob ratio was determined on a subsample of cobs, and grain yield was adjusted to 14% moisture content. To calculate biomass and harvest index, three planting holes from each plot were randomly selected and the dry weight of grain, cobs and other plant matter was determined.

At maturity, ten bean plants were randomly selected from each plot to estimate average number of pods per plant and number of grains per pod. Bean plants were harvested from the central area of each plot, dried in the sun and threshed manually. Beans were then weighed and moisture content was measured to adjust yield to 14% moisture.

Economic analysis

For each treatment at each site, total cost was calculated as the sum of manual labor, mechanized land preparation and inputs associated with all management practices performed before, during, and after the growing cycle. Though farmers occasionally rent land for cultivation, land was assumed to be owned by the farmer and rental costs were not incorporated into the economic analysis. Local currencies were converted to USD based on the exchange rate on November 8, 2017. Costs of inputs were quoted from local agricultural supply stores. The cost of irrigation was calculated as the total cost of supplies (i.e., pump, water storage, motor, tubing, and associated hardware) and installation, considering a depreciation period of five years for the equipment. The cost of manual labor was estimated by local agronomists who assisted in the implementation of the field trials and have ample experience in the region and was based on the amount of labor a local farmer would need to perform each task on one hectare. Gross revenue was calculated by multiplying the maize and bean (if applicable) yields of each experimental unit by the price that farmers typically receive for their crop (based on pre-trial semi-structured interviews). Net profit was calculated as the difference between the gross profit and the total cost of inputs for each treatment.

Statistical approach

Maize and bean grain yields and net profits were analyzed using a multifactor ANOVA, with each site and treatment factor (fertilization, planting arrangement, irrigation, and pest and disease control) included as a fixed effect and block, whole plot, and subplots included as random effects. Since there were significant interactions between site and treatment, site-by-site analysis was conducted in the same way, excluding site from the model. All analyses were performed using R statistical software (R Core Team, 2017), and residual and normal-QQ plots were examined to ensure that the data met the assumptions of ANOVA (normality and homogeneity of variance).

Tukey-adjusted pairwise comparisons, generated by the emmeans package in R (Lenth, 2018), were used to estimate the difference in maize yield between optimized management and farmer practices for each treatment factor. To calculate yield effect, or the proportion increase in yield attributed to each treatment factor, the estimated difference between factor levels was divided by mean yield of the farmer-practice level. The “overall” yield effect, or the effect of optimizing all treatment factors, was based on the comparison of the treatment with all factors under optimized management vs. the typical farmer practice (control).

RESULTS

Farmer interviews

The semi-structured farmer interviews suggested that management practices varied among sites and generally depended on whether farming systems were for subsistence or commercial purposes (Table 7). Commercial systems were usually more dependent on hybrid seeds, mechanization and pesticide and herbicide use, while subsistence systems employed traditional practices, including use of native varieties, manual land preparation, and minimal to no pesticide use. Average farm size varied according to region, ranging from 0.4 to 4.5 ha (Table 7).

Farmer-perceived limitations to production included both biophysical factors, such as water stress and increased incidence of pests and disease, as well as socioeconomic factors, such as lack of economic access to inputs and small farm size (Table 8). The most frequently mentioned limitations were water stress due to unreliable rainfall and inadequate nutrient management. Farmers were also requested to name pests and diseases that commonly impact their maize and bean yields (Table 9). Some of the most commonly mentioned pests were the larva of *Phyllophaga spp.*, which can damage maize roots in the early vegetative stages, and *Spodoptera frugiperda*, which causes foliar damage and direct injury to the ear.

Rainfall

The 2017 growing season experienced approximately average rainfall levels at all sites. Monthly rainfall corresponded roughly with the monthly average precipitation rates and rainfall was distributed evenly throughout the growing season. Study sites received between 759 and

2133 mm during the 2017 growing season (Fig. 2), and therefore supplementary irrigation was only applied to the supplemental irrigation treatments two to four times at each site.

Maize Yields

Supplemental irrigation did not significantly increase yields in the year studied. However, optimized nutrient management, optimized planting arrangement, and pest and disease control all had positive effects on maize yield when analyzed across all sites and with varying degrees of influence on yield at the individual site level (Fig. 3; Table 10).

In Chimaltenango, El Paraíso, and La Libertad, optimized pest and disease control significantly increased grain yield by 30%, 26%, and 15% respectively. Optimized fertilization and optimized planting arrangement had significant positive effects on yield in Quetzaltenango (38% increase due to fertilization and 26% due to planting arrangement) and Suchitepéquez (16% due to fertilization and 18% due to planting arrangement). In El Paraíso, the optimized fertilization plan negatively affected production, with a 10% decrease in grain yield.

In Quetzaltenango, a significant interaction effect (p=0.03) was observed between planting arrangement and fertilization. Pairwise comparison between planting arrangement and fertilization levels showed that relative response to optimized fertilization decreased when planting arrangement was optimized (Fig. 4); the yield increase associated with fertilizer levels was significant in treatments with the local planting arrangement (70%; p=0.005), but not in treatments with the optimized arrangement (18%; p=0.21).

Bean Yields

When analyzed across the four sites that included beans, none of the factors had a significant effect on bean yields; however, significant effects were observed at the individual site level (Fig. 5; Table 11). In El Paraíso, pest and disease control and fertilization both significantly increased bean yields by 28% and 22%, respectively, while in Quetzaltenango, optimized planting arrangement improved bean yields by 51% ($p < 0.05$). In La Libertad, the optimized fertilizer plan negatively impacted bean yield, with a 10% reduction (0.23 Mg ha^{-1} ± 0.06; $p = 0.008$) relative to the farmer practice.

Economic Analysis

While the management factors evaluated represent ways in which maize and bean production can be increased, an increase in yield did not always result in an increase in net profit (Table 12). Optimized planting arrangements in Quetzaltenango and Suchitepéquez caused an increase in net profit of \$272 ha^{-1} (a 75% increase) and \$170 ha^{-1} (a 31% increase), respectively. In Quetzaltenango, optimized fertilization also resulted in a \$375 ha^{-1} (90%) increase in net profit. No other treatments at any of the sites resulted in a significant increase in profit.

Several factors that increased inputs, but did not have large positive effects on yield, resulted in a significant decrease in net profit. For example, in El Paraíso, optimized fertilization resulted in a \$756 ha^{-1} (99%) decrease in net profit, and in La Libertad, optimized pest and disease control resulted in a \$395 ha^{-1} (25%) net profit decrease. While irrigation did not lead to any significant increase in production, it also was not costly enough to significantly decrease net profit.

Yield Gaps

Including all sites, the optimization of all management factors significantly increased maize yield ($p=0.001$) relative to farmer practices, from 3.6 Mg ha^{-1}, to the attainable yield of 4.7 Mg ha^{-1}, resulting in an estimated overall yield gap 1.1 ± 0.3 Mg ha^{-1} across all sites (Fig. 6). At individual sites, the attainable yield was consistently larger than the farmer level treatment, but the yield gap was only statistically significant in Quetzaltenango ($p=0.001$). The attainable yield ranged between 3.55 Mg ha^{-1} and 6.28 Mg ha^{-1} and varied significantly across sites ($p=0.026$). However, farmer-level yield and yield gap were not significantly different among sites ($p>0.05$).

For bean yields across all sites, the average attainable yield (1.3 Mg ha^{-1} ± 0.8) did not significantly differ from the farmer-level yield (1.1 Mg ha^{-1} ± 0.8; $p>0.05$; Fig. 7). The yield gap was only statistically significant ($p<0.001$) in El Paraíso, where the yield gap was an estimated 0.20 Mg ha^{-1}, the difference between the farmer-level yield (0.35 Mg ha^{-1}) and the attainable yield (0.55 Mg ha^{-1}). While both farmer-level yield and attainable yield vary significantly according to site ($p<0.01$), estimated yield gap was not different among sites ($p>0.05$).

DISCUSSION

While water stress was not a principal limitation due to rainfall distribution in 2017, inadequate nutrient management, suboptimal seed arrangement, and pest and disease stress all limited yields under typical farmer practices. However, yield and limitations to production varied across sites according to the ecological context and conventional management practices in the region.

Overall, yield of farmer-level treatments averaged 3.6 t/ha, and was thus higher than the 2.2 t/ha average for the region (Hengsdijk & Lengevel, 2009). Research farms are commonly situated on more fertile soil (van Ittersum et al., 2013; Table 10), and, aside from the farmer-level treatment factors evaluated in the study, stresses such as weeds and untimely management were intentionally minimized in order to observe the attainable yield.

Water Stress

Previous yield gap studies show that water stress is a major limitation globally to the production of staple grains in rainfed systems (Cassman, 1999; Rockstrom, 2000; Rost et al., 2009). Mueller et al. (2012), for example, modelled the effect of water stress and nutrient deficiency in under-yielding grain (maize, wheat and rice) systems worldwide and found that 16% of areas could achieve attainable yield solely by applying adequate amounts of irrigation.

In Central America, water stress undoubtedly affects crop production. The mid-summer drought (regionally known as 'la Canicula'), or period of reduced precipitation that typically occurs in July and August, poses a major limitation in the region, as this period typically coincides with the grain-filling stage of maize development (Edmeades et al., 1997). In the three years prior to this study (2014-2016), El Niño conditions led to widespread drought throughout the region. Crop harvests were decreased by 50-90%, and 1.6 million people were left moderately or severely food insecure in El Salvador, Guatemala and Honduras (Diaz & Burgeon, 2016). In interviews conducted at the start of this study, farmers recovering from recent harvest losses frequently cited drought and climate variability as a major limitation to production (Table 8).

Although rainfall totals were about average in 2017, the mid-summer drought was less pronounced, and quantity and distribution of rainfall throughout the growing season was seemingly sufficient to meet crop demands. Despite other findings, farmer-perceived limitations, and our hypothesis that water stress would limit yields, no significant yield differences were observed between irrigated and rainfed treatments for either maize or beans at any of the study sites (Fig. 3, 5). These findings highlight the need to consider multiple years of data, given the large inter-annual yield variability that is attributed to climatic trends (Lobell et al., 2009). The minimal water stress observed in the study year presented the advantage of allowing other limiting factors to be expressed and explored more thoroughly.

Pest and disease stress

Optimized pest and disease control resulted in an average maize yield increase of 16% (Fig. 3) across all sites, but did not significantly improve bean yields overall (Fig. 5). As our study includes a mixture of subsistence and commercial systems, farmer-level pest and disease control regimens varied across sites according to the degree of intensification of local farmer practices. In Chimaltenango, Quetzaltenango, and Lempira, for example, pesticides are not typically used due to high input costs as well as local traditions (Table 7). Farming systems in these regions are normally smaller and subsistence-based. Conversely, farmers in La Libertad and El Paraíso, are typically larger, more commercial systems, and customarily use insecticides and seed treatments, although at relatively low levels.

The effect of pest and disease control also depended on the biotic stresses present at each site and the degree to which local farmers typically control such stresses. In Chimaltenango, for example, the main pest outbreaks were the larva of *Phyllophaga spp.*, which causes damage to roots, and *Spodoptera frugiperda*, which causes foliar damage and direct injury to the ear. The farmer-level pest and disease treatment did not receive any pesticides and therefore exhibited notable damage, while pests were monitored and controlled in the optimized treatments, resulting in a maize yield increase of 30% (Fig. 3).

Meanwhile, in the lowland regions of El Paraiso and La Libertad, which are characterized by more rainfall and higher average temperatures, the main biotic stress in the 2017 growing season was the tar spot complex, a disease caused by a synergistic interaction of fungal species *Phyllachora maydis* and *Monographella maydis* (Hock et al., 1995). Farmers working in these commercial systems regularly use insecticides and seed treatments to control *S. frugiperda*, *Phyllophaga spp.* and other known pests. Despite these efforts, both El Paraiso and La Libertad saw significant yield increases with optimized pest and disease control measures. This likely occurred because fungicides are expensive and must be applied preventatively in order to effectively control tar spot complex and other diseases.

In Lempira and Quetzaltenango, optimized pest and disease control did not significantly increase maize yield (Fig. 3). Farmer practice at these sites did not include pesticide use, but pest and disease incidence was low.

While pest and disease control is not a new concern for farmers, climate change is worsening the issue by changing the distribution, population dynamics, and frequency of incidence (Lal, 2015). Tar spot complex, for example, had a devastating effect on maize production in southern Mexico in the 1980s (Hock et al., 1995), but its presence in La Libertad and El Paraíso is relatively recent. New outbreaks of pests and disease could be caused by the changes in rainfall patterns and higher temperatures associated with climate change, leaving farmers to look for solutions to maintain or enhance crop productivity (Rosenzweig et al., 2001). Integrated pest management plans based on economic thresholds as well as technical knowledge should be identified to reduce yield losses in an economically viable manner.

Nutrient Deficiency

Nutrient deficiency has been widely considered to be a prominent contributor to yield gaps (Tittonell & Giller, 2013; Breman & Debrah, 2003; Mueller et al., 2012). When Mueller et al. (2012) modelled the effect of water and nutrient application in grain systems, an estimated 73% of systems could achieve attainable yield through changes in nutrient inputs alone. Nutrient limitations are also strongly perceived at the farmer level. For example, in pre-trial interviews, 54% of farmers cited nutrient limitation as a barrier to production (Table 8). The implementation of optimized fertilization plans had a significantly positive effect on maize yield overall (Fig. 3). However, at the site level, it significantly increased maize yields in only two out of the six sites (Quetzaltenango and Suchitepéquez) and bean yields in one site (El Paraíso), fewer than anticipated given the large expected contribution of nutrient deficiency to the yield gap.

Inconsistent fertilizer responses across sites can be related to the different baseline levels of fertilizer being applied and differences in nutrient recommendations, which were informed by government extension services and local NGOs. Research stations and plots designated for experimentation are commonly situated on fertile soils with favorable topography and routinely have higher baseline soil fertility than is found in farmers' fields (van Ittersum et al., 2013), potentially minimizing the difference in nutrient limitation between the local and optimized fertilization treatments. Baseline soil analyses of each trial site (Table 1) showed that organic matter content, pH, and, in some cases, even available P and K levels were generally at acceptable levels, which may not be the case on surrounding farmers' fields. This could explain why optimized fertilizer plans did not increase maize yields in Lempira, La Libertad, and Chimaltenango (Fig. 3).

Optimized fertilization plans involved an adjustment in nutrient rates as well as timing and method of application, so observed yield effects due to fertilization result from the cumulative effect of these factors. In Suchitepéquez, for example, the optimized fertilizer plan increased total N and P applied and fractionated doses into four applications instead of the usual two applications that farmers apply. Fertilizer was also buried rather than broadcasted (Table 3), which is known to increase its availability and reduce losses (Bryla, 2011). These changes, combined with an overall increased rate, resulted in a significant increase in maize yield (Fig. 3). In Quetzaltenango, the first fertilization of the optimized plan was applied 10 days after planting, whereas farmers typically wait until silking for the first fertilization. Fertilization in the vegetative stage is essential for adequate root development, which in turn affects growth and production throughout the growing cycle (Scharf et al., 2002). The difference in timing between the local and optimized plans contributed to the large increase in yield (39%) between fertilization treatments at this site. Timing and method of application could represent promising intervention strategies to improve nutrient use efficiency without increasing fertilization rates and while reducing associated environmental and economic costs.

Planting Arrangement

In Central America, planting arrangements are commonly less than optimal; the number of seeds planted per hole is high while spacing between planting holes is wide (Barber, 1999). Traditional planting arrangements have been implemented to reduce labor, at the cost of increased crowding and greater intraspecific competition, resulting in lower water, light and nutrient use efficiency (Andrade et al., 2002). Optimized planting arrangement was incorporated into the treatment design for three of the six study sites. This practice significantly increased yields in two sites and resulted in an average 18% increase in maize yield across all three sites in which it was studied, making it the most influential factor evaluated in this study (Fig. 3).

The optimized planting arrangement did not necessarily increase planting density. Chimaltenango was the only site in which optimized planting arrangement increased seed density, albeit slightly, from 50,000 plants/ha (at 5 seeds per hole, planted every 1 m^2) to 60,000 plants/ha (at 3 seeds per hole, planted every 0.5 m^2; Table 4). However, this did not result in any significant effect on either maize or bean yields. Conversely, in Suchitepéquez, the change from local to optimized planting arrangement decreased seed density from 67,000 plants ha^{-1} (at 3 seeds per hole, planted every 0.45 m^2) to 53,300 plants ha^{-1}(1 seed per hole, planted every 0.19 m^2), and resulted in an 18% (0.6 Mg ha^{-1} ± 0.2) increase in grain yield. This is consistent with previous findings that indicate narrowing row spacing, while maintaining seeds per hole and overall seed density, reduces intraspecific competition and increases light, water, and nutrients use efficiency (Andrade et al., 2002).

Farmers in the hillside region of Quetzaltenango, Guatemala plant at 1 m between planting holes, with 6 seeds per hole (60,000 plants/ha). Reducing this spacing to 0.5 m between planting holes with 3 seeds per hole (still 60,000 plants/ha) resulted in a 26% (1.3 Mg ha^{-1} ± 0.3) yield increase in maize and a 51% (0.20 Mg ha^{-1} ± 0.07) in beans. The lower yields associated with the local planting pattern could be attributed to the barrenness and decrease in kernel size associated with interplant competition for resources (Sangoi, 2001). In the early stages of development, plants in less crowded environments can develop greater root length density, allowing for better nutrient use efficiency throughout the growing season (Barbieri et al., 2008). This was further confirmed by a significant interaction effect ($p = 0.02$) between planting arrangement and fertilization, where optimized fertilization mainly increased yield in the suboptimal planting arrangement (Fig. 4). In conditions similar to Quetzaltenango, the optimization of planting arrangements could present an opportunity to increase yield through enhanced nutrient use efficiency without the need to increase farm inputs.

Profitability and Risk Aversion

While agronomic management can be optimized to lessen the yield gap, crop productivity is determined in large part by farmer decisions that take into consideration profit maximization (Tilman et al., 2002). Additional inputs, such as fertilizer, water, seed, labor and pest control, have been shown to have diminishing returns as yield approaches potential levels. Thus, an increase in productivity does not guarantee an increase in net farmer profit (Lobell et al., 2009).

The experimental design in this study focused on the identification of yield limiting factors and treatments were not designed with the aim of testing economically feasible options for farmers. Therefore, the economic analysis gives a first idea of the economic feasibility of applying certain technologies, but results need to be interpreted with caution, and it is likely that other, more sustainable and profitable technologies will need to be evaluated to minimize the identified yield limiting factors. While many of the identified limitations to crop growth were mitigated using agricultural inputs, the increase in production was not always reflected in net profits (Table 12).

Optimized fertilization plans necessitated an increase in input costs as well as manual labor, since fertilizer rates were often fractionated into several applications rather than the local practice of just one or two applications per cycle. However, in Quetzaltenango, the optimized fertilizer practice was relatively similar to the local practice, and thus the cost of labor increase was relatively small. This resulted in an improvement in yield that was sufficient to justify the optimized fertilization practice. Optimized planting arrangement also represents an increase in manual labor, since planting is largely done by hand in this region, and halving the seed spacing results in approximately double the manual labor for both planting and fertilization. However, labor costs in this region are relatively low (about \$10 person^{-1} day^{-1}), and since optimizing planting arrangement does not require any additional inputs, the treatment cost was less than that of fertilizer or pest and disease control (Table 12). In the two out of three cases in which optimized planting arrangement increased production (Suchitepéquez and Quetzaltenango), net profit was also significantly improved.

Actual farmer yields are not only limited by high input costs, but also by risk aversion (George, 2014). The inherent riskiness of grain production is often high, particularly under rainfed conditions and as climate patterns become increasingly unpredictable (Hayman et al., 2010). Drought years could render all investment in agricultural inputs a loss and can prevent farmers from having the capital to invest in more inputs the following year. In the pre-trial interviews, farmers frequently identified the tar spot complex as a limitation to production (Table 9), but they also discussed the risk of investing in fungicides to control it. Fungicides must be applied preventatively to be effective, and the incidence of the disease is highly variable, depending on rainfall and temperature patterns. Investment in fungicides is therefore viewed as risky and impractical, even though farmers are fully aware of the rising incidence of tar spot complex. When aiming to close the yield gap, economically feasible strategies as well as technologies that reduce farmer uncertainties, must be identified for technologies to be adopted at the farmer level (Lobell et al., 2009).

Recommendations for Development Policy and Further Research

In recent years, yield gap studies have emphasized the importance of site-specific ecological intensification, or local analysis that seeks to understand how more efficient use of abiotic resources, complemented by deliberate use of agricultural inputs, can increase crop productivity (Cassman, 1999; Tittonell & Giller, 2013). Our findings are in full agreement with this idea and suggest that reliance on inputs without consideration for costs and associated uncertainties can enhance productivity, but often with negative consequences for farmer profits. By understanding management and resource deficiencies at a local level, technologies can be developed that are accessible to farmers, require less initial investment, and promote long-term resource use efficiency in agricultural systems.

In addition to the technologies tested here, we suggest that the introduction of more agroecological approaches could also effectively address production limitations and contribute to enhanced productivity and sustainability in the long-term. For example, improved residue management through conservation agriculture and/or agroforestry practices have been shown to support enhanced soil biological activity, increased water capture and retention, erosion control, soil organic matter stabilization as well as improved nutrient uptake and recovery (Castellanos-Navarrete et al., 2012, Murphy et al., 2016; Kearney et al., 2017). Such outcomes are critical for enhancing the resilience of agroecosystems in the face of climate change, which is expected to increase the frequency and severity of droughts as well as the intensity of rainfall events and associated erosion (Zhang et al., 2007). Other agroecological strategies, such as cropping system diversification, offer promise for addressing yield gaps related to pest and disease limitation (Letourneau et al. 2011). As with more traditional agronomic inputs (e.g., fertilizers, pesticides), the effectiveness of agroecological options are likely to be highly context dependent (Coe et al. 2016), and further research is needed to better understand the potential of these technologies to close yield gaps while supporting ecosystem services and overall sustainability in a way that is accessible to smallholder farmers.

CONCLUSION

Water scarcity, pest and disease stress, nutrient deficiency, and suboptimal planting arrangement are all factors which limit crop production and should be considered as we aim to close yield gaps. In this research the treatment and site combinations that caused an increase in both crop productivity and net profit included management changes that promoted improved resource use efficiency. In particular, we note that optimized planting arrangement appeared to make better use of local fertilization rates through decreased interplant competition. The extent to which each factor limits production is site-specific and dependent on local management practices and agroecological context. Therefore, public and private development efforts that seek to increase production should conduct site-specific analyses in a participatory fashion to identify limitations pertinent to the area in question. Strategies to close the yield gap should also consider more agroecological approaches and be based on principles that seek to increase resource use efficiency, thereby decreasing the environmental and economic costs associated with excessive input use.

TABLES

Table 1. Characteristics of study sites selected for field trials to evaluate production limitations in six priority maize- and bean-producing regions in Central America.

Country	Department	Altitude (masl)	Average Temperature (ºC)	Rainfall (mm yr^{-1})	Available P Concentration (mg/kg)[a]	Available K Concentration (mg/kg)[a]	pH	SOM content[b] (%)	Soil texture[c]
Guatemala	Suchitepéquez	315	29	3500	< 10.0	277.2	5.91	2.87	Clay loam
Honduras	El Paraíso	450	23	1100	81.7	675.3	6.82	3.26	Sandy loam
El Salvador	La Libertad	460	26	1500	42.9	276.3	6.03	1.62	Sandy loam
Honduras	Lempira	700	25	1400	10.0	72.0	5.40	3.53	Clay loam
Guatemala	Chimaltenango	1533	18	1050	53.2	234.2	5.69	1.94	Clay loam
Guatemala	Quetzaltenango	2390	15	800	47.0	211.0	6.99	4.08	Sandy clay loam

[a] based on Mehlich 3 extraction

[b] Walkley-Black method

[c] based on hydrometer method

Table 2. Treatment design for six field trials established to evaluate limitations to production of maize and beans in Honduras, Guatemala, and El Salvador in the 2017 growing season.

Site(s)	Chimaltenango, Guatemala Quetzaltenango, Guatemala				Suchitepéquez, Guatemala			La Libertad, El Salvador Lempira, Honduras El Paraíso, Honduras		
Trt. No.	Irrigation	Fertilization	Pest & Disease Control	Planting Arrangement	Irrigation	Fertilization	Planting Arrangement	Irrigation	Fertilization	Pest & Disease Control
1	I*	O*	O	O	I	O	O	I	O	O
2	I	O	O	L	I	O	L	I	O	L
3	I	O	L	O	I	L	O	I	L	O
4	I	O	L	L	I	L	L	I	L	L
5	I	L*	O	O	R	O	O	R	O	O
6	I	L	O	L	R	O	L	R	O	L
7	I	L	L	O	R	L	O	R	L	O
8	I	L	L	L	R	L	L	R	L	L
9	R*	O	O	O	NA*	NA	NA	NA	NA	NA
10	R	O	O	L	NA	NA	NA	NA	NA	NA
11	R	O	L	O	NA	NA	NA	NA	NA	NA
12	R	O	L	L	NA	NA	NA	NA	NA	NA
13	R	L	O	O	NA	NA	NA	NA	NA	NA
14	R	L	O	L	NA	NA	NA	NA	NA	NA
15	R	L	L	O	NA	NA	NA	NA	NA	NA
16	R	L	L	L	NA	NA	NA	NA	NA	NA

*I - Irrigation; R – Rainfed; O – optimized; L – local; NA – not applicable since not all treatments present at all sites

Table 3. Fertilization plan for six field trials established to evaluate limitations to production of maize and beans in Honduras, Guatemala, and El Salvador in the 2017 growing season.

	Optimized Fertilization Plan			Local Fertilization Plan		
	Rates (kg ha^{-1})	Timing	Method	Rates (kg ha^{-1})	Timing	Method
Suchitepéquez	188 N 56 P 24 K 2 foliar applications of micronutrients.*	Fertilizer applied in 4 applications at 0, 10, 25, and 40 days after planting.	Fertilizer buried with machete approximately 5 cm deep and 3 cm from base of plant.	129 N 17 P	Fertilizer applied in 2 applications at 10 and 35 days after maize planting.	Fertilizer broadcast on soil surface.
El Paraíso	238 N 65 P 97 K 3 foliar applications of micronutrients to maize, and 4 to beans.	Fertilizer applied in 4 applications at 0, 20, and 30 days after maize planting and 5 days after bean planting.	Fertilizer buried with machete approximately 5 cm deep and 3 cm from base of plant.	113 N 20 P 19 K 1 foliar application of micronutrients to beans.	Fertilizer applied in 2 applications at 8 and 25 days after maize planting.	Fertilizer broadcast on soil surface.
La Libertad	174 N 65 P 65 K 3 foliar applications to maize, 4 to beans.	Fertilizer applied in 4 applications at 8, 25, and 35 days after maize planting and 6 days after bean planting	Fertilizer buried with machete approximately 5 cm deep and 3 cm from base of plant.	116 N 32 P 16 K	Fertilizer applied in 3 applications at 8 and 30 days after maize planting, and 6 days after bean planting.	Fertilizer broadcast on soil surface.
Lempira	207 N 74 P 97 K 3 foliar applications of micronutrients.	Fertilizer applied in 3 applications at 0, 28, and 45 days after maize planting.	Fertilizer buried with machete approximately 5 cm deep and 3 cm from base of plant.	125 N 39 P	Fertilizer applied in 2 applications at 10 and 40 days after maize planting.	Fertilizer buried with machete approximately 5 cm deep and 3 cm from base of plant.
Chimaltenango	180 N 30 P 3 foliar applications of micronutrients.	Fertilizer applied in 2 applications at 30 days after maize planting and at maize flowering.	Fertilizer buried with hoe and incorporated into the calza**,	128 N 39 P	Fertilizer applied in 1 application, 60 days after maize planting.	Fertilizer buried with hoe and incorporated into the calza**,
Quetzaltenango	180 N 13 P 24 K 3 foliar applications of micronutrients.	Fertilizer applied in 2 applications at 10 days after maize planting and at maize flowering.	Fertilizer buried with hoe and incorporated into the calza**,	129 N 17 P 32 K	Fertilizer applied in 2 applications at 60 days and 90 days after maize planting.	Fertilizer buried with hoe and incorporated into the calza**,

*Foliar micronutrient application consisted of 9.1% N, 6.6% P_2O_5, 5% K_2O, 1250 ppm S, 332 ppm B, 17 ppm Co, 666 ppm Zn, 332 ppm Cu, 42 ppm Mo, 207 ppm Ca, 332 ppm Mn, 415 ppm Fe, and 207 ppm Mg.

**The *calza* is a traditional practice in which soil is formed into a volcano-like structure at the base of maize stalks.

Table 4. Optimized and local planting arrangements for six field trials established to evaluate limitations to production of maize and beans in Honduras, Guatemala, and El Salvador in the 2017 growing season.

Site	Optimized Planting Arrangement	Local Planting Arrangement
Suchitepéquez	Rows of maize spaced 0.75 m apart, 0.25 m between planting holes with 1 seed each for an overall density of 53,300 plants/ha	Rows of maize spaced 0.90 m apart, 0.50 m between planting groups of 3 seeds for an overall density of 67,000 plants/ha.
El Paraíso	N/A*	Rows of maize spaced 0.75 m apart, 0.40 m between planting groups of 2 seeds for an overall density of 66,700 plants/ha; 0.20 m from each row of maize, a row of beans planted with 0.40 m between planting groups of 3 seeds for a density of 200,000 plants/ha.
La Libertad	N/A	Rows of maize spaced 0.80 m apart, 0.40 m between planting groups of 2 seeds for an overall density of 62,500 plants/ha; 0.10 m from each row of maize, a row of beans will be planted with 0.40 m between planting groups of 2 seeds for a density of 125,000 plants/ha.
Lempira	N/A	Rows of maize spaced 1 m apart, 0.50 m between planting groups of 2 seeds for an overall density of 40,000 plants/ha; 0.20 m from each row of maize, a row of beans planted with 0.50 m between planting groups of 2 seeds for a density of 80,000 plants/ha.
Chimaltenango	Rows of maize spaced 1 m apart, 0.50 m between planting groups of 3 seeds for an overall density of 60,000 plants/ha 2 groups of 2 bean seeds planted at the base of each planting hole for a density of 80,000 plants/ha.	Rows of maize spaced 1 m apart, 1 m between planting groups of 5 seeds for an overall density of 50,000 plants/ha; 2 groups of 3 bean seeds planted at the base of each planting hole for a density of 60,000 plants/ha.
Quetzaltenango	Rows of maize spaced 1 m apart, 0.50 m between planting groups of 3 seeds for an overall density of 60,000 plants/ha 2 bean seeds planted at the base of each planting hole for a density of 40,000 plants/ha.	Rows of maize spaced 1 m apart, 1 m between planting groups of 6 seeds for an overall density of 60,000 plants/ha; 2 bean seeds planted at base of each planting hole for a density of 20,000 plants/ha.

*In the event that planting arrangement was not evaluated as a factor in the trial, the local plan applies to all treatments.

Table 5. Pest and disease control plans for six field trials established to evaluate limitations to production of maize and beans in Honduras, Guatemala, and El Salvador in the 2017 growing season.

Site	Optimized	Local*
Suchitepéquez, Guatemala	N/A	Seed was treated (imidacloprid, thiodicarb) and phorate was applied to the soil during planting. Cipermectrina was applied various times throughout the cycle to control *Phyllophaga spp.* and *S. frugiperda.*
El Paraíso, Honduras	Seed was treated (tiametoxam), and phorate was applied to the soil when planting. Lufenuron, profenofos, tiametoxam, lambda-cihalotrina, fluazifop-p-butil, and diafentiuron were applied various times throughout the cycle to control *S. frugiperd* and *Phyllophaga spp.* in maize and *Diabrotica spp*, *Bemisia tabaci*, and *S. plebeia* in beans. Trifloxistrobina, tebuconazol, azoxystrobin, and ciptroconazol were also applied several times to combat *Rhytisma acerinum* in maize and *P. griseola* in beans.	Maize seed was treated (imidacloprid, thiodicarb). 2 applications of lufenuron and profenofos to control *S. frugiperda* in maize. 1 application of trifloxistrobina and tebuconazol to control *Rhytisma acerinum;* 1 application of tiametoxam and lambda-cihalotrina to control *Diabrotica spp.* and *Bemisia tabaci* in beans.
La Libertad, El Salvador	Seed was treated (imidacloprid, thiodicarb). Lufenuron, profenofos, florpirifos, imidacloprid, deltametrina, bifentrina, and propamocarb were applied various times throughout the cycle to control *S. frugiperd* and *Phyllophaga spp* in maize and *Diabrotica spp*, *Bemisia tabaci*, and *S. plebei* in beans. Azoxistrobina, difenoconazole were also applied several times to combat *Rhytisma acerinum* in maize and *P. griseola* in beans.	Seed was treated (metilcarbamato). 2 applications of clorpirifos to control *S. frugiperda* and *Phyllophaga spp*. in maize and 1 application of thiacloprid and beta-cyfluthrin to control *Diabrotica spp.* and *Bemisia tabaci* in beans.
Lempira, Honduras	Seed was treated (metilcarbamato), and phorate was applied to the soil when planting. Lufenuron, profenofos, tiametoxam, and lambda-cihalotrina were applied various times throughout the cycle to control *S. frugiperd* and *Phyllophaga spp.* in maize and *Apion godmani* in beans. Azoxystrobin and ciptroconazol were applied to control *Rhytisma acerinum* (maize) and *Phaeoisariopsis griseola* (beans).	Apart from seed treatment (methylcarbamate), no insecticides or fungicides utilized.
Chimaltenango, Guatemala	Seed was treated (imidacloprid, thiodicarb). Etridiazole, thiodicarb, thiophanate-methyl, thiacloprid, beta-cyfluthrin, lambda-cihalotrin, and deltametrina were applied to control *S. frugiperda* (in maize) and *Apion godmani* (in beans). Azoxistrobina was applied to control *Rhytisma acerinum* (maize) and *Rhizoctonia ofusarium* (beans).	No insecticides or fungicides utilized.
Quetzaltenango, Guatemala	Seed was treated (imidacloprid, thiodicarb). Etridiazole, thiophanate-methyl, thiacloprid, beta-cyfluthrin, lambda-cihalotrin, and deltametrina were applied to control *S. frugiperda* (in maize) and *Apion godmani* (in beans). Azoxistrobina was applied to control *Rhytisma acerinum* (maize) and *Rhizoctonia ofusarium* (beans).	No insecticides or fungicides utilized.

*In the event that pest and disease control was not evaluated as a factor in the trial, the local plan applies to all treatments.

Table 6. Planting dates, seed type, land preparation, and weed management for six field trials established to evaluate limitations to production of maize and beans in Honduras, Guatemala, and El Salvador in the 2017 growing season. Management practices apply to all treatments evaluated in study sites.

Site	Maize planting date	Maize seed	Bean planting date	Bean seed	Land Preparation	Planting Method	Weed control	Plot size (m^2)
Suchitepéquez	May 19	Dekalb 390, (commercial white hybrid)	NA	NA	Land mechanically tilled to a depth of 60 cm, followed by 2 passes of a disc harrow to a depth of 20 cm in April.	Seeds planted to a depth of approximately 5 cm with machete.	Weeds controlled using available herbicides as needed.	135
El Paraíso	June 23	HS 23 Cristiani (commercial white hybrid)	Oct 2	DICTA De Horo (improved red bean)	Land mechanically tilled in May using romplow, rows formed manually immediately before planting.	Seeds planted to a depth of approximately 5 cm with machete.	Weeds controlled using available herbicides as needed.	72
La Libertad	June 8	H59 (white hybrid)	Sept 19	CENTA EAC (improved red bean)	Land mechanically tilled in May.	Seeds planted to a depth of approximately 5 cm with machete.	Weeds controlled using available herbicides as needed.	67.2
Lempira	June 27	DICTA Sequia (improved white variety resistant to drought)	Oct 2	Cuarenteno (red bean variety that matures in 45 days)	Herbicides and machete used to clear weeds a week before planting.	Seeds planted to a depth of approximately 5 cm with machete.	Weeds controlled using available herbicides as needed.	40
Chimaltenango	March 21	Native white variety	Aug 29	Native climbing black bean variety	Land manually tilled to a depth of 40 cm in January. The *calza* performed in two steps- one in April and the other in May.	Seeds planted with a hoe to a depth of 20 cm to reach residual soil moisture before wet season begins.	Manually controlled 3 times throughout cycle (April, June, August).	121
Quetzaltenango	April 19-21	ICTA Compuesto Blanco (improved white variety)	April 19-21	ICTA Labor Ovalle (Climbing black bean)	Land manually tilled to a depth of 20 cm in December. The *calza** performed in June.	Seeds planted with a hoe to a depth of 20 cm to reach residual soil moisture before wet season begins.	Manually controlled 3 times throughout cycle (May, June, August).	120

* The *calza* is a traditional practice in which soil is formed into a volcano-like structure at the base of maize stalks.

Table 7. Farm characteristics and general management practices in six study sites in Central America as determined by interviews with local farmers during the 2017 growing season.

Site	Subsistence/ Commercial	Farm Size (ha)*	2015 Maize Yield (Mg ha^{-1})*	Seed Type	Tillage	Pesticide use	Fertilizer application
Suchitepéquez (n=5)	Commercial	1.5 ± 0.7	3.0 ± 0.5	Hybrid	Mechanized	Yes	Broadcast
El Paraíso (n=5)	Commercial	4.5 ± 0.9	2.8 ± 1.0	Hybrid	Mechanized	Yes	Broadcast
La Libertad (n=6)	Commercial	1.2 ± 0.4	3.1 ± 0.7	Hybrid	Mechanized	Yes	Broadcast
Lempira (n=7)	Subsistence	1.7 ± 0.3	1.1 ± 0.2	Improved variety	None	No	Buried
Chimaltenango (n=9)	Subsistence	0.8 ± 0.2	1.9 ± 0.4	Native	Manual	No	Buried
Quetzaltenango (n=7)	Subsistence	0.4 ± 0.1	2.2 ± 0.5	Improved variety	Manual	No	Buried

*Values represent mean ± standard error.

Table 8. Farmer-perceived limitations to maize and bean production as reported in semi-structured interviews in six study sites in Central America prior to the 2017 growing season.

	Site						
Limitation	Suchitepéquez (n=5)	El Paraíso (n=5)	La Libertad (n=6)	Lempira (n=7)	Chimaltenango (n = 9)	Quetzaltenango (n=7)	Average (n=39)
Nutrient management†	60%	0%	100%	71%	33%	57%	54%
Drought/water stress	40%	100%	50%	57%	78%	86%	69%
Storm damage (hail, wind and rain)	0%	20%	0%	0%	22%	0%	7.6%
Lack of improved seed	20%	0%	17%	0%	0%	29%	10%
Increased incidence of pest and disease	20%	40%	0%	14%	0%	29%	15%
Lack of manual labor	0%	0%	0%	29%	22%	0%	10%
Economic access to inputs	40%	20%	0%	14%	22%	0%	15%
Small farm size	0%	0%	33%	0%	11%	0%	7.6%

†Nutrient management included any mention of degraded soils, lack of access to fertilizer and/or lack of technical knowledge regarding nutrient application.

Table 9. Farmer-reported pests and disease that affect maize and bean yields as reported in semi-structured interviews in six study sites in Central America prior to the 2017 growing season.

		Suchitepéquez (n=5)	El Paraíso (n=5)	La Libertad (n=6)	Lempira (n=7)	Chimaltenango (n=9)	Quetzaltenango (n=7)
Maize Pests/Diseases	*Phyllophaga* spp. larva	x	x		x	x	x
	S. frugiperda	x	x	x	x	x	
	M. communis		x	x		x	
	Grain rot						x
	B. maydis						x
	Tar spot complex	x	x	x	x		
	B. tabaci	x					
Bean Pests/Diseases	*Diabrotica* spp.	NA	x	x		x	
	T. godmani	NA		x	x	x	x
	T. auricalcium	NA		x	x	x	x
	Yellowing leaves	NA					x
	B. tabaci	NA	x	x			
	P. latus	NA	x	x			
	T. cucumeris	NA			x		
	Aphis spp.	NA			x		

Table 10. Main and interaction effects of irrigation (irr), recommended fertilization (fert), improved pest and disease control (p&d), and optimized planting arrangement (plant) on maize yields in six regions of Central America in the 2017 growing season. P-values are presented for all main and two-way interaction effects.

	El Paraíso	Suchitepéquez	Quetzaltenango	La Libertad	Lempira	Chimaltenango
Irr	0.73	0.80	0.85	0.96	-0.25	0.49
P&D	0.007**	NA	0.73	0.04*	0.32	0.03*
Fert	0.01*	0.02*	<0.001**	0.10	0.29	0.57
Plant	NA	0.02*	<0.001**	NA	NA	0.58
Irr:P&D	0.82	NA	0.64	0.79	0.34	0.16
Irr:Fert	0.06	0.42	0.45	0.71	0.69	0.08
Irr:Plant	NA	0.093	0.48	NA	NA	0.14
P&D:Fert	0.58	NA	0.28	0.45	0.92	0.36
P&D:Plant	NA	NA	0.85	NA	NA	0.99
Fert:Plant	NA	0.25	0.03*	NA	NA	0.67

* indicates significance to an alpha level of 0.05. ** indicates significance to an alpha level of 0.01.

Table 11. Main and interaction effects of irrigation (irr), recommended fertilization (fert), improved pest and disease control (p&d), and optimized planting arrangement (plant) on bean yields in four regions of Central America in the 2017 growing season. P-values are presented for all main and two-way interaction effects.

	El Paraíso	La Libertad	Quetzaltenango	Chimaltenango
Irr	0.48	0.74	0.66	0.80
P&D	0.02*	0.92	0.23	0.82
Fert	0.01*	0.03*	0.63	0.44
Plant	NA	NA	0.008**	0.89
Irr:P&D	0.57	0.89	0.94	0.92
Irr:Fert	0.94	0.06	0.85	0.46
Irr:Plant	NA	NA	0.73	0.99
P&D:Fert	0.07	0.96	0.33	0.80
P&D:Plant	NA	NA	0.89	1.0
Fert:Plant	NA	NA	0.57	0.18

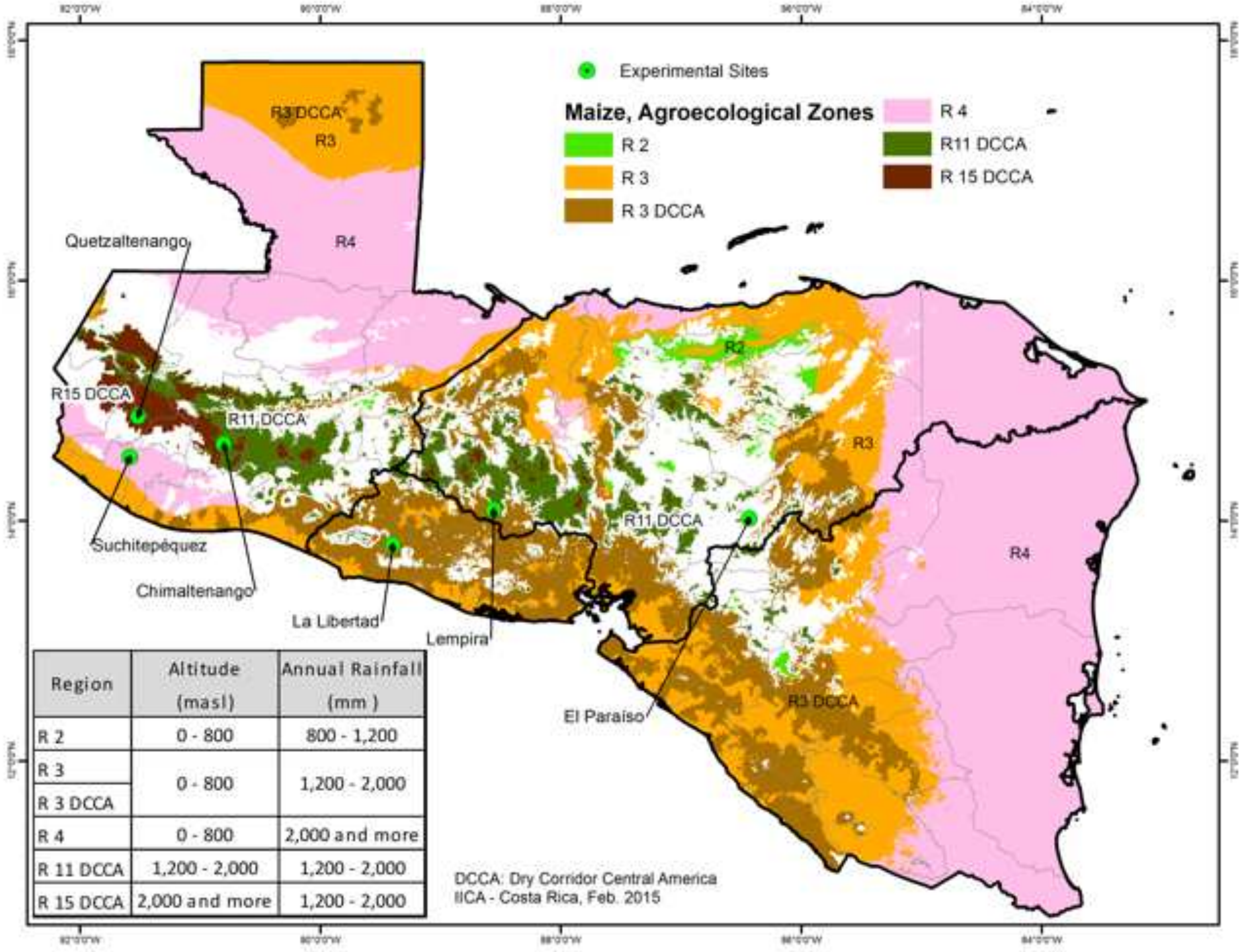
* indicates significance to an alpha level of 0.05. ** indicates significance to an alpha level of 0.01

Table 12. Yield increase (YI) for maize and beans, change in gross profit, difference in treatment cost, and change in net profit for each irrigation, improved pest and disease control, recommended fertilization, and optimized planting arrangement for six regions of Central America in the 2017 growing season. Differences (in gross revenue, treatment cost, and net profit) are expressed in USD ha^{-1} and were calculated by subtracting the local treatment level from the optimal level. Rows in gray emphasize factor and site combinations that show positive change in net profit.

Factor	Site	% YI Maize	% YI Beans	Optimal gross revenue (USD ha^{-1})	Optimal treatment cost (USD ha^{-1})	Optimal net profit (USD ha^{-1})	Local gross revenue (USD ha^{-1})	Local treatment cost (USD ha^{-1})	Local net profit (USD ha^{-1})	Difference in gross revenue (USD ha^{-1})	Difference in treatment cost (USD ha^{-1})	Difference in net profit (USD ha^{-1})
Pest and disease control	El Paraiso	26**	28*	2380	1928	452	1880	1560	320	500**	368	132
	La Libertad	15*	-0.48	3520	2333	1187	3331	1749	1582	189	584	-395*
	Quetzaltenango	2.2	22	2093	2499	-406	1971	2023	-52	122	476	-354
	Chimaltenango	31*	3.1	2888	2670	218	2491	2077	414	397	593	-196
	Lempira	11	NA	1231	1314	-83	1110	883	227	121	431	-310
Fertilization	El Paraiso	-10**	22**	2085	2074	11	2182	1415	767	-97	659	-756***
	La Libertad	9.4	-9.6*	3390	2231	1159	3460	1850	1610	-70	381	-451***
	Quetzaltenango	39***	0.07	2305	2347	-42	1758	2175	-417	547***	172	376**
	Chimaltenango	-3.9	-11	2590	2410	180	2789	2337	452	-199	73	-272
	Suchitepéquez	16*	NA	1248	1920	-672	1080	1331	-251	168*	589	-421***
	Lempira	9.7	NA	1226	1212	14	1116	984	132	110	228	-118
Irrigation	El Paraiso	-2	-5.5	2105	1777	328	2160	1712	448	-55	65	-120
	La Libertad	0.3	1.7	3445	2127	1318	3405	1955	1450	40	172	-132
	Quetzaltenango	-1.3	7.7	2037	2331	-294	2026	2192	-166	11	139	-128
	Chimaltenango	8.1	-3.9	2714	2436	278	2665	2311	354	49	125	-76
	Suchitepéquez	-7.0	NA	1123	1725	-602	1206	1526	-320	-83	199	-282
	Lempira	-7.6	NA	1123	1202	-79	1218	994	224	-95	208	-303
Planting arrangement	Quetzaltenango	26***	51**	2302	2396	-94	1761	2127	-366	541***	269	273*
	Chimaltenango	3.9	2.0	2728	2512	216	2651	2235	416	77	277	-200
	Suchitepéquez	19*	NA	1264	1640	-376	1065	1611	-546	199*	29	170*

* indicates alpha = 0.05. ** indicates alpha = 0.01. *** indicates alpha = 0.001.

FIGURES



Region	Altitude (masl)	Annual Rainfall (mm)
R 2	0 - 800	800 - 1,200
R 3	0 - 800	1,200 - 2,000
R 3 DCCA		
R 4	0 - 800	2,000 and more
R 11 DCCA	1,200 - 2,000	1,200 - 2,000
R 15 DCCA	2,000 and more	1,200 - 2,000

Figure 1. Study sites and six priority agroecological zones, characterized by long-term annual rainfall and elevation, in Honduras, El Salvador, Guatemala, and Nicaragua.

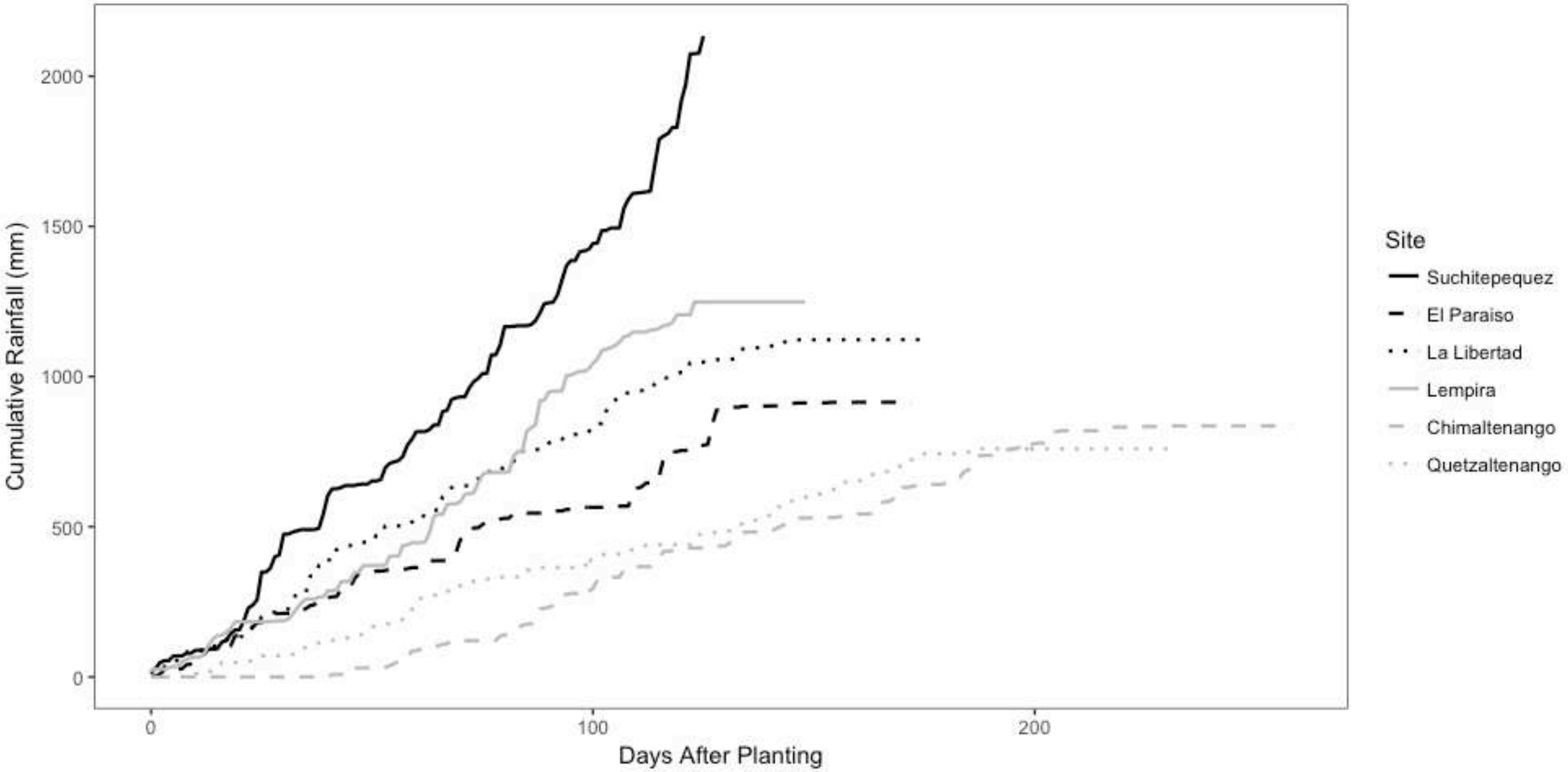


Figure 2. Cumulative daily rainfall during maize growing period in six regions of Central America.

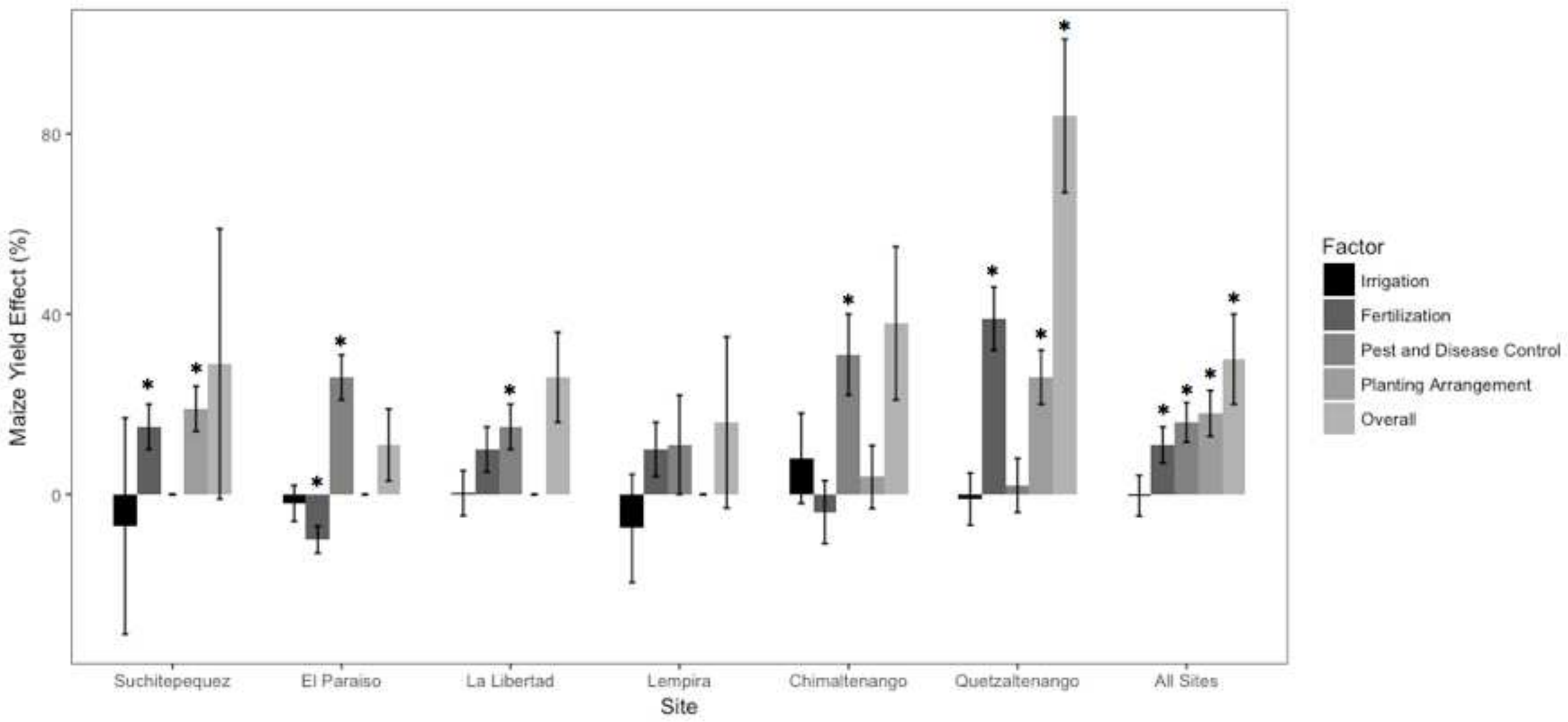


Figure 3. Effect of irrigation, optimized fertilization, optimized pest and disease control, and optimized planting arrangement on maize yields in six regions of Central America in the 2017 growing season. Data shown for individual sites as well as averaged across all sites. Yield effect for a particular factor is defined to be the estimated difference in mean yields for the optimized and farmer-replicated level divided by the farmer-replicated level. Error bars represent standard error of the mean. * indicates significance at 0.05 alpha level.

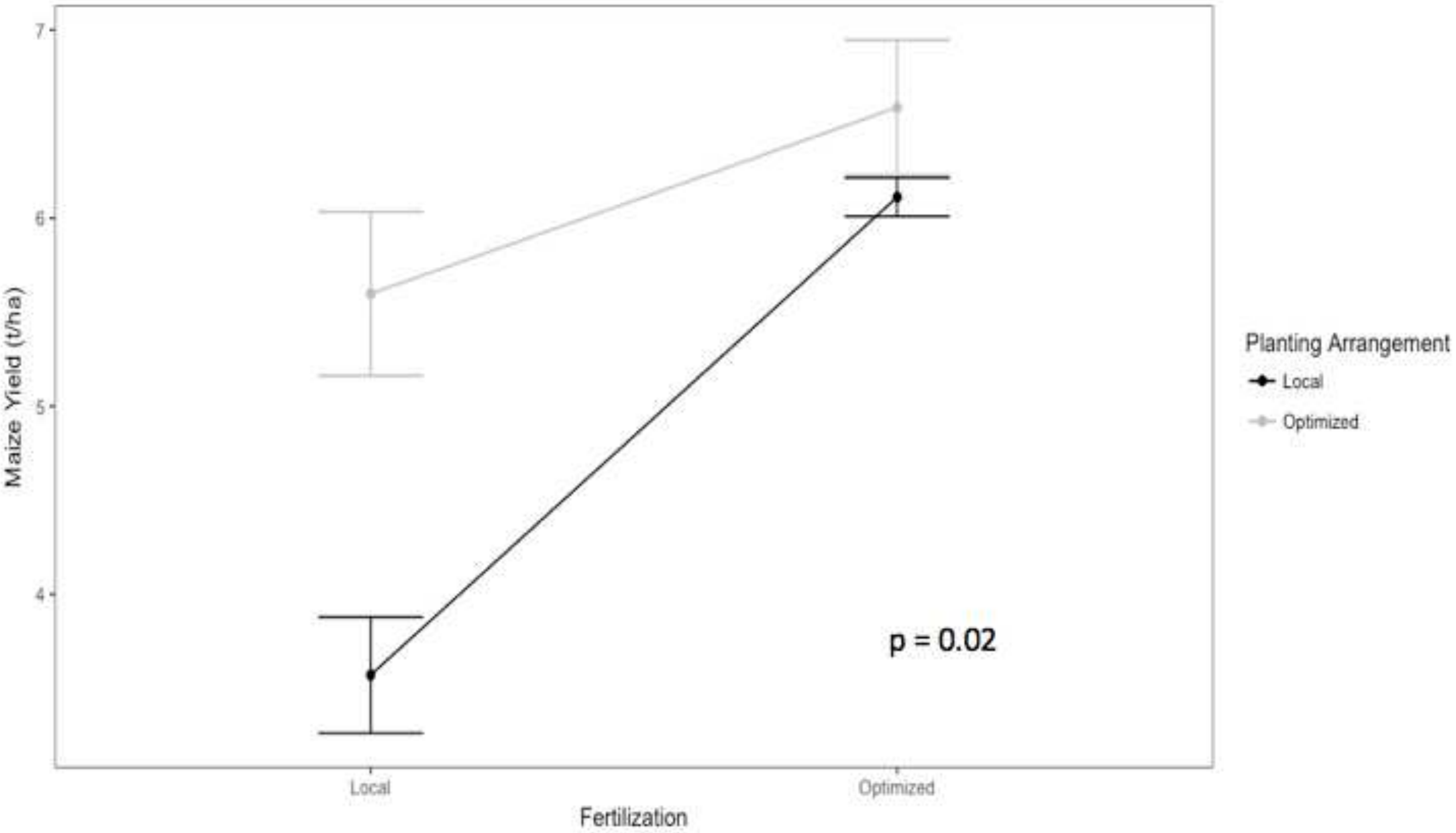


Figure 4. Interaction effect between planting arrangement and fertilization on maize yield in Quetzaltenango in the 2017 growing season. Error bars indicate standard error of the mean.

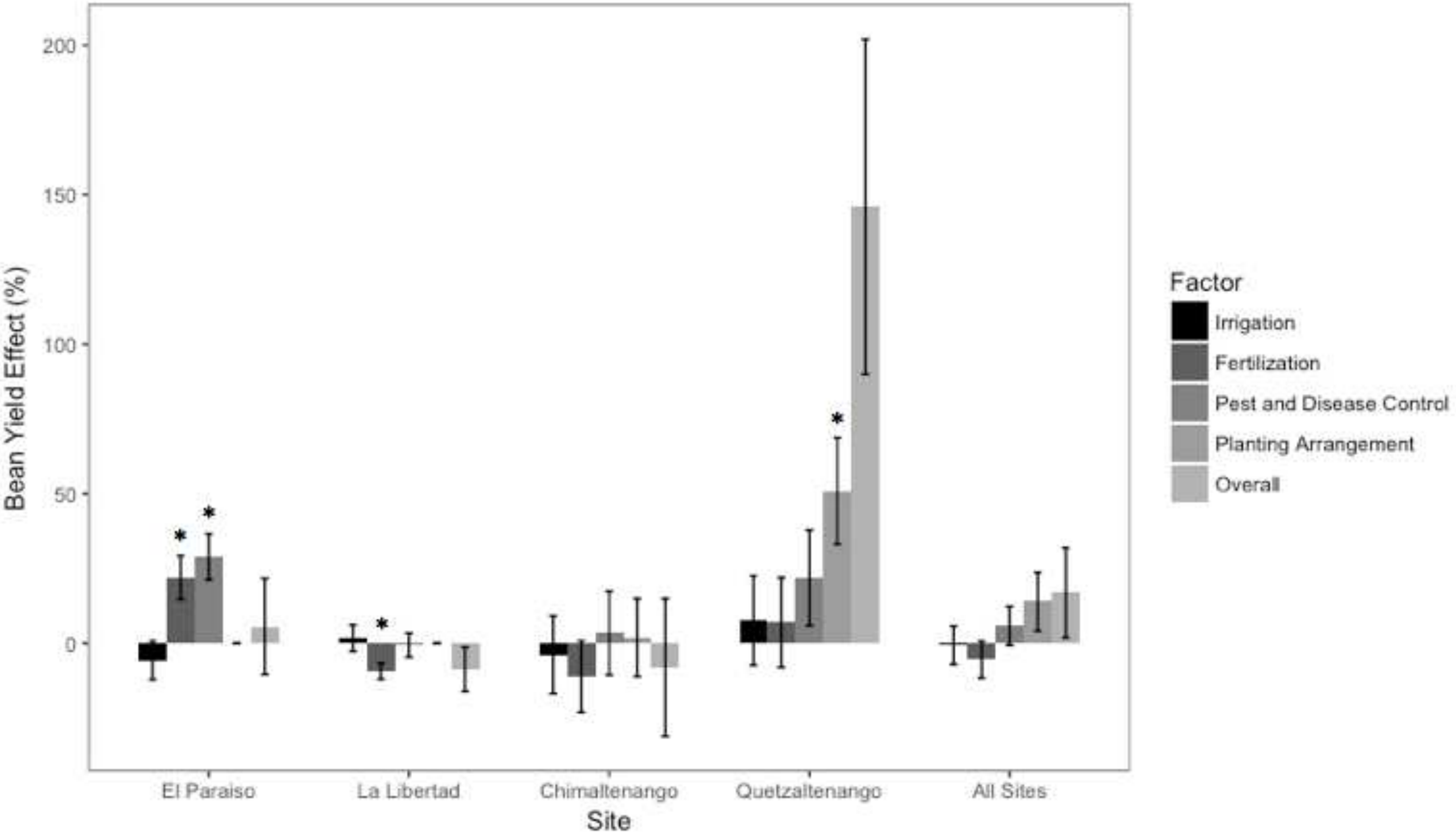


Figure 5. Effect of irrigation, optimized fertilization, optimized pest and disease control, and optimized planting arrangement on bean yields in four regions of Central America in the 2017 growing season. Data are shown for individual sites as well as averaged across all sites. Yield effect for a particular factor is defined to be the estimated difference in mean yields for the optimized and farmer-replicated level divided by the farmer-replicated level. Error bars represent standard error of the mean. * indicates significance at 0.05 alpha level.

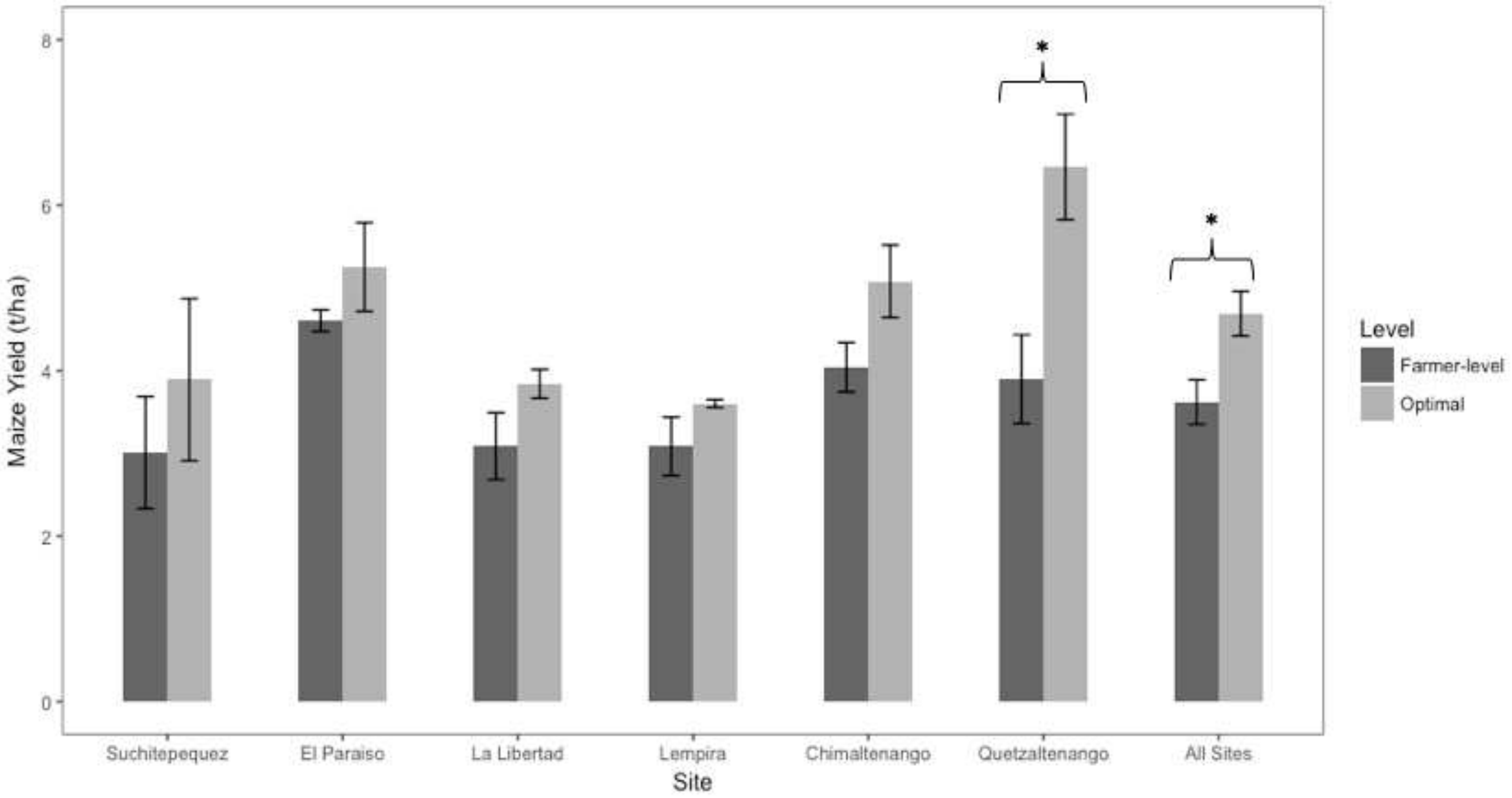


Figure 6. Attainable maize yield (estimated by average yield of treatment with irrigation, optimized pest and disease control, optimized fertilization, and optimized planting arrangement) and farmer-level maize yield (estimated by average yield of treatment with rainfed crop, local pest and disease plan, local fertilization, and local planting arrangement) at six regions in Central America, as well as averaged across all sites. Error bars represent standard error of the mean. * indicates significant difference between attainable yield and farmer-level yield at alpha=0.05.

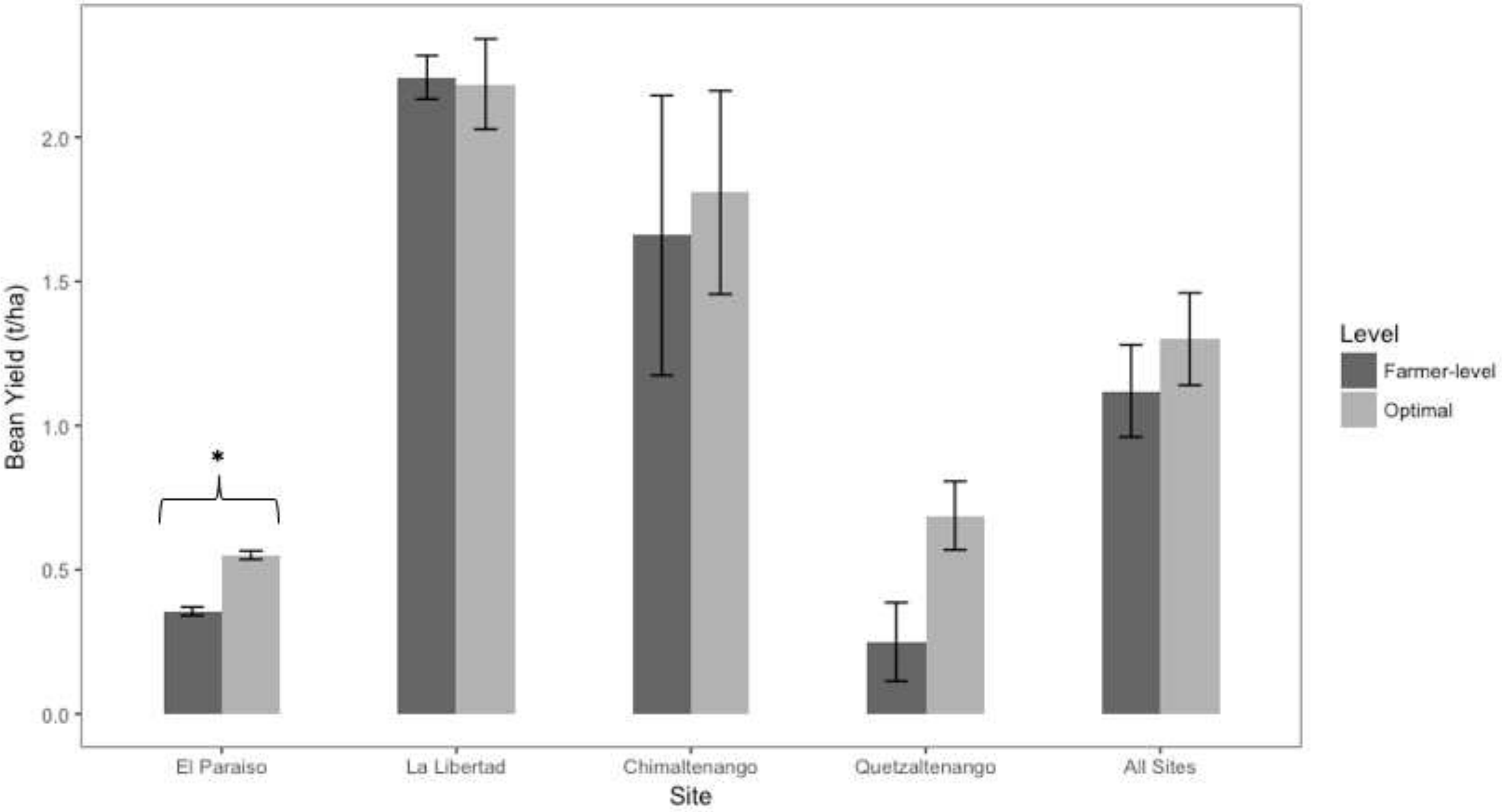


Figure 7. Attainable bean yield (estimated by average yield of treatment with irrigation, optimized pest and disease control, optimized fertilization, and optimized planting arrangement) and farmer-level bean yield (estimated by average yield of treatment with rainfed crop, local pest and disease plan, local fertilization, and local planting arrangement) at four regions in Central America, as well as averaged across all sites. Error bars represent standard error of the mean. * indicates significant difference between attainable yield and farmer-level yield at alpha=0.05.

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