The Effect of Permanent Raised Beds on Maize Yield in Mexico

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Capstone Report

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Executive Summary

This study used data collected from CIMMYT (International Maize and Wheat Improvement Center) research platform network initiated in 2012. Analyses did not detect significant effects of Permanent Raised Beds (PRB) on maize yield in most of the farming conditions for the trials, where PRB had been used for less than 5 years. The irrigation type had a significant main effect on maize yield, however, crop residue and bed-width main effects were not significant. A significant interaction was detected between irrigation and bed width for PRB with crop residues under irrigation. A significant interaction was detected between crop residue and bed width for non-PRB in rainfed trials. As expected, irrigated corn yielded much better than in rainfed conditions. Under rainfed conditions where residues are removed, farmers should practice PRB or conventional tillage or zero tillage without beds. Under rainfed conditions with crop residues kept, farmers should practice narrow PRB.

Abstract

Growing corn in Permanent raised beds (PRB) has been shown to improve cropping system performance around the world. It can help farmers improve soil quality, reduce irrigation water use, reduce production costs, and maintain stable yields. However, it can also increase input costs for equipment purchase, and cause weed and pest problems. According to previous research, bed width, crop residue and irrigation type appear to modify the effects of PRB. Within this context I conducted a study towards the following objective: To measure the main effects of irrigation type, bed width, and crop residue on maize yield, and to how PRB affects maize yield in different farming conditions in Mexico. This study used data collected from CIMMYT (International Maize and Wheat Improvement Center) research platform network initiated in 2012. In order to use data from multiple experiments that had a variety of experimental designs, I first analyzed sets of experiments repeated over time in the same plots, estimated marginal means and standard errors for each treatment in each year and site and merged these means and standard errors into a file. Then, I performed a new analysis using the file as input data. Because many factor combinations were missing in the data, I used contrasts to test for differences between specific combinations of factor levels. Analyses did not detect significant effects of PRB on

maize yield in most of the farming conditions for the trials, where PRB had been used for less than 5 years. The irrigation type had a significant main effect on maize yield, however, crop residue and bed-width main effects were insignificant. In the trials where crops were rainfed and residues were removed, narrow PRB treatments had significantly better yield than narrow non-PRB treatments (narrow PRB: 5710 $\pm$ 1.2 Kg/ha at a 95% confidence interval; narrow non-PRB: 1510 $\pm$ 1.3 Kg/ha at a 95% confidence interval). There was a significant interaction between irrigation and bed width for PRB with crop residues under irrigation. Narrow PRB have larger effect on increasing grain yield than wide PRB in rainfed trials than in irrigation trials. On the other hand, there was a significant interaction between crop residue and bed width for non-PRB in rainfed trials, whereby, when residue was removed, yields were much lower when narrow beds were used than when no beds were used. Yields increased significantly more by the addition of residues when narrow beds were used than when no beds were used. As expected, irrigated corn yielded much better than in rainfed conditions. Under rainfed conditions where residues are removed, farmers should practice PRB or conventional tillage or zero tillage without beds. Under rainfed conditions with crop residues kept, farmers should practice narrow PRB.

Introduction

In recent years, permanent raised beds (PRB) have been used as one way reduce tillage and combined with the principles of conservation agriculture (CA) to help farms improve soil health, reduce irrigation water use, reduce production costs, and maintain stable yields. The positive effects of PRB in cropping systems have been demonstrated globally, which will be elaborated in the following paragraphs.

In Pakistan's Punjab, PRB had a positive impact on cotton and wheat yields, and increased the farm net income, compared to the conventional farming system. Growing wheat and cotton on PRB used less irrigation water as well and it may save up to 50–60% of irrigation water (Gill, Ahmad & Awan 2005). In Bangladesh, increases in wheat yields under PRB were observed, including greater biomass, longer spikes, greater number of grains per spike and plumper grains. Wheat sown on PRB saves 30% irrigation water (Meisner *et al.* 2006). In the semi-arid tropics of southern Lombok, Indonesia, PRB were effective in increasing soil water content, reducing irrigation water requirement, and improving water use efficiency in rice cropping system (Ma'Shum *et al.* 2005). In the North China Plain, PRB were effective in increasing grain yield due to improved soil properties and reduced waterlogging. Moreover, PRB yields increased by >3% over the six years compared to conventional yields (He *et al.* 2015). In Yaqui Valley, Mexico, higher wheat yields have been obtained with PRB combined with residue retention, which were associated with gradual changes in soil physical, chemical and biological parameters that are related to tillage and residue management practices (Sayre, Limon & Govaerts 2005). In the Mediterranean region, soil quality was significantly higher in soil with furrows in PRB than with conventional tillage under flat conditions (Panettieri, Carmona, Melero, Madejón & Gómez-Macpherson 2013).

However, PRB also increase costs. For example, the cost of bed farming machinery could be very high. Some growers may need to completely change farming machinery for building and maintaining the beds before they transition into PRBs (Beecher, Thompson, Dunn & Mathews 2005). The occurrence of weeds may increase if crops are gown on PRB (Gill *et al.* 2005). Sustainable increases in both productivity and profitability are possible when residue mulching is combined with PRB (Meisner *et al.* 2006), but retention of residues from the previous crop may cause difficulties in spraying operations, provide shelter to insects/pests and obstruct other field operations (Gill *et al.* 2005). Sowing and operating machines may easily cause the permanent beds to lose shape, making them very rounded as soil falls off the shoulders and into the furrows (Wightman, Peries, Bluett & Johnston 2005).

Residue, bed width, and the duration of the bed appear to modify the effect of PRB. At least 25% of the residue should be retained with PRB for it to work well (Meisner *et al*. 2006), and at least six years are required to begin to realize the agronomic and economic benefits of PRB (He *et al.* 2015). Bed width of 70–80 cm (furrow to furrow) achieves more efficient irrigation water use compared with beds 1.2 m or wider (Sayre *et al.* 2005).

Compared to conventional maize farming in Mexico, which requires repeated intensive tillage over time, less retention of residues, less crop rotation and has detrimental effects on soil structure, studies have generally confirmed that maize sown on PRB yields more due to the improvement of soil health and there is a reduction of irrigation water use. The increase in grain yield for maize in PRB was more than 20% for each of the planting years, with an average value of 30% (Hassan, Hussain & Akbar 2005). PRB with residue retention resulted in higher and more stable maize yield than traditional management (Govaerts, Sayre & Deckers 2005).

Less research has been done on the effects of PRB width. Narrow beds may save more irrigation water compared to wider PRB (Sayre *et al.* 2005). But no research has determined the relationship between the width of PRB and maize crop yield. On the other hand, since maize is a water-sensitive crop and heavily dependent on climate conditions (Conde *et al.* 1998), PRB may have different effects on crop yield in irrigated and rainfed sites in Mexico.

Within this context I conducted a study towards the following objective: to determine the main effect of irrigation type, bed width, and crop residue on maize yield, and to figure out how PRBs affect maize yield under different farming conditions in Mexico. The overall aim of this experiment is to increase Mexican maize farmers' income through giving them suggestions for better cropping system, lower input costs and better yields of crops.

Materials and methods

Experimental sites

This study used data collected from CIMMYT research platform network, which is a nationwide network of trials on conservation agriculture and sustainable intensification initiated in 2012. The experiments were conducted at six rainfed sites and four irrigated sites across Mexico (Fig. 1): six rainfed sites including Apaseo el alto (20°4' N, 100°6' W), Cadereyta (20°7' N, 99°8' W) , Hopelchen (19°7' N, 89°8' W), Indaparapeo (19°7' N, 100°9' W), San Juan Cotzocon (17°1' N, 95°7' W), and San Martín de Hidalgo (20°4' N, 103°9' W); four irrigation sites including San Juan del Rio (20°3' N, 99°9' W), Guasave (25°5' N, 108°4' W), Ahome (25°9' N, 109°1' W), and Irapuato (20°6' N, 101°3' W). The climate in rainfed sites varied from Mediterranean, humid subtropical, to monsoon, with annual perception ranging from 600 to 1200 mm. The climate in irrigation sites varied from semi-arid, Mediterranean, to subtropical highland, with annual rainfall ranging from 170 to 700 mm.

The test sites reflecting variation in climate, cropping systems and farming practices were chosen to adequately represent the target region in Mexico.

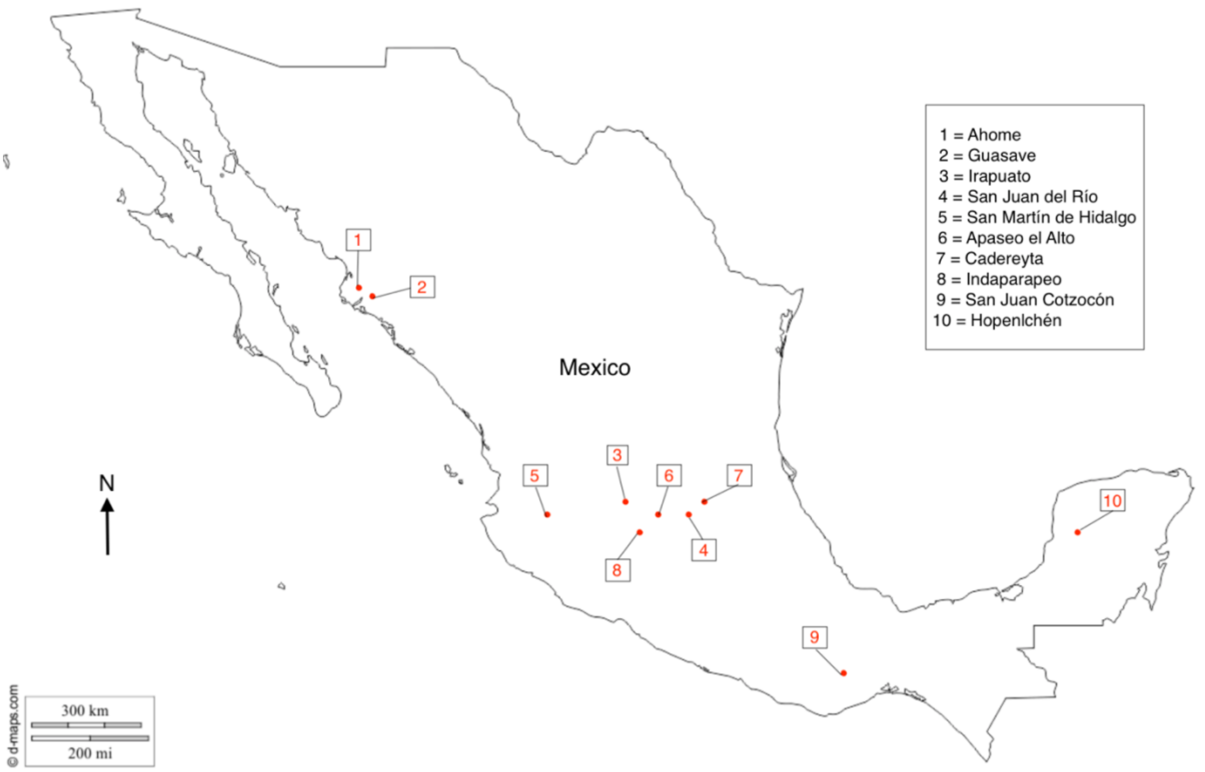

Fig.1 A map of Mexico showing the ten sites of the study with the major cropping systems in Mexico.

Statistical Analysis

Analyses were carried out for six rainfed sites (Apaseo el alto, San Juan Cotzocon, Indaparapeo, San Martin de Hidalgo, Cadereyta, and Hopelchen) and four irrigated sites (Guasave, Irapuato, San Juan del Rio, and Ahome). All sites have data from at least three years, except Hopelchen, Irapuato, and San Juan del Rio.

Four explanatory variables for yield and their different levels in this experiment included in the analysis were as follows:

Bed Width. The type of beds included in the database search comprised wide (Bed width greater than 1 m), narrow (Bed width less than 1 m but greater than 0.6 m), and none (no bed).

Irrigation Type. Irrigation types included irrigation and rainfed. In the sites with high annual precipitation, crops are rainfed for most of the year. In sites with low annual precipitation, farmers usually use gravity irrigation systems to transport water through fields from either storage reservoirs or deep tube wall (Sayre & Hobbs 2004). The most widely used method of irrigation is furrow irrigation.

Crop Residue. In the treatments with crop residues, grain was removed at harvest, and 0%, 10%, 25%, 30%, 50% or 100% of the stubble were left in the field under different treatments. Farmers chopped residues either with combine harvester-mounted choppers or by tractor-drawn field choppers. For my analysis, I classified treatments into two levels: with or without residue (+residue or -residue).

Tillage Type. The type of tillage included conservational tillage, conventional tillage, and zero tillage. In conventional tillage, primary and secondary tillage operations normally performed in preparing a seedbed and/or cultivating for a given crop grown in a given geographical area, usually resulting in < 30% cover of crop residues remaining on the surface after completion of the tillage sequence. In zero tillage, a procedure whereby a crop is planted directly into the soil with no primary or secondary tillage since harvest of the previous crop. No-till is sometimes practiced in combination with subsoiling to facilitate seeding and early root growth, whereby the surface residue is left virtually undisturbed except for a small slot in the path of the subsoil shank (Soil Science Society of America 2001). Compared with conventional tillage, conservational tillage has a marked reduction in the burning of crop residues, less tillage, and more variety of crops. Only conservational tillage has PRB treatments in this experiment.

One response variable in this experiment was included in the analysis:

Crop Yield. Grain yield at 14% moisture.

The definition of PRB for two levels:

Permanent Raised Bed (PRB). After beds are formed, the normal tillage work on beds is done. The only tillage on PRB is the use of shovels or disc tools in the furrow bottoms to reshape the beds (Sayre *et al.* 2005). The goal of using PRB is to use them continuously for as long as feasible. PRB in this experiment can also be regarded as the combination of conservation tillage and bed width greater than 0.6 m. Two types of PRB were included in the analysis: CPA (wide permanent raised bed, bed width greater than 1 m) and CP (narrow permanent raised bed, bed width less than 1 m but greater than 0.6 m).

In order to use data from multiple experiments that had a variety of experimental designs, I analyzed sets of experiments repeated over time in the same plots and calculated estimated marginal means and standard errors for each treatment in each year and site. Then, these means and standard errors were merged into a file and a new analysis was performed with the following model in R (Pinheiro, Bates, DebRoy & Sarkar 2019), using the lme4 package (Bates, Mächler, Bolker & Walker 2015): lme(log(estimate_yield) ~ flat_trt, random = ~ 1 | site_year, weights = ~ I(1/SE^2). Flat_trt represents all combinations of irrigation type, crop residue, tillage type and bed width that were observed in the experiments. Fig. 2 shows all combinations in this experiment. Considering the many factor combinations are missing, a factorial analysis of variance was not possible, so I used selected contrasts and the corresponding t- tests. In all sites, significant differences between treatments were tested at $p < 0.05$.

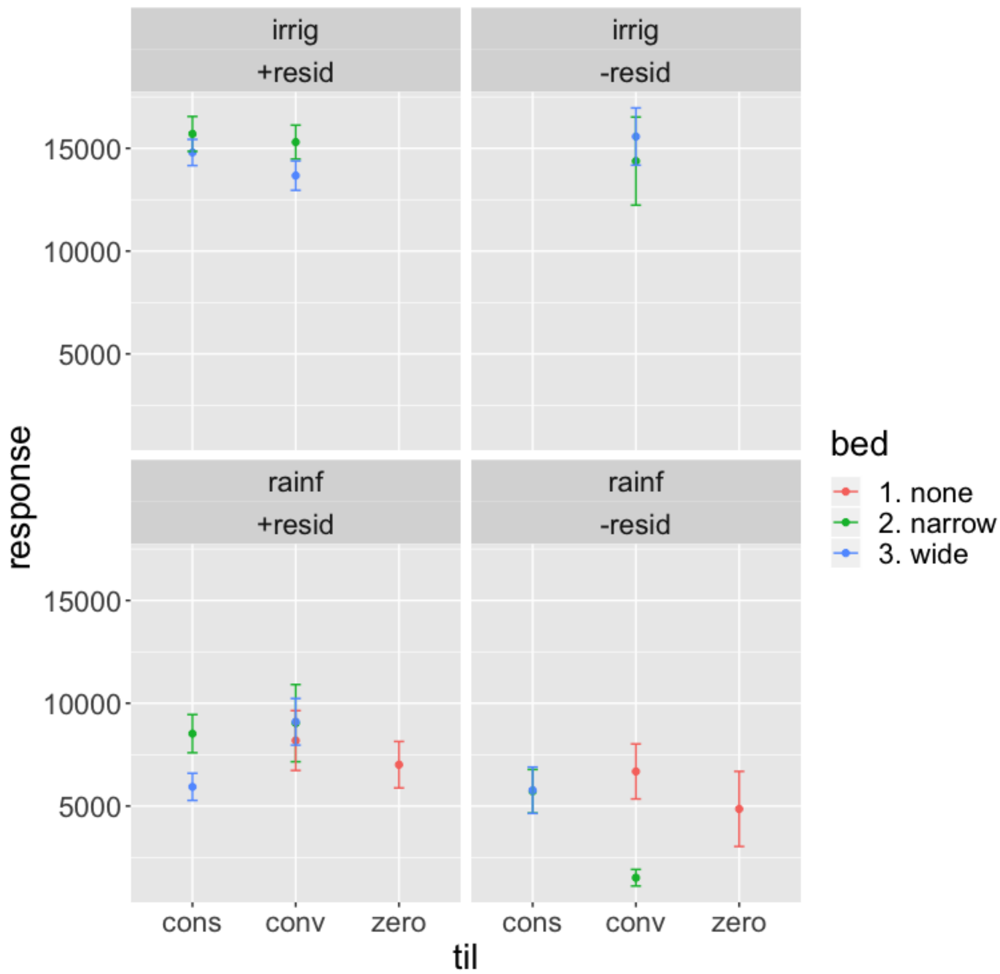

Fig.2 Treatments and responses

Results

Impact of irrigation type

In the trials where crops were planted on beds (PRB or conventional beds), and residue was kept after the harvest (+residue), estimated mean corn yield from irrigated trials was 14913 kg/ha (Mean $\pm$ se = 9.61 $\pm$ 0.0255 in log transformation at a 95% confidence interval). Estimated mean corn yield from rainfed trials was 8022 kg/ha (8.99 $\pm$ 0.072 in log transformation at a 95% confidence interval). The difference detected between rainfed and irrigated trials were significant ($P < 0.0001$).

Impact of crop residue

In the trials where crops were irrigated in conventional tillage, estimated mean corn yield from treatments in which residue was kept after the harvest (+residue), was 14472.42 kg/ha (9.58 $\pm$ 0.0375 in log transformation at a 95% confidence interval). Estimated mean corn yield from treatments in which residue was removed after the harvest (-residue), was 14913.17 kg/ha (9.61 $\pm$ 0.0869 in log transformation at a 95% confidence interval). No significant differences were detected between +residue and -residue in those trials ($P = 0.7210$).

In the trials where crops were rainfed in conservation tillage, estimated mean corn yield from treatments in which residues was kept after the harvest (+residue), was 7115.281 kg/ha (8.87 $\pm$ 0.0779 in log transformation at a 95% confidence interval). Estimated mean corn yield from treatments, which residue was removed after the harvest (-residue), was 5767.535 kg/ha (8.66 $\pm$ 0.135 in log transformation at a 95% confidence interval). No significant differences were detected between +residue and -residue in those trials ($P = 0.1733$).

Impact of bed width

In trials where crops were planted on beds (PRB or conventional beds), and residues were kept, estimated mean corn yield from narrow beds was 11614 kg/ha (9.36 $\pm$ 0.0617 in log transformation at a 95% confidence interval). Estimated mean corn yield from wide trials was 10198 kg/ha (9.23 ± 0.0451 in log transformation at a 95% confidence interval). No significant differences were detected between narrow and wide bed treatments in those trials (P = 0.0889).

Performance of PRB in different environmental conditions

In the trials where crops were irrigated, and crop residues were kept, estimated mean corn yield under permanent raised beds treatment was 15214 kg/ha (9.63 ± 0.0345 in log transformation at a 95% confidence interval). Estimated mean corn yield under non-permanent raised beds treatment (narrow and wide beds under conventional tillage) was 14472 kg/ha (9.58 ± 0.0375 in log transformation at a 95% confidence interval). No significant differences were detected between permanent and non-permanent beds' treatments in those trials (P = 0.30).

In the trials where crops were rainfed, and crop residues were kept, estimated mean corn yield under permanent raised bed treatment was 7115 kg/ha (8.87 ± 0.0779 in log transformation at a 95% confidence interval). Estimated mean corn yield under non-permanent raised beds treatment (narrow and wide beds under conventional tillage) was 9045 kg/ha (9.11 ± 0.121 in log transformation at a 95% confidence interval). No significant differences were detected between permanent and non-permanent bed treatments in those trials (P = 0.09).

In the trials where crops were rainfed, and residues were removed, estimated mean corn yield under narrow permanent raised beds treatment was 5710 kg/ha (8.65 ± 0.186 in log transformation at a 95% confidence interval). Estimated mean corn yield under narrow non-permanent raised beds treatment (narrow beds under conventional tillage) was 1510 kg/ha (7.32 ± 0.266 in log transformation at a 95% confidence interval). Significant differences were detected between permanent and non-permanent beds' treatments in those trials (P < 0.0001). On the other hand, there is no significant yield difference between narrow PRB and wide PRB (P = 0.9733). Neither nor between narrow PRB treatment and treatments without beds in conventional tillage (P = 0.4565), and between narrow permanent raised beds treatment and treatments without beds in zero tillage (P = 0.6993).

Interaction between irrigation type and bed width for trials with PRB and crop residues was kept

In the trials where crops were irrigated and crop residues was kept, estimated mean corn yield under permanent raised beds treatment was 15214 kg/ha (9.63 $\pm$ 0.0345 in log transformation at a 95% confidence interval), which was the average of narrow and wide beds, since they did not differ from each other. On the other hand, estimated mean corn yield under PRB treatment from the trials, where crops were rainfed, and crop residues was kept did differ between narrow (8522 kg/ha, se = 930 in log transformation was 6.83) and wide (5935 kg/ha, se = 660 in log transformation was 6.49) beds ($P = 0.0228$). The impact of the width of PRB on crop yield was significantly affected by irrigation type ($P < 0.001$). Narrow PRB had a larger effect on yield in rainfed than irrigated trials (Fig. 3).

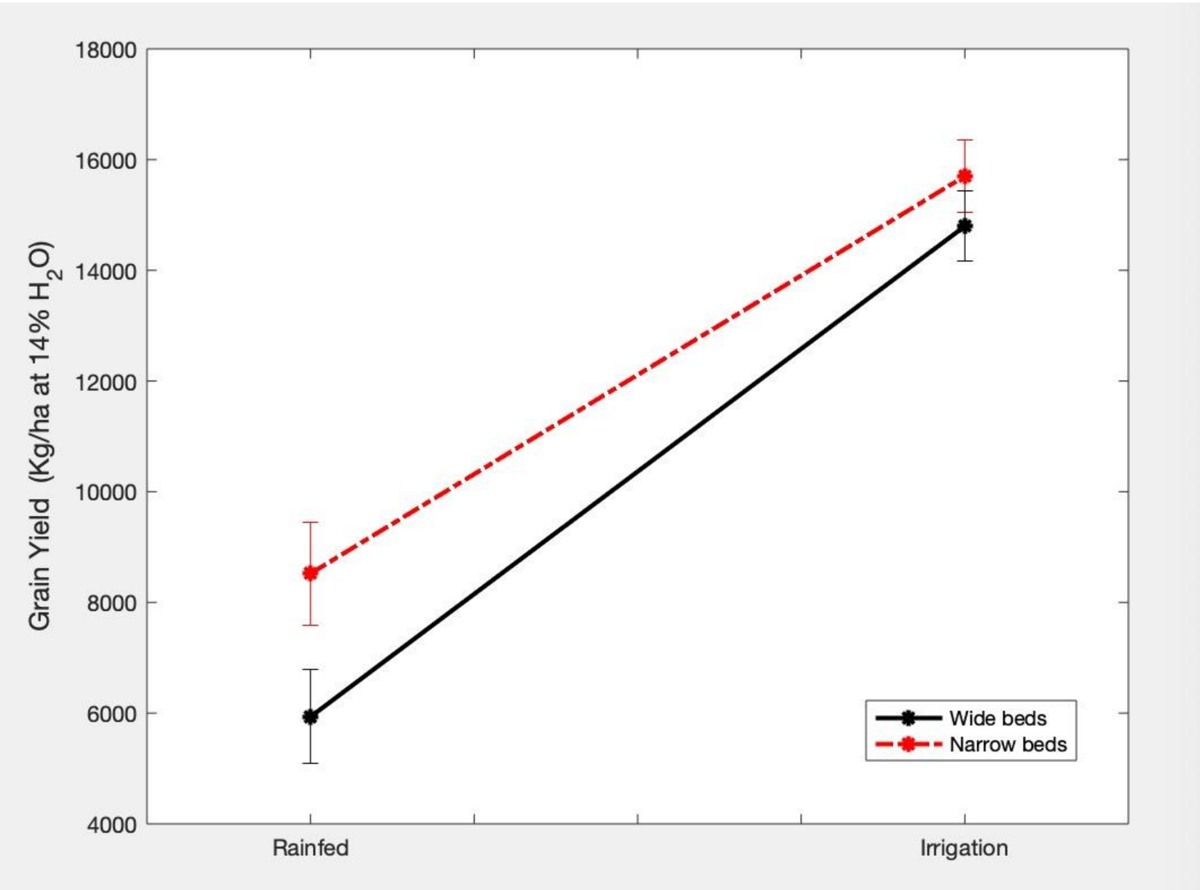

Fig 3. Interaction between irrigation type and bed width for PRB with crop residue

Interaction between crop residue and bed width for PRB in rainfed trials

In the trials where crops were rainfed, estimated mean corn yield under narrow permanent raised beds treatment with residue was 6974 kg/ha (8.85 ± 0.108 in log transformation at a 95% confidence interval). Estimated mean corn yield under wide permanent raised beds treatment without residue was 5825 kg/ha (8.67 ± 0.112 in log transformation at a 95% confidence interval). The impact of the width of permanent raised beds on crop yield was not significantly affected by crop residue ($P = 0.17$).

Interaction between crop residue and bed width for non-PRB in rainfed trials

In the trials where crops were rainfed, estimated mean corn yield under conventional tillage with narrow bed treatment was 3714 kg/ha (8.22 ± 0.169 in log transformation at a 95% confidence interval). It did differ between +residue (9033 kg/ha, se = 1877 in log transformation was 7.53) and -residue (1515 kg/ha, se = 403 in log transformation was 5.99) treatment ($P < 0.001$). Estimated mean corn yield under conventional tillage with no bed was 7405 kg/ha (8.91 ± 0.134 in log transformation at a 95% confidence interval), which was the average of +residue and -residue, since they did not differ from each other ($p = 0.4504$). The impact of the bed width on crop yield was significantly affected by crop residue ($P < 0.0019$). Maize yield exhibited a significant interaction between use of beds and residue in rainfed sites. When no residue was added yields were much lower when narrow beds were used than when no beds were used. Yields increased significantly more by the addition of residues when narrow beds were used than when no beds were used, such that there was no difference in yield due to bed use when residues were not removed (Fig. 4).

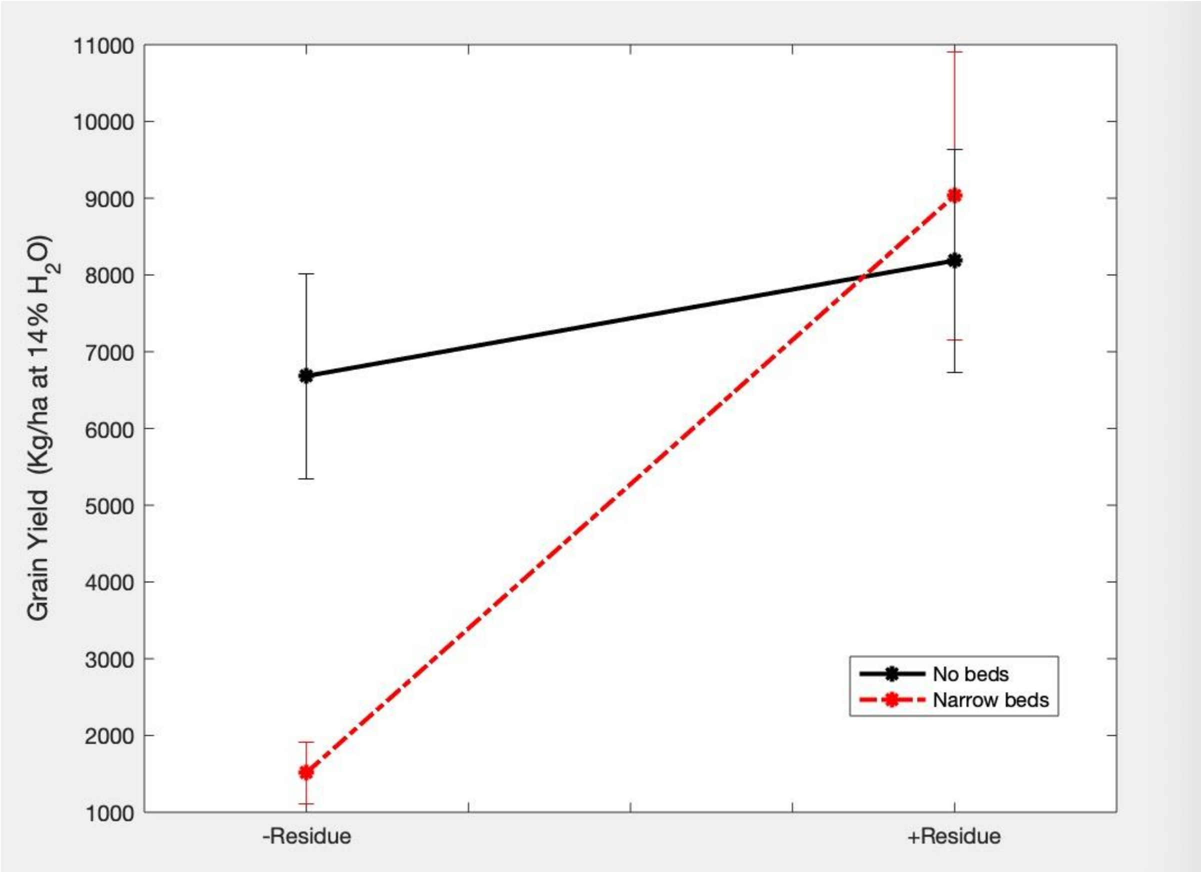

Fig 4. Interaction between crop residue and bed width for non-PRB in rainfed trials

Discussion

Although PRB has attracted widespread attention among scientists and researchers, the benefits of its adoption are not as clear cut in all farming conditions. The meta-analysis of CIMMYT's data evaluated the impact of PRB on maize yield under different farming conditions in Mexico.

The results revealed that the adoption of PRB does not significant effect on maize yield in most of the farming conditions. The only one result shown that PRB (narrow) has significant better yield than bed (narrow) in conventional tillage is in rainfed trials, where crop residue was removed from the field after harvest. When it comes to the trials, where the crop residue was kept after harvest, the PRB's effect on maize yield is neither significant in rainfed trials nor irrigation trials. However, based on the previous research on PRB, PRB's effect on crop yield change depending on crop residue. Researchers claimed that residue mulch is critical and has to be combined with PRB for maximizing and sustaining its beneficial effects (Govaerts, Sayre, Lichter, Dendooven & Deckers 2007). However, in the trials in this experiment, where maize was rainfed, and crop residue were kept, non-PRB treatments yield 1930 kg/ha more than PRB treatments. Three possible reasons can be used to explain why crop residue's main effect is not significant, and it's even negative in some situations. First, due to the limit data I have, most of the trials in this experiment have less than four years data. If each trial has more than 5 years data, then the crop residue may have enough time to improve the soil quality, and may have significant effect on maize crop yield. Only analyzing the last year data for each trial can be another option to solve the limit data problem. Second, some research mentioned that at least 25% of the residue should be retained with PRB for it to work well (Meisner *et al*. 2006). However, for my analysis, I classified treatment with residue (+residue) any situation where not all residue was removed (0% crop residue left in the field). Third, retention of residues from the previous crop may cause difficulties in spraying operations, provide shelter to insects/pests and obstruct other field operations (Gill *et al.* 2005). Another notable finding of this study is the differential response of crop residue observed in non-PRB treatments from rainfed trials. Mazie grown under non-PRB treatment in rainfed environments responded better to crop residue than maize grown under PRB treatment in rainfed environments.

Irrigation type has a significant main effect on maize yield, irrespective PRB treatments or non-PRB treatments. In the trials where maize was irrigated, yield averaged 6891 kg/ha more than the trials where maize was rainfed. This result shows that maize yield may depend on stable of water supply. Due to unstable of precipitation in rainfed trials, crops are facing higher water stress during the crop growth. On the other hand, the monsoon may easy to break the rainfed crop in dry seasons, which can result in partial or complete failure of the crops.

Bed width's main effect was not significant, but its p-value is close to 0.05. There is no evidence to prove that bed width can cause the change of maize yield in this experiment. However, analysis results indicated that there is an interaction between irrigation type and bed width for PRB treatments in the trials, where crop residue was kept after harvest. The impact of the width of permanent raised beds on crop yield was significantly affected by irrigation type ($P < 0.001$) in this situation. This indicated that narrow PRB may achieve more efficient irrigation water use compared with wide PRB, especially in the low level of percipatation rainfed area.

This study did not consider the impacts of bed width on soil health, such as soil bulk density, water holding capacity and microorganisms, and water use efficiency, but admitted that there could be other positive effects of PRB on maize yield.

As for overall suggestions to farmers, since irrigation farming system yield much better than rainfed farming system, Mexican farmers should plant maize in the place with high levels of precipitation and choose to irrigate the crop. Farmers working in the fields where crops were rainfed and residues was removed, should practice PRB, treatment without beds in conventional tillage or treatment without beds in zero tillage. In the trials, where crops were rainfed, and crop residues was kept after harvest, Mexican farmers should not practice wide PRB but narrow PRB or conventional tillage.

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Appendix

R code

```
library(tidyverse)
library(lme4)
library(emmeans)
library(lmerTest)
library(effects)
library(car)
library(nlme)
library(HH)
library(knitr)
library(multcomp)
library(multcompView)
library(ggplot2)

# Load data
getwd()
setwd("/Users/shanheyiqian/Desktop/")
d <- read.csv("maize.csv")
str(d)

# Create lookup tables for factors
site2irrg <- c(rep("rainf", 6), rep("irrig", 4))
names(site2irrg) <- c("Apaseo el alto",
            "San Juan Cotzocon",
            "Indaparapeo",
            "San Martin de Hidalgo",
            "Cadereyta", "Hopelchen",
            "Guasave",
            "Irapuato I",
            "San Juan del Rio III",
            "Ahome")

abrev2till <- c("zero", "conv", "min", "cons", "cons", "min", "conv", "conv", "min", "min")
names(abrev2till) <- c("CL", "LC", "LM", "CP", "CPA", "CPM", "CC", "CCA", "CM", "CMA")

# Make a data frame with all the relevant variables.
# Note that tillage and beds are combined into a single factor because not all
# combinations are present. minimum till has only have few observations so it is removed.
# residue is simplified into none or at least some.
maize <- d %>%
  filter(crop == "maize") %>%
  mutate(rep = factor(rep),
     year = factor(year),
     treat = factor(treat.n),
```

```
        env = factor(paste(site, year, sep = "_")),
        block = factor(paste(site, rep, sep = "_")),
        plot = factor(paste(block, treat, sep = "_")),
        irrigation = factor(unname(site2irrg[as.character(site)]),
                    levels = c("rainf", "irrig")),
        tillage = factor(unname(abrev2till[as.character(code)]),
                  levels = c("zero", "min", "cons", "conv")),
        f_resid = factor(ifelse(residue > 0, "+resid", "-resid"),
                  levels = c("-resid", "+resid")),
        beds = factor(as.character(beds), levels = c("none", "wide", "narrow")),
        til_bed = factor(paste(tillage, beds, sep = "_"))) %>%
  filter(tillage != "min") %>%
  mutate(til_bed = factor(til_bed))

str(maize)

#================== Multistage analyses ==============

# Set 1: Apaseo el alto, 2014 - 2015.
group1 <- maize %>%
  filter(a_group == "set 1") %>%
  mutate(final.treat = paste(til_bed, f_resid, sep = "_"),
        treat = factor(treat),
        year = factor(year),
        final.treat = factor(final.treat))

g1m <- lmer(yield ~ final.treat + treat + year + (1|block/plot), data = group1, na.action =
na.exclude)
g1m.emm.s <- emmeans(g1m, c("final.treat", "year"))
g1m.emm.s

# Set 2: Apaseo el alto, 2016 - 2017
group2 <- maize %>%
  filter(a_group == "set 2") %>%
  mutate(final.treat = paste(til_bed, f_resid, sep = "_"),
        treat = factor(treat),
        year = factor(year),
        final.treat = factor(final.treat))

g2m <- lmer(yield ~ final.treat + treat + year + (1|block/plot), data = group2, na.action =
na.exclude)
g2m.emm.s <- emmeans(g2m, c("final.treat", "year"))
g2m.emm.s

# Set 3: Apaseo el alto, 2018.
group3 <- maize %>%
  filter(a_group == "set 3") %>%
```

```
  mutate(final.treat = paste(til_bed, f_resid, sep = "_"),
         treat = factor(treat),
         year = factor(year),
         final.treat = factor(final.treat))

g3m <- lmer(yield ~ final.treat + treat + (1 | block), data = group3, na.action = na.exclude)
g3.emm.s <- emmeans(g3m, "final.treat")
g3.emm.s

# Set 4: Cadereyta, 2015 - 2018.
group4 <- maize %>%
  filter(a_group == "set 4") %>%
  mutate(final.treat = paste(til_bed, f_resid, sep = "_"),
         treat = factor(treat),
         year = factor(year),
         final.treat = factor(final.treat))

g4m <- lmer(yield ~ final.treat + treat + year + (1 | block/plot),
            data = group4, na.action = na.exclude)
g4m.emm.s <- emmeans(g4m, c("final.treat", "year"))
g4m.emm.s

# Set 5: Hopelchen, 2016.
group5 <- maize %>%
  filter(a_group == "set 5") %>%
  mutate(final.treat = paste(til_bed, f_resid, sep = "_"),
         treat = factor(treat),
         year = factor(year),
         final.treat = factor(final.treat))

g5m <- lmer(yield ~ final.treat + treat + (1 | block), data = group5, na.action = na.exclude)
g5.emm.s <- emmeans(g5m, c("final.treat"))
g5.emm.s

# Set 6: Hopelchen, 2017.
group6 <- maize %>%
  filter(a_group == "set 6") %>%
  mutate(final.treat = paste(til_bed, f_resid, sep = "_"),
         treat = factor(treat),
         year = factor(year),
         final.treat = factor(final.treat))

g6m <- lmer(yield ~ final.treat + treat + (1 | block), data = group6, na.action = na.exclude)
g6.emm.s <- emmeans(g6m, c("final.treat"))
g6.emm.s

# Set 7: Indaparapeo, 2013.
```

```
group7 <- maize %>%
  filter(a_group == "set 7") %>%
  mutate(final.treat = paste(til_bed, f_resid, sep = "_"),
         treat = factor(treat),
         year = factor(year),
         final.treat = factor(final.treat))

g7m <- lmer(yield ~ final.treat + treat + (1 | block), data = group7, na.action = na.exclude)
g7.emm.s <- emmeans(g7m, c("final.treat"))
g7.emm.s

# Set 8: Indaparapeo, 2014.
group8 <- maize %>%
  filter(a_group == "set 8") %>%
  mutate(final.treat = paste(til_bed, f_resid, sep = "_"),
         treat = factor(treat),
         year = factor(year),
         final.treat = factor(final.treat))

g8m <- lmer(yield ~ final.treat + treat + (1 | block), data = group8, na.action = na.exclude)
g8.emm.s <- emmeans(g8m, c("final.treat"))
g8.emm.s

# Set 9: Indaparapeo, 2015. Deleted

# Set 10: Indaparapeo, 2016.
group10 <- maize %>%
  filter(a_group == "set 10") %>%
  mutate(final.treat = paste(til_bed, f_resid, sep = "_"),
         treat = factor(treat),
         year = factor(year),
         final.treat = factor(final.treat))

g10m <- lmer(yield ~ final.treat + treat + (1 | block), data = group10, na.action = na.exclude)
g10.emm.s <- emmeans(g10m, c("final.treat"))
g10.emm.s

# Set 11: Indaparapeo, 2017.
group11 <- maize %>%
  filter(a_group == "set 11") %>%
  mutate(final.treat = paste(til_bed, f_resid, sep = "_"),
         treat = factor(treat),
         year = factor(year),
         final.treat = factor(final.treat))

g11m <- lmer(yield ~ final.treat + treat + (1 | block), data = group11, na.action = na.exclude)
g11.emm.s <- emmeans(g11m, c("final.treat"))
```

```
g11.emm.s

# Set 12: San Martin de Hidalgo, 2015.
group12 <- maize %>%
  filter(a_group == "set 12") %>%
  mutate(final.treat = paste(til_bed, f_resid, sep = "_"),
         treat = factor(treat),
         year = factor(year),
         final.treat = factor(final.treat))

g12m <- lmer(yield ~ final.treat + treat + (1 | block), data = group12, na.action = na.exclude)
g12.emm.s <- emmeans(g12m, c("final.treat"))
g12.emm.s

# Set 13: San Martin de Hidalgo, 2016.
group13 <- maize %>%
  filter(a_group == "set 13") %>%
  mutate(final.treat = paste(til_bed, f_resid, sep = "_"),
         treat = factor(treat),
         year = factor(year),
         final.treat = factor(final.treat))

g13m <- lmer(yield ~ final.treat + treat + (1 | block), data = group13, na.action = na.exclude)
g13.emm.s <- emmeans(g13m, c("final.treat"))
g13.emm.s

# Set 14: San Martin de Hidalgo, 2017.
group14 <- maize %>%
  filter(a_group == "set 14") %>%
  mutate(final.treat = paste(til_bed, f_resid, sep = "_"),
         treat = factor(treat),
         year = factor(year),
         final.treat = factor(final.treat))

g14m <- lmer(yield ~ final.treat + treat + (1 | block), data = group14, na.action = na.exclude)
g14.emm.s <- emmeans(g14m, c("final.treat"))
g14.emm.s

# Set 15: Irapuato I, 2014,2016.
group15 <- maize %>%
  filter(a_group == "set 15") %>%
  mutate(final.treat = paste(til_bed, f_resid, sep = "_"),
         treat = factor(treat),
         year = factor(year),
         final.treat = factor(final.treat))

g15m <- lmer(yield ~ final.treat + treat + year + (1 | block/plot),
```

```
           data = group15, na.action = na.exclude)
g15.emm.s <- emmeans(g15m, c("final.treat", "year"))
g15.emm.s

# Set 16: San Juan Cotzocon, 2014 - 2017.
group16 <- maize %>%
  filter(a_group == "set 16") %>%
  mutate(final.treat = paste(til_bed, f_resid, sep = "_"),
        treat = factor(treat),
        year = factor(year),
        final.treat = factor(final.treat))

g16m <- lmer(yield ~ final.treat + treat + year + (1 | block/plot),
           data = group16, na.action = na.exclude)
g16.emm.s <- emmeans(g16m, c("final.treat", "year"))
g16.emm.s

# Set 17: Guasave, 2014 - 2015.
group17 <- maize %>%
  filter(a_group == "set 17") %>%
  mutate(final.treat = paste(til_bed, f_resid, sep = "_"),
        treat = factor(treat),
        year = factor(year),
        final.treat = factor(final.treat))

g17m <- lme(yield ~ treat + year, random = ~ 1 | block/plot, data = group17, na.action =
na.exclude)
plot(g17m)
anova(g17m)

g17.emm.s <- emmeans(g17m, c("treat","year"))
g17.emm.s
g17.contrast <- contrast(g17.emm.s,
                    list(avg.CPnarrow17.14 = c(1, 0, 0, 0, rep(0, 4)),
                         avg.CCnarrow17.14 = c(0, 1, 0, 0, rep(0, 4)),
                         avg.CPAwide17.14 = c(0, 0, 1, 0, rep(0, 4)),
                         avg.CCAwide17.14 = c(0, 0, 0, 1, rep(0, 4)),
                         avg.CPnarrow17.15 = c(rep(0, 4), 1, 0, 0, 0),
                         avg.CCnarrow17.15 = c(rep(0, 4), 0, 1, 0, 0),
                         avg.CPAwide17.15 = c(rep(0, 4), 0, 0, 1, 0),
                         avg.CCAwide17.15 = c(rep(0, 4), 0, 0, 0, 1)))
confint(g17.contrast)

# Set 18: Guasave, 2017 - 2018.
group18 <- maize %>%
  filter(a_group == "set 18") %>%
  mutate(final.treat = paste(til_bed, f_resid, sep = "_"),
```

```
        treat = factor(treat),
        year = factor(year),
        final.treat = factor(final.treat))

g18m <- lme(yield ~ treat + year, random = ~ 1 | block/plot, data = group18, na.action =
na.exclude)
plot(g18m)
anova(g18m)

g18.emm.s <- emmeans(g18m, c("treat","year"))
g18.emm.s
g18.contrast <- contrast(g18.emm.s,
                list(avg.CPAwide18.17 = c(1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
rep(0, 20)),
                  avg.CCAwide18.17 = c(0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
rep(0, 20)),
                  avg.CCnarrow18.17 = c(0, 0, 1/4, 1/4, 1/4, 1/4, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
0, 0, rep(0, 20)),
                  avg.CPnarrow18.17 = c(0, 0, 0, 0, 0, 0, 1/14, 1/14, 1/14, 1/14, 1/14, 1/14,
1/14, 1/14, 1/14, 1/14, 1/14, 1/14, 1/14, 1/14, rep(0, 20)),
                  avg.CPAwide18.18 = c(rep(0, 20), 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
0, 0, 0),
                  avg.CCAwide18.18 = c(rep(0, 20), 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
0, 0, 0),
                  avg.CCnarrow18.18 = c(rep(0, 20), 0, 0, 1/4, 1/4, 1/4, 1/4, 0, 0, 0, 0, 0, 0, 0,
0, 0, 0, 0, 0, 0, 0),
                  avg.CPnarrow18.18 = c(rep(0, 20), 0, 0, 0, 0, 0, 0, 1/14, 1/14, 1/14, 1/14,
1/14, 1/14, 1/14, 1/14, 1/14, 1/14, 1/14, 1/14, 1/14, 1/14)))

confint(g18.contrast)

# Set 19: San Juan del Rio III, 2017.
group19 <- maize %>%
  filter(a_group == "set 19") %>%
  mutate(final.treat = paste(til_bed, f_resid, sep = "_"),
        treat = factor(treat),
        year = factor(year),
        final.treat = factor(final.treat))

g19m <- lmer(yield ~ final.treat + treat + (1 | block), data = group19, na.action = na.exclude)
g19.emm.s <- emmeans(g19m, c("final.treat"))
g19.emm.s

# Set 20: Ahome, 2014.
group20 <- maize %>%
  filter(a_group == "set 20") %>%
  mutate(final.treat = paste(til_bed, f_resid, sep = "_"),
```

```
       treat = factor(treat),
       year = factor(year),
       final.treat = factor(final.treat))

g20m <- lmer(yield ~ final.treat + treat + (1 | block), data = group20, na.action = na.exclude)
g20.emm.s <- emmeans(g20m, c("final.treat"))
g20.emm.s

# Set 21: Ahome, 2015.
group21 <- maize %>%
  filter(a_group == "set 21") %>%
  mutate(final.treat = paste(til_bed, f_resid, sep = "_"),
       treat = factor(treat),
       year = factor(year),
       final.treat = factor(final.treat))

g21m <- lmer(yield ~ final.treat + treat + (1 | block), data = group21, na.action = na.exclude)
g21.emm.s <- emmeans(g21m, c("final.treat"))
g21.emm.s

# Set 22: Ahome, 2017.
group22 <- maize %>%
  filter(a_group == "set 22") %>%
  mutate(final.treat = paste(til_bed, f_resid, sep = "_"),
       treat = factor(treat),
       year = factor(year),
       final.treat = factor(final.treat))

g22m <- lmer(yield ~ final.treat + treat + (1 | block), data = group22, na.action = na.exclude)
g22.emm.s <- emmeans(g22m, c("final.treat"))
g22.emm.s

# Set 23: Ahome, 2018.
group23 <- maize %>%
  filter(a_group == "set 23") %>%
  mutate(final.treat = paste(til_bed, f_resid, sep = "_"),
       treat = factor(treat),
       year = factor(year),
       final.treat = factor(final.treat))

g23m <- lmer(yield ~ final.treat + treat + (1 | block), data = group23, na.action = na.exclude)
g23.emm.s <- emmeans(g23m, c("final.treat"))
g23.emm.s

#================== Final analyses =============

# Load data set
```

```
d <- read.csv("maize.csv")

# Create lookup tables for factors
site2irrg <- c(rep("rainf", 6), rep("irrig", 4))
names(site2irrg) <- c("Apaseo el alto",
                      "San Juan Cotzocon",
                      "Indaparapeo",
                      "San Martin de Hidalgo",
                      "Cadereyta", "Hopelchen",
                      "Guasave",
                      "Irapuato I",
                      "San Juan del Rio III",
                      "Ahome")

abrev2till <- c("zero", "conv", "cons", "cons", "conv", "conv")
names(abrev2till) <- c("CL", "LC", "CP", "CPA", "CC", "CCA")

# Make a data frame with all the relevant variables.
maize <- d %>%
  filter(crop == "maize") %>%
  mutate(rep = factor(rep),
         year = factor(year),
         treat = factor(treat.n),
         env = factor(paste(site, year, sep = "_")),
         block = factor(paste(site, rep, sep = "_")),
         plot = factor(paste(block, treat, sep = "_")),
         irrigation = factor(unname(site2irrg[as.character(site)]),
                             levels = c("rainf", "irrig")),
         tillage = factor(unname(abrev2till[as.character(code)]),
                          levels = c("zero", "min", "cons", "conv")),
         f_resid = factor(ifelse(residue > 0, "+resid", "-resid"),
                          levels = c("-resid", "+resid")),
         beds = factor(as.character(beds), levels = c("none", "wide", "narrow")),
         til_bed = factor(paste(tillage, beds, sep = "_"))) %>%
  filter(tillage != "min") %>%
  mutate(til_bed = factor(til_bed))

# Select explanatory variables from dataset
maize2 <- maize %>% distinct(site, year, code, beds, residue, irrigation, tillage, f_resid,
estimate_yield, SE)

# Combine variables
maize2 <- maize2 %>%
  mutate(til_bed = factor(paste(tillage, beds, sep = "_")),
         site_year = factor(paste(site, year, sep = "_")),
         flat_trt = paste(irrigation, til_bed, f_resid, sep = "_"))
```

```
with(maize2, table(tillage, beds, f_resid))

# Establish model
mxx <- lme(log(estimate_yield) ~ flat_trt,
        random = ~ 1 | site_year, weights = ~ I(1/SE^2), data = maize2)

# Use residual plot to check the assumptions of an OLS linear regression model
plot(residuals(mxx, type = "n") ~ fitted(mxx))

# Results
emm_mxx <- emmeans(mxx, "flat_trt", type = "response")
as.data.frame(emm_mxx)

# Results analysis by using coefficient method
# Irrigation type main effect.
irrig_vs_rainf <- contrast(emm_mxx,
                    list(c(1/4, 1/4, 1/4, 0, 1/4, 0, -1/4, 0, -1/4, 0, -1/4, 0, 0, 0, -1/4, 0, 0)))
irrig_vs_rainf

mean.irrig <- contrast(emm_mxx, list(c(1/4, 1/4, 1/4, 0, 1/4, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0)))
mean.irrig
mean.rainf <- contrast(emm_mxx, list(c(0, 0, 0, 0, 0, 0, 1/4, 0, 1/4, 0, 1/4, 0, 0, 0, 1/4, 0, 0)))
mean.rainf

exp(9.61)
exp(8.99)

# Crop residue main effect
# Situation 1: Irrigation + conventional tillage
residue_vs_noresidue_1 <- contrast(emm_mxx,
                    list(c(0, 0, 1/2, -1/2, 1/2, -1/2, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0)))
residue_vs_noresidue_1

mean.residue <- contrast(emm_mxx, list(c(0, 0, 1/2, 0, 1/2, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0)))
mean.residue

mean.noresidue <- contrast(emm_mxx, list(c(0, 0, 0, 1/2, 0, 1/2, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0)))
mean.noresidue

exp(9.58)
exp(9.61)

## Situation 2: Rainfed + conservation tillage
residue_vs_noresidue_2 <- contrast(emm_mxx,
                    list(c(0, 0, 0, 0, 0, 0, 1/2, -1/2, 1/2, -1/2, 0, 0, 0, 0, 0, 0, 0)))
residue_vs_noresidue_2
```

```
mean.residue <- contrast(emm_mxx, list(c(0, 0, 0, 0, 0, 0, 1/2, 0, 1/2, 0, 0, 0, 0, 0, 0, 0, 0)))
mean.residue

mean.noresidue <- contrast(emm_mxx, list(c(0, 0, 0, 0, 0, 0, 0, 1/2, 0, 1/2, 0, 0, 0, 0, 0, 0, 0)))
mean.noresidue

exp(8.87)
exp(8.66)

# Bed width main effect (+reside)
narrow_vs_wide <- contrast(emm_mxx,
                     list(c(1/4, -1/4, 1/4, 0, -1/4, 0, 1/4, 0, -1/4, 0, 1/4, 0, 0, 0, -1/4, 0, 0)))
narrow_vs_wide

mean.narrow <- contrast(emm_mxx, list(c(1/4, 0, 1/4, 0, 0, 0, 1/4, 0, 0, 0, 1/4, 0, 0, 0, 0, 0,
0)))
mean.narrow
mean.wide <- contrast(emm_mxx, list(c(0, 1/4, 0, 0, 1/4, 0, 0, 0, 1/4, 0, 0, 0, 0, 0, 1/4, 0, 0)))
mean.wide

exp(9.36)
exp(9.23)

# PRB's effect in different farming conditions.
# Situation 1: Permanent raised beds (prb) VS Non-permenent raised beds (nprb) in irrigated
trials/+residue.
prb1_vs_nprb1 <- contrast(emm_mxx,
                    list(c(1/2, 1/2, -1/2, 0, -1/2, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0)))

prb1_vs_nprb1

mean.prb <- contrast(emm_mxx, list(c(1/2, 1/2, 0, 0, 0, 0, 0, 0, 0, 0, 0,0,0,0,0,0,0)))
mean.prb
mean.noprb <- contrast(emm_mxx, list(c(0, 0, 1/2, 0, 1/2, 0, 0, 0, 0, 0, 0,0,0,0,0,0,0)))
mean.noprb

exp(9.63)
exp(9.58)

# Situation 2: Permanent raised beds VS Non-permenent raised beds in rainfed
trials/+residue.
prb2_vs_nprb2 <- contrast(emm_mxx,
                    list(c(0, 0, 0, 0, 0, 0, 1/2, 0, 1/2, 0, -1/2, 0, 0, 0, -1/2, 0, 0)))
prb2_vs_nprb2

mean.prb <- contrast(emm_mxx, list(c(0, 0, 0, 0, 0, 0, 1/2, 0, 1/2, 0, 0, 0, 0, 0, 0, 0, 0)))
mean.prb
```

```
mean.noprb <- contrast(emm_mxx, list(c(0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1/2, 0, 0, 0, 1/2, 0, 0)))
mean.noprb

exp(8.87)
exp(9.11)

# Situation 3: Permanent raised beds VS Non-permenent raised beds in rainfed trials/-
residue.
prb3_vs_nprb3 <- contrast(emm_mxx,
                list(c(0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, -1, 0, 0, 0, 0, 0)))

prb3_vs_nprb3

mean.prb <- contrast(emm_mxx, list(c(0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0)))
mean.prb
mean.noprb <- contrast(emm_mxx, list(c(0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0)))
mean.noprb

exp(8.65)
exp(7.32)
# test: rainf_cons_narrow_-resid VS rainf_conv_none_-resid
prb4_vs_nprb4 <- contrast(emm_mxx,
                list(c(0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, -1, 0, 0, 0)))
prb4_vs_nprb4
# test: rainf_cons_narrow_-resid VS rainf_zero_none_-resid
prb5_vs_nprb5 <- contrast(emm_mxx,
                list(c(0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, -1)))
prb5_vs_nprb5
# test: rainf_cons_narrow_-resid VS rainf_cons_wide_-resid
prb6_vs_prb6 <- contrast(emm_mxx,
                list(c(0, 0, 0, 0, 0, 0, 0, 1, 0, -1, 0, 0, 0, 0, 0, 0, 0)))
prb6_vs_prb6


# Interaction between irrigation/bed width for cons tillage/+ residue.
irrig_vs_rainf <- contrast(emm_mxx,
                 list(c(1/2, 1/2, 0, 0, 0, 0, -1/2, 0, -1/2, 0, 0, 0, 0, 0, 0, 0, 0)))
irrig_vs_rainf

mean.irrig <- contrast(emm_mxx, list(c(1/2, 1/2, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0)))
mean.irrig
mean.rainf <- contrast(emm_mxx, list(c(0, 0, 0, 0, 0, 0, 1/2, 0, 1/2, 0, 0, 0, 0, 0, 0, 0, 0)))
mean.rainf

narrow_vs_wide <- contrast(emm_mxx,
                 list(c(0, 0, 0, 0, 0, 0, 1/2, 0, -1/2, 0, 0, 0, 0, 0, 0, 0, 0)))
narrow_vs_wide
```

```
exp(9.63)
exp(8.87)
log(929)
log(660)

# Interaction between beds width/residue for rainfed and cons.
narrow_vs_wide <- contrast(emm_mxx,
                    list(c(0, 0, 0, 0, 0, 0, 1/2, -1/2, 1/2, -1/2, 0, 0, 0, 0, 0, 0, 0)))
narrow_vs_wide

mean.narrow <- contrast(emm_mxx, list(c(0, 0, 0, 0, 0, 0, 1/2, 1/2, 0, 0, 0, 0, 0, 0, 0, 0, 0)))
mean.narrow

mean.wide <- contrast(emm_mxx, list(c(0, 0, 0, 0, 0, 0, 0, 0, 1/2, 1/2, 0, 0, 0, 0, 0, 0, 0)))
mean.wide

exp(8.85)
exp(8.67)

# Interaction between beds width/residue for rainfed and conv (non-PRB).
narrow_vs_none <- contrast(emm_mxx,
                    list(c(0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1/2, 1/2, -1/2, -1/2, 0, 0, 0)))
narrow_vs_none

mean.narrow <- contrast(emm_mxx, list(c(0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1/2, 1/2, 0, 0, 0, 0, 0)))
mean.narrow

na.residue_vs_na.noresidue <- contrast(emm_mxx,
                              list(c(0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1/2, -1/2, 0, 0, 0, 0, 0)))
na.residue_vs_na.noresidue
log(1877)
log(403)

mean.none <- contrast(emm_mxx, list(c(0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1/2, 1/2, 0, 0, 0)))
mean.none

n.residue_vs_n.noresidue <- contrast(emm_mxx,
                            list(c(0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1/2, -1/2, 0, 0, 0)))
n.residue_vs_n.noresidue

exp(8.22)
exp(8.91)

# Treatment & response figure
result_df <- as.data.frame(emm_mxx2) %>%
```

```
  separate(flat_trt, into = c("irrig", "til", "bed", "resid"), sep = "_") %>% mutate(bed =
dplyr::recode(bed, none = "1. none", narrow = "2. narrow", wide = "3. wide"))

ggplot(data = result_df, aes(y = response, x = bed, group = til, color = til)) +
  geom_point() +
  facet_wrap(~ irrig + resid)+
  geom_errorbar(aes(ymin=response-SE, ymax=response+SE), width=.1)

ggplot(data = result_df, aes(y = response, x = til, group = bed, color = bed)) +
  geom_point() +
  facet_wrap(~ irrig + resid)+
  geom_errorbar(aes(ymin=response-SE, ymax=response+SE), width=.1)+
  theme(text = element_text(size = 20))

# Citation
citation()
citation("lme4")
```