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Mulching on family maize farms in the tropics: A systematic review

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A R T I C L E I N F O

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A B S T R A C T

Family farms, predominantly reliant on family labour, produce approximately three-quarters of the World's food. Maize (*Zea mays)* is the world's most produced cereal. Yet in much of the tropics, actual maize yields are far below those attainable with best-bet practices. While any advantage of adding mulch might depend on soil fertility level, mulch quality, amount of rainfall, irrigation, and other factors, no ranking of their importance has been found. Our objectives were to disentangle these influences to assess how mulch affects yields on different fertility soils under different precipitation regimes. We conducted a systematic review in Web of Science, obtaining 50 papers on experiments from the tropics. Fewer trials have been conducted in Asia and Pacific (n = 10) than in Africa (n = 20) or Latin America and the Caribbean (n = 20). Twenty mulches had been tested of which *Leucaena leucocephala* had been used in 25% of trials. Mulch was more commonly applied after (n = 15) than before (n = 18) sowing or at sowing (n = 14); three trials did not mention application timing. Mulch increased grain yield and biomass. The positive effect of mulch was greater when combined with mineral fertilizer, implying a synergistic rather than a substitutional effect and demonstrating its applicability, even for farmers able to afford inputs. Mulch increased both maize grain yield and total biomass so is recommended as a sustainable practice in general, but particularly on low fertility soils in lower rainfall areas. Future work should model mass loss and nutrient release of different mulch types under different agroecological conditions.

1. Introduction

Family farming is frequently referred to in both the popular press and the academic literature as "the backbone" of countries, of economies and of regions. Yet a globally accepted definition of family farming is lacking (Graeub et al., 2016). Nevertheless, Lowder et al. (2016) roughly estimated that >500 million of the 570 million farms worldwide are family farms held by a single individual or household. These produce approximately three-quarters of the World's food (Food and Agriculture Organization of the United Nations, 2014). Estimates on the percentage of the World's agricultural land managed by family farms vary from 50% (Graeub et al., 2016) to 75% (Lowder et al., 2016). Family farms that are smaller than two hectares operate about 12% of farmland globally with smaller farms overly represented in poorer countries (Lowder et al., 2016).

Maize, *Zea mays* (L.) is currently the world's number one cereal crop with an estimated 1162 million tonnes produced in 2020 (FAO, 2020) on 216 million farms worldwide. The greatest increases in production in the last ten years have been attained in the Americas (FAO, 2020). Maize can be grown in both temperate and tropical regions and scores highest when compared with other "green revolution cereals"(rice and wheat) for both nutritional value and water efficiency. Particularly in the tropics, yields are reduced by a plethora of factors. These include biotic factors, particularly losses to weeds (Page et al., 2012), insect pests, including, most recently, the fall armyworm (Overton et al., 2021), pathogens (Savary et al., 2019) and also vertebrates, such as rodents (e.g. Swanepoel et al., 2017 for Africa) and birds (Norgrove, 2021). Abiotic constraints include low soil fertility and water stress, coupled with lack of inputs. These combined stresses can lead to a vicious downward spiral, with land can degraded through the cropping cycle by biomass burning and soil erosion (das Aguiar et al., 2009; Read et al., 2016). Despite supply-side risks, demand for maize is projected to increase by 30% by 2050 due to the increasing world population (Food and Agriculture Organization of the United Nations, 2016). The number of maize farms is estimated to increase by 5% (from 216 to 227 million) by 2030 (Erenstein et al., 2021). Actual on-farm yields are often far below those attainable (Neumann et al., 2010; Affholder et al., 2013; Folberth et al., 2013; Food and Agriculture Organization of the United Nations, 2016), with yield gaps frequently exceeding 5 t per hectare in vast tracts of the world (Neumann et al., 2010), particularly those poorer regions where

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the majority are small family farms (Lowder et al., 2016).

Overarching these factors is the spectre of climate change. By climate change, we follow the definition of the National Oceanic and Atmospheric Administration's (NOAA): "*a long-term gradual change in average weather conditions whereas climatic variability is a yearly fluctuation in weather around a long-term average value*". Estimated maize yield loss was, on average, ~4% between 1981 and 2010 due to global warming alone, even when taking carbon dioxide fertilisation effects into account (Iizumi et al., 2018). The IPCC (2007) synthesised studies on the effects of higher temperatures on maize, demonstrating that any mean temperature increase in tropical areas will lead to yield declines (Nicholls et al., 2008). Recent studies have predicted an 8% reduction in global maize production by 2030 and a 23% reduction by 2050 (Haile et al., 2017). More pessimistically, an increase of 4 °C in West Africa is likely to cause yield reductions of 37% and severe crop failures which previously only occurred approximately once every 20 years are expected to happen every 2.5 years (Parkes et al., 2018). The latest IPCC report has synthesised data on the effects of climate change on maize yield. It is projected, with a medium degree of certainty, that maize yields will decline in N Africa, sub-Saharan Africa, Southern Europe, Eastern Europe, Australasia, Latin American and the Caribbean (Bezner Kerr et al., 2022). North America was the only region where yields were projected to increase (Bezner Kerr et al., 2022). Furthermore, such estimates do not account for the effects of climate change on other system components such as pests and disease pressure (Nicholls et al., 2008) and other biotic pressures. For example, Landau et al. (2021) calculated that yield losses to weed competition are exacerbated by adverse weather.

How to increase yields without resorting to quick-fix methods that would ultimately degrade the future resource base? Lipper et al. (2020) highlighted how short-term measures to increase productivity can conflict with longer-term agroecosystem sustainability goals. By agroecosystem sustainability, we return to the concept of Schaller (1993) who emphasised, amongst other points, that systems should maintain or improves soil properties and that inputs from renewable rather than non-renewable resources should be prioritized. Mulching, an age-old technique used on family farms throughout the tropics (Thurston, 1997) potentially fulfils these criteria. Mulching is "*a technology whereby at least 30% of the soil surface is covered by organic material*" (Erenstein, 2003). Mulching can provide ecological benefits such as protecting the soil surface, reducing evaporation, increasing soil faunal abundance, microbial activity and reducing soil erosion. In areas where inorganic fertilizer is scarce or inaccessible due to price, certain mulches might be a more appropriate source of nitrogen and phosphorus, the yield limiting factors in many parts of the tropics (Folberth et al., 2013).

Many field trials have been conducted in the tropics on the impact of mulch on annual crops, mostly confirming these benefits (Erenstein, 2003). Mulching can increase grain yields yet its impact depends on many factors: length of trial and mulch application (das Aguiar et al., 2009), soil fertility level (Anda and Kurnia, 2010), amount of rainfall (Baijukya et al., 2005), application of mineral fertilizer (Kodzwa et al., 2020; Saidou et al., 2003), mulch amount (de Moura et al., 2008a), tillage (de Moura et al., 2008a; Lal, 1995; Murphy et al., 2016), frequency of mulch application (Isaac et al., 2004) and others. No systematic assessment has been found on how important each of these factors is and how they interact. Yet this is an essential step in the design of interventions to reduce the maize yield gap which can then be disseminated by extension services. We aimed to disentangle how mulch addition affects maize yields on soils of different fertility under various rainfall regimes and identify best-bet scenarios. To achieve this, we conducted a systematic literature review of the effects of mulching on maize yield in the tropics.

2. Material and methods

2.1. Literature search, inclusion and exclusion criteria

We searched for the following search string in Web of Science (v 5.35) in March 2020: TS = (mulch OR "green manure" OR "cover crop*" OR covercrop* OR "ground cover" OR groundcover or "legume* cover" OR "plant residue*" OR "crop residue" OR "soil cover" OR "soil conservation" OR "climate smart" OR climate-smart) AND TS = (experiment* OR study OR studies OR trial* OR research* OR plot*) AND TS = (tropic* OR "tropical countr*" or "tropical zone*" OR "tropical climate*" OR "tropical soil*") AND TS = (maize) NOT TI = (review*). We had 345 hits, of which 150 were trials on mulching in maize in the tropics. A "backward snowball" (sensu Wohlin, 2014) was also done by checking the reference sources of the captured papers, resulting in 30 additional publications. Papers were evaluated using the "Preferred Reporting Items for Systematic Reviews and Meta-Analyses" (PRISMA) method (Moher et al., 2009) and scanned by assessing the title and abstract using the following inclusion criteria:

1. Study carried out in the geographic tropics (23.5°N-23.5°S)
2. Maize being the test crop and is either grown as a monocrop or in an alley cropping systems with no other food crop
3. Included at least one mulch species
4. Mulch biomass was applied on the soil surface shortly before or during the maize growth period
5. Study had a non-mulch control treatment

Fifty papers fulfilled requirements. From these, data were extracted for individual mulch treatments so 177 pairs of mulch and non-mulched control treatments with otherwise identical treatments were included. For example, in one trial the treatment 'tillage + mulch' was compared to 'tillage only' and the treatment 'no-till + mulch' was compared to 'no-till only'.

Table 1
Soil fertility categorization of papers in the systematic literature review.

Soil fertility level	Soil orders (USDA classification)	#	Sources
1	Oxisol, Spodosol	5	Agus et al., 1999, Agus et al., 1998; Baijukya et al., 2005; Maclean et al., 1992; Saidou et al., 2003
2	Ultisol, Inceptisol	21	das Aguiar et al., 2009, 2010; Anikwe et al., 2003; Baijukya et al., 2005; de Moura et al., 2017, de Moura et al., 2016, de Moura et al., 2014, de Moura et al., 2010, de Moura et al., 2009, de Moura et al., 2008b, de Moura et al., 2008a; de Moura-Silva et al., 2016; Hauser and Nolte, 2002; Isaac et al., 2004; Murphy et al., 2016; Norgrove et al., 2003; Oelbermann et al., 2006; Okeyo et al., 2014; Quinland, 1984; Sangakkara et al., 2008; Schroth and Lehmann, 1995
3	Alfisol, Andisol, Mollisol, Entisol	23	Are et al., 2011; Badejo et al., 1995; Barrios et al., 1996; Cogle et al., 1997; Fischer et al., 2002; Gill et al., 1996; Govaerts et al., 2007, Govaerts et al., 2006; Kamara et al., 2000; Kaur and Arora, 2019; Kinama et al., 2007, Kinama et al., 2005; Lal, 1997a, 1997b, Lal, 1995, Lal, 1974; Leblanc and McGraw, 2006; Mulongoy and van der Meersch, 1988; Onduru et al., 2008; Ortiz-Ceballos and Fragoso, 2004; Tian et al., 1993; Verhulst et al., 2011; Xu et al., 1993
–		2	Bhattacharyya et al., 2018; Das et al., 2018

Note: 1: rather low; 2: medium; 3: rather high; –: no information given ($n = 51$, as one paper included multiple sites).

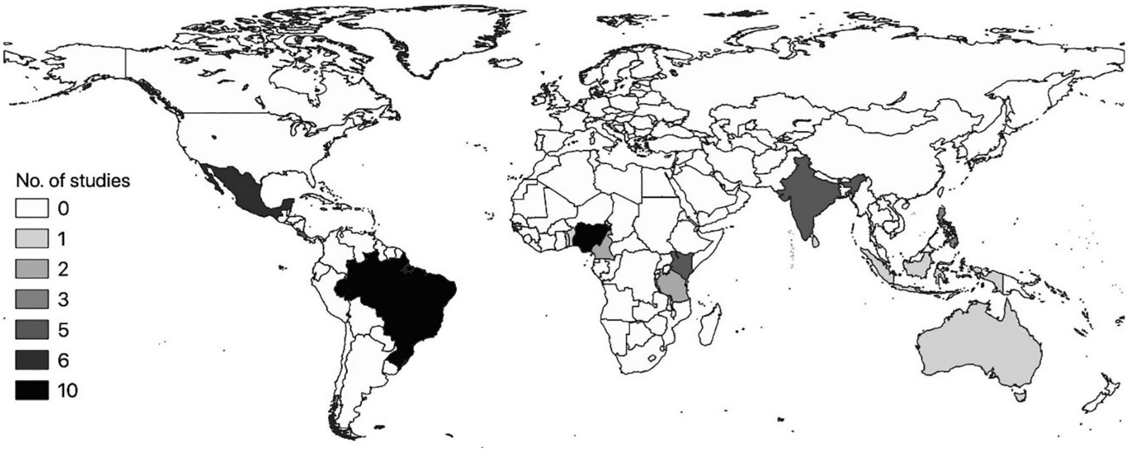

Fig. 1. Geographical scope of papers reporting the testing of mulch application in the tropics ($n = 50$).

2.2. Data processing

Statistical analyses were conducted in R (v. 3.6.1) and R Studio (v. 1.2.5019) using maize grain yield ($n = 148$) and total maize biomass ($n = 70$) as response variables. Ratios of grain or biomass values to the control values were calculated for each of these 177 pairs (Hedges et al., 1999). Ratios were used so that we could focus on treatment differences rather than on site-to-site effects. These were then divided by 10 so as to range from 0 to 1 and then were arc-sine square root transformed to fulfil normality and homoskedasticity assumptions (Liermann et al., 2004). The degree of overdispersion used was 0.1. Variables having at least 70 occurrences were selected and multiple linear regressions were performed (Smith and Glass, 1977). These were the following categorical variables: Köppen-Geiger climate classification, compiled through the temperature, the amount of rainfall per year, and precipitation mode (Kottek et al., 2006; Af, Am, Aw, Bsh, Cwb); precipitation category (defined as low <800 mm/year, medium 800–1500, high >1500); precipitation seasonality (unimodal, bimodal); trial length (long-term so > two years, short-term so < two years); soil fertility level (1 = low, 2 = medium, 3 = high; see Table 1 for definitions); fertilizer addition to all treatments (yes/no); mulch type (fresh plant material, straw, litter); time of mulch application (before, at, after sowing); and, soil preparation (till, no-till). The following continuous variables were also included: amount of precipitation; elevation of the trial site; length of the maize growing season; plant density; amount (Mg ha^{-1}) of mulch applied, the amount of total nitrogen (kg ha^{-1}) added by the mulch (N_{eq}), and the total nitrogen concentration (% N) of the mulch. Some continuous variables were calculated, for example the average of the N content of the mulch when two mulching species were included in the trial. Further information can be found in the supplementary material. The response variables assessed were: maize dry grain yield ratio (yield of the mulch treatment divided by the yield of the respective control treatment) and total maize dry biomass ratio (biomass of the mulch treatment divided by the biomass of the respective control treatment. Sixteen explanatory variables were included in the models used to estimate maize grain yield and total biomass.

Correlations between explanatory variables were common (Annex 1) and those >±0.7 were assessed and some were removed from the model. The Köppen classification and rainfall categories were removed, due to high correlations with the amount of rainfall. The amount of mulch applied and the nitrogen equivalents (N_{eq}) applied by the mulch were removed from the model as they correlated highly with the total amount of nitrogen applied (mulch and fertilizer). The variable ‘mulch type’ was removed as it correlated strongly with the N_{eq} concentration of the mulch. The length of the trial, the rainfall pattern and the elevation were lastly removed due to correlation to the variables ‘rainfall amount’ and ‘mulch N concentration’. The statistical model to estimate both variables, maize grain yield and total maize biomass, is shown below:

$$\begin{aligned}\text{Variable} \sim\, & soil\_fertility + fertilizer\_addition + soil\_preparation + rainfall\_amount \\ & + length\,growing\_season + maize\_density + mulch\,N\_concentration \\ & + total\,N\_added\end{aligned}$$

2.2.1. Development of the maize grain yield model

The maize grain yield ratio for each treatment was transformed and inserted as the following variable into the statistical model mentioned above: asin(*sqrt*(0.1 * *grain_yield*).

Data were transformed and 66 data points were retained in the model, yet the assumption problems of residual normality and homoskedasticity were not solved. The normality and homoskedasticity tests were rejected. It was decided to continue with this model and not to further transform the data. The fertilizer addition, the amount of rainfall and the maize density were significant ($p < 0.05$), the soil preparation was barely not significant ($p = 0.064$) and the other variables were not significant. The model explained 42% of the variance (multiple R-squared = 0.42) and the residual standard error was 0.15. The model was simplified and two non-significant variables were removed: length of the growing season and total N added. The final model with 76 data points was:

$$\begin{aligned}\big(\text{asin}\big(sqrt\big(0.1{*}grain\_yield\big) \sim\, & soil\_fertility + fertilizer\_addition \\ & + soil\_preparation + rainfall\_amount \\ & + maize\_density + mulch\ N\_concentration\big).\end{aligned}$$

Table 2

Summary of the ratios between mulched and control treatments for maize grain yield and total maize biomass.

Ratio	n	Mean	Median	Minimum	Maximum	1st Quartile	3rd Quartile	SD
Maize grain yield	148	1.77	1.31	0.11	7.25	1.09	2.00	1.24
Total maize biomass	70	1.47	1.23	0.62	3.81	1.09	1.54	0.65

Note: SD: standard deviation; n: number of data pairs.

The model fit was slightly lower (multiple R-squared = 0.39), the residual standard error was the same, yet the Akaike's Information Criterion (AIC) was lower. Despite transformation, the residuals were not normally distributed and the homoskedasticity assumption was rejected. The data were not transformed further. Maintaining soil fertility, soil preparation and mulch N concentration in the model improved the fit despite not being significant at 0.05.

2.2.2. Development of the total maize biomass model

The total maize biomass ratio for each treatment was transformed and inserted as the following variable into the statistical model, as explained in 2.2.

The variable 'soil preparation' was removed from the biomass dataset as neither level of soil preparation (till, no-till) was represented in this biomass data set, this variable was removed from the model and tillage effect could not be assessed. This model showed a very high model fit with a multiple R^2 of 0.92 for the 22 data points and a root mean square error of 0.03. The variables maize density and mulch N concentration were removed because of singularities and the final model analyzed was:

$$\left(\operatorname{asin}\left(sqrt(0.1^{*}biomass\_DM\ \right) \sim soil\_fertility + rainfall\_amount + length\ growing\_season + mulch\ N\_concentration + total\ N\_added\ \right)$$

The model fit and root mean square error did not change. Further reduction in the model did not improve the model fit. The tests did not reject the assumptions, therefore the normal distribution and homoskedasticity were accepted for this model (see Annex 4 for the visual assumption check of the biomass model). The soil fertility level 2 was not represented in this model and its effect could not be assessed.

3. Results

3.1. Distribution and thematic scope of studies

Fifty studies were included in this analysis of which 20 were from Africa, 20 from Latin America and Caribbean and 10 from Asia and Pacific (Fig. 1). The Köppen-Geiger climate classification distribution (Kottek et al., 2006) was: Af (tropical rainforest) eight trials, Am (tropical monsoon) 21, Aw (tropical savanna) 12, Bsh (steppe) five and Cwb (dry-winter subtropical highland) four trials.

Following the USDA soil classification, five papers described studies on low fertility Oxisols or Spodisols and the rest were divided evenly between medium and high fertility sites (Table 1). These soil fertility levels were considered as factors in the data analysis. The soil preparation was mentioned in most trials (9 trials without indication), more of which were conducted under no-till ($n = 19$ papers) rather than under till conditions ($n = 13$). Nine trials included tillage as a factor and therefore both soil preparations were considered. Twenty trials were in alley cropping systems. In almost three-quarters of the trials, mulch was applied only once and three mulch applications was the maximum (done in three trials). Mulch was applied either before sowing ($n = 18$), at sowing ($n = 14$) or after sowing ($n = 15$); four trials included the time of application as a factor and the timing was different for each treatment; three trials did not give information on the time of application. Twenty-eight trials included mulch as a single factor, many included tillage or fertilizer (8 and five trials) as factor combinations and several had a three-factorial combination. The most tested mulch was the leguminous shrub *Leucaena leucocephala* (Lam.) de Wit (n = 13), maize residues were tested in 11 trials and in total, 20 different mulching species were used (f.ex. *Cajanus cajan*, *Gliricidia sepium*, *Acacia mangium*).

Eight papers did not contain data on maize yield parameters and rather focused on soil parameters. Ten papers focused only on maize growth and yield data; the rest of the papers considered data on maize growth, yield and soil parameters. The effect on weeds ($n = 6$), pest and diseases (n = 1) and economics (n = 6) were seldomly assessed. Other parameters considered only once were greenhouse gas emissions, rainfall use efficiency, nutrient budget, wheat equivalent yield, irrigation water, residue N and K use efficiency, root distribution and weight.

3.2. Comparisons between maize yield and biomass between mulched systems and controls

The final model for the maize grain yield ratio with 76 data points included the following independent parameters: soil fertility, fertilizer addition, soil preparation, amount of precipitation, maize density and the N concentration of the mulching material. The multiple R-squared of this model was 0.39.

On average, maize grain yield with mulching was 77% higher than without mulching under the same conditions ($n = 148$). Approximately 10% of the datapoints were deemed outliers and these influenced the mean (see Annex 2 for the distribution). The data range was high (maximum-minimum: 7.14) A better measure to consider would be the median: the median of the ratio of maize grain yield was 1.31 (. Table ***2***). The median grain yield of mulch treatments was 31% higher than the median grain yield of the control treatments.

The model was used to estimate the ratio of the maize grain yield with the following input parameters: soil fertility level 2, without additional fertilizer, with tillage, 1500 mm rain/year, a maize density of 50,000 plants/ha and mulching material with 2.5% N_{eq} concentration gave an estimate of the maize grain yield ratio of 2.29. The same for a treatment with fertilizer addition would give an estimated grain yield ratio of 2.71. When fertilizer was added to the mulch treatment, the effect of the mulch on the grain yield was higher than without fertilizer addition, considering that the other variables stay the same.

The fertilizer addition, the amount of precipitation, the maize density and the N_{eq} concentration of the mulch significantly influenced the maize grain yield ($p < 0.05$), but not the soil fertility level ($p = 0.09$) or the soil preparation ($p = 0.07$). The effect of the mulch on the maize grain yield depended on whether additional fertilizer was applied in the trial (higher effect with additional fertilizer), on the amount of precipitation (more precipitation = lower effect of the mulch), on the maize density (higher density = lower effect of the mulch) and on the nitrogen concentration of the mulch (the higher the nitrogen concentration, the lower the effect of the mulch).

As an illustration of the statistical model, the following equation shows the regression for the soil fertility level 2:

$$\mathit{Grain\_yield} \sim 2.68 + 2.88{*}10\hat{}(-5){*}\mathit{soil\_fertility} + 0.42{*}\mathit{fertilizer\_addition} - 0.23{*}\mathit{soil\_preparation}\ (\mathit{level} = \mathit{till}) - 2.44{*}10\hat{}(-7){*}\mathit{rainfall\_amount} - 4.89{*}10\hat{}(-11){*}\mathit{maize\_density} - 0.06{*}\mathit{mulch\ N\_concentration})$$

The final model of the total maize biomass ratio included different independent variables: soil fertility; amount of precipitation; length of the growing season; the N content of the mulch; and, the total N added.

The multiple r-squared of this model was 0.92. On average, total maize biomass when mulched was 47% higher than without mulching under the same conditions in the 54 papers assessed. 70 data points were analyzed for the total maize biomass ratio and they showed an average ratio of 1.47 with a standard deviation of 0.65 (.

Table *2*) and only few outliers (see Annex 3 for further information on data distribution).

The soil fertility levels, the amount of rainfall and the length of the maize growing season significantly influenced the total maize biomass ratio ($p < 0.05$); the nitrogen concentration of the mulch and the total nitrogen addition did not show significant effects on total biomass ratio. As an illustration of the statistical model, the following equation shows the regression for the soil fertility level 3 (high soil fertility):

$$\text{Biomass\_DM} \sim 9.13 - 7.02{*}\mathit{soil\_fertility}\ (\mathit{level} = 3) - 7.9{*}10\hat{}(-6)\ \mathit{rainfall\_amount} + 3.0{*}10\hat{}(-4)\ \mathit{lengthgrowing\_season} + 4.9{*}10\hat{}(-4)\ \mathit{mulch\ N\ concentration} - 6.8{*}10\hat{}(-8)\ \mathit{total\ N\_added})$$

The model was used to estimate the ratio of the total maize biomass with the following input parameters: low soil fertility soil (level = 1), with 1′500 mm rain per year, with a maize growing season of 95 days, a nitrogen concentration of the mulch of 2.5% and a total addition of 100 kg N_{eq}/ha resulted in an estimated total maize biomass ratio of 9.17. The same for a high soil fertility (level = 3) would give an estimate of 2.14; this would mean that the total maize biomass on this soil is 214% higher for mulched treatments than for the control, non-mulch treatment. The difference between the two soil fertility levels (1 and 3) was significant. The effect of the mulch on the total maize biomass depends on the soil fertility (high fertility = lower mulch effect), on the amount of rainfall (more rainfall = lower effect) and the length of the maize growing season (longer season = higher mulch effect).

4. Discussion

Mulching generally improved maize yields, so family farmers can use this technology, reducing the yield gap and thus satisfying part of the projected increase in demand. Implementing mulching may also lead to ecological benefits by maintaining lower topsoil temperatures, promoting faster decomposition, lowering soil bulk density, and increasing soil organic carbon concentrations (Norgrove and Hauser, 2015). A greater positive impact of mulch was realized at lower maize densities. A likely explanation is the known positive effect mulching reducing weed competition and this would be more evident at lower maize densities as the weed pressure in low density stands can be higher.

Inorganic fertilizer addition, in tandem, significantly increased the mulch effect on the maize grain yield thus these factors interacted synergistically rather than substituting for each other. This may be because many mulches have a high C:N ratio and may risk immobilizing nutrients (das Aguiar et al., 2010). Combining with fertilizer would counteract this effect while being superior to fertilizer alone due to the physical protection of soil. Lal (1995) even found that the effect of mulch was only significant if applied with mineral fertilizer. MacLaren et al. (2022) found only substitutional effects between mulch and fertilizer when assessing results of thirty experiments. They found that mulch effects were only significant at low or no fertilizer application and not at high fertilizer application rates, although these experiments included six different crops and data from Europe and Africa were pooled. Tilander and Bonzi (1997) found that sorghum yield in Burkina Faso was increased more by the mulch application in the unfertilized treatments than in the fertilized treatments, in line with the review of MacLaren et al. (2022). Norgrove and Hauser (2014), reviewing plantain research in West Africa, found that mulching increased yield whether additionally fertilized or not.

In the grain yield model, the N concentration of the mulch significantly influenced the yield ratio; increasing N concentrations decreased the grain yield ratio. This is a paradox given that low C:N ratios can decrease grain yield (Saidou et al., 2003). However, mulch with high nitrogen concentration decomposes faster and releases nitrogen faster (Isaac et al., 2000). So N release from high N rich mulches might not synchronize so well with crop demand. In areas where the soil-water conserving and protective attributes of mulch are crucial, fast decomposition would leave the soil more exposed. Finding an equilibrium between nutrient immobilization and nutrient release is crucial when choosing a mulching material for a particular environment. Further primary research on this point doing multilocational trials to determine the threshold edaphic and climatic conditions which determine the effect of mulch N concentration on yield is be needed.

Mulch had a greater effect on lower fertility soils than on higher fertility soils, ceteris paribus. This highlights its potential usefulness for smallholder farmers who are often marginalized to low fertility land. Additionally, the amount of rainfall and the length of the growing season significantly influenced the biomass ratio: the higher the rainfall, the lower the biomass ratio and the longer the growing season, the higher the biomass ratio. The amount of rainfall significantly influenced both the maize grain yield and biomass ratios: the higher the rainfall, the lower the ratios so mulch is more important in lower rainfall zones. In the semi-arid and drought-prone regions, the water-conserving role of mulch is paramount (Baijukya et al., 2005; Cogle et al., 1997; Rao et al., 1991; Uwizeyimana et al., 2018). In a trial in Tanzania, Baijukya et al. (2005) found that mulch applied on two soils with differing soil fertility levels did not result in significantly different total maize biomass or grain yield.

On medium fertility soils, the mulch treatment performed as well as the corresponding nitrogen treatment (equal amount of N_{eq} as the mulch treatment), whereas on low fertility soils, nitrogen addition gave significantly higher yields than the mulch treatment. Rainfall might have confounded this result as the low fertility soil was in a high rainfall zone and the high fertility soil in a low rainfall zone (Baijukya et al., 2005). In the high rainfall zone, the water-conserving effect of the mulch might not have been important and the nutrient addition of the mulch did not have enough influence on the maize biomass and yield. In the low rainfall zone with the medium fertility soil, the water-conserving effect of the mulch seemed to be important, possibly because enough nutrients were present in the soil and an addition with mineral N fertilizer was not needed. This was supported by the biomass model, in which the nutrient addition of the mulch did not significantly influence the biomass ratio, but the rainfall amount and soil fertility level did.

5. Conclusion

Mulch increased both maize grain yield and total maize biomass and should be recommended as a sustainable practice in general, but particularly on low fertility soils and in lower rainfall areas. The "mulching effect" on maize grain yield was accentuated when combined with fertilizer addition, so mulch can be recommended even to farmers who can afford fertilizer so they can also benefit from such synergies. The effect of mulching on grain yield was particularly beneficial in cases where the plant density was low. The major research gap found was that few publications reported the C:N ratio of the mulching material hence it could not be included in the analysis. Future work should model the mass loss of nutrient release of different mulch types under different agroecological conditions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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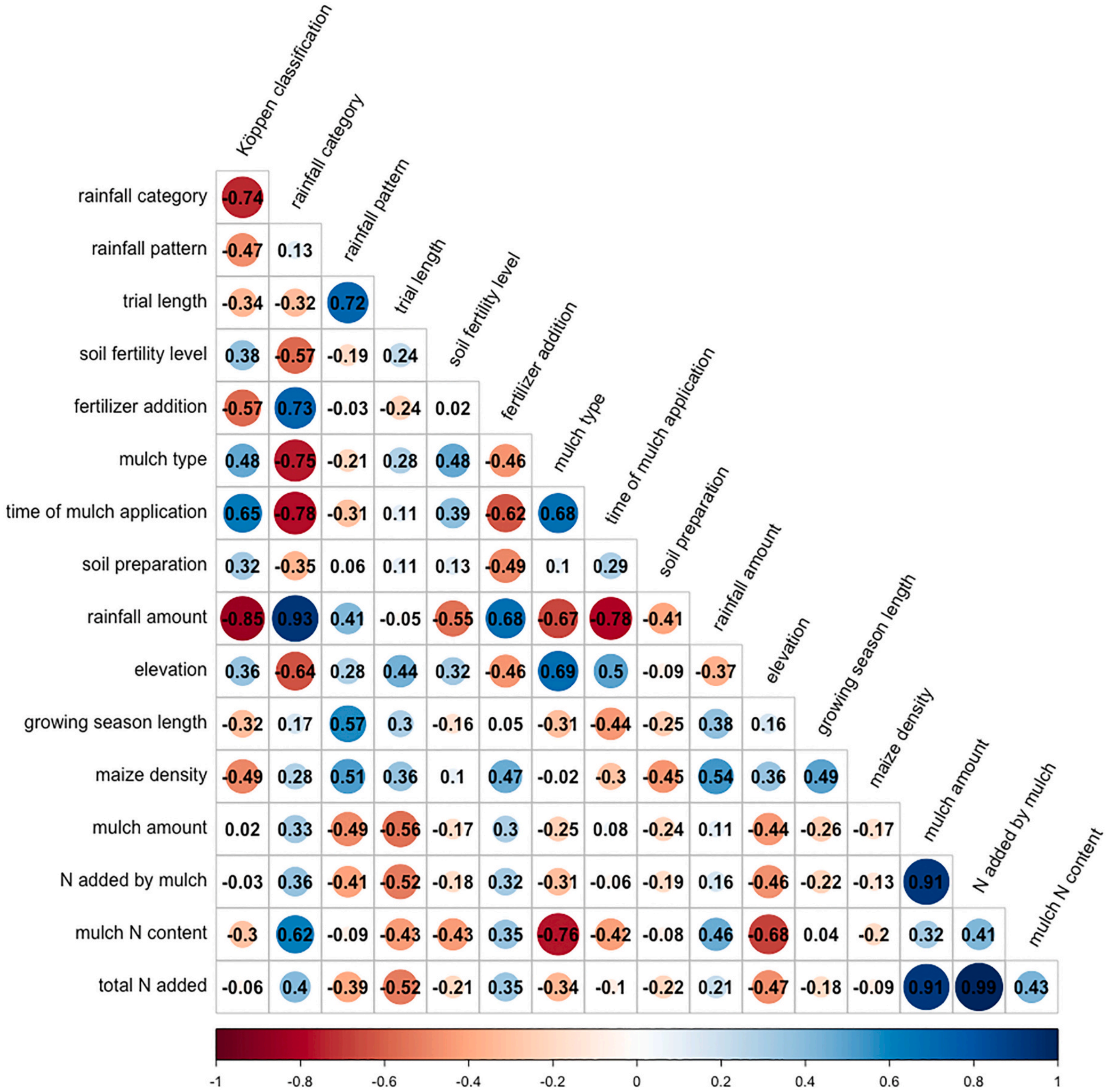
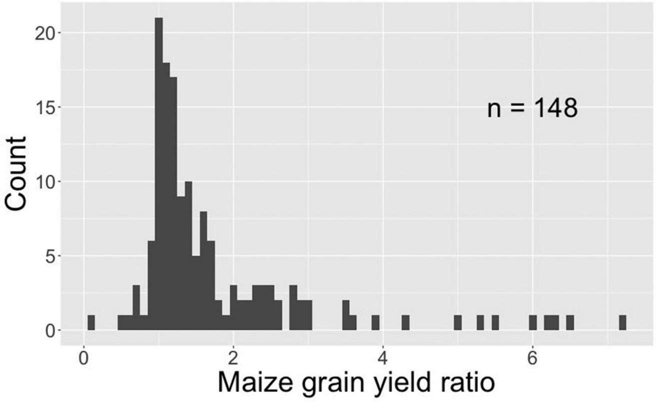
Annexes

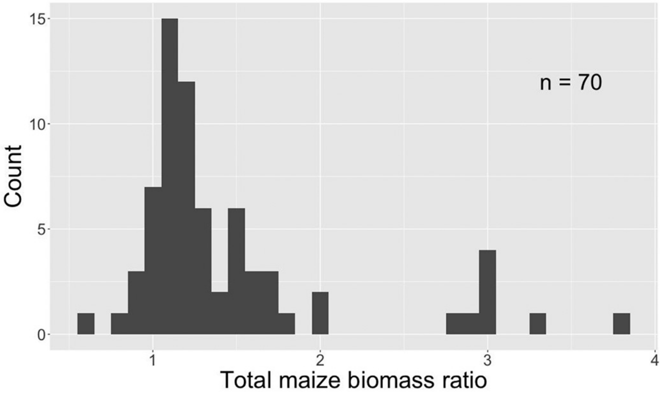


	Köppen classification	rainfall category	rainfall pattern	trial length	soil fertility level	fertilizer addition	mulch type	time of mulch application	soil preparation	rainfall amount	elevation	growing season length	maize density	mulch amount	N added by mulch	mulch N content
rainfall category	-0.74															
rainfall pattern	-0.47	0.13														
trial length	-0.34	-0.32	0.72													
soil fertility level	0.38	-0.57	-0.19	0.24												
fertilizer addition	-0.57	0.73	-0.03	-0.24	0.02											
mulch type	0.48	-0.75	-0.21	0.28	0.48	-0.46										
time of mulch application	0.65	-0.78	-0.31	0.11	0.39	-0.62	0.68									
soil preparation	0.32	-0.35	0.06	0.11	0.13	-0.49	0.1	0.29								
rainfall amount	-0.85	0.93	0.41	-0.05	-0.55	0.68	-0.67	-0.78	-0.41							
elevation	0.36	-0.64	0.28	0.44	0.32	-0.46	0.69	0.5	-0.09	-0.37						
growing season length	-0.32	0.17	0.57	0.3	-0.16	0.05	-0.31	-0.44	-0.25	0.38	0.16					
maize density	-0.49	0.28	0.51	0.36	0.1	0.47	-0.02	-0.3	-0.45	0.54	0.36	0.49				
mulch amount	0.02	0.33	-0.49	-0.56	-0.17	0.3	-0.25	0.08	-0.24	0.11	-0.44	-0.26	-0.17			
N added by mulch	-0.03	0.36	-0.41	-0.52	-0.18	0.32	-0.31	-0.06	-0.19	0.16	-0.46	-0.22	-0.13	0.91		
mulch N content	-0.3	0.62	-0.09	-0.43	-0.43	0.35	-0.76	-0.42	-0.08	0.46	-0.68	0.04	-0.2	0.32	0.41	
total N added	-0.06	0.4	-0.39	-0.52	-0.21	0.35	-0.34	-0.1	-0.22	0.21	-0.47	-0.18	-0.09	0.91	0.99	0.43

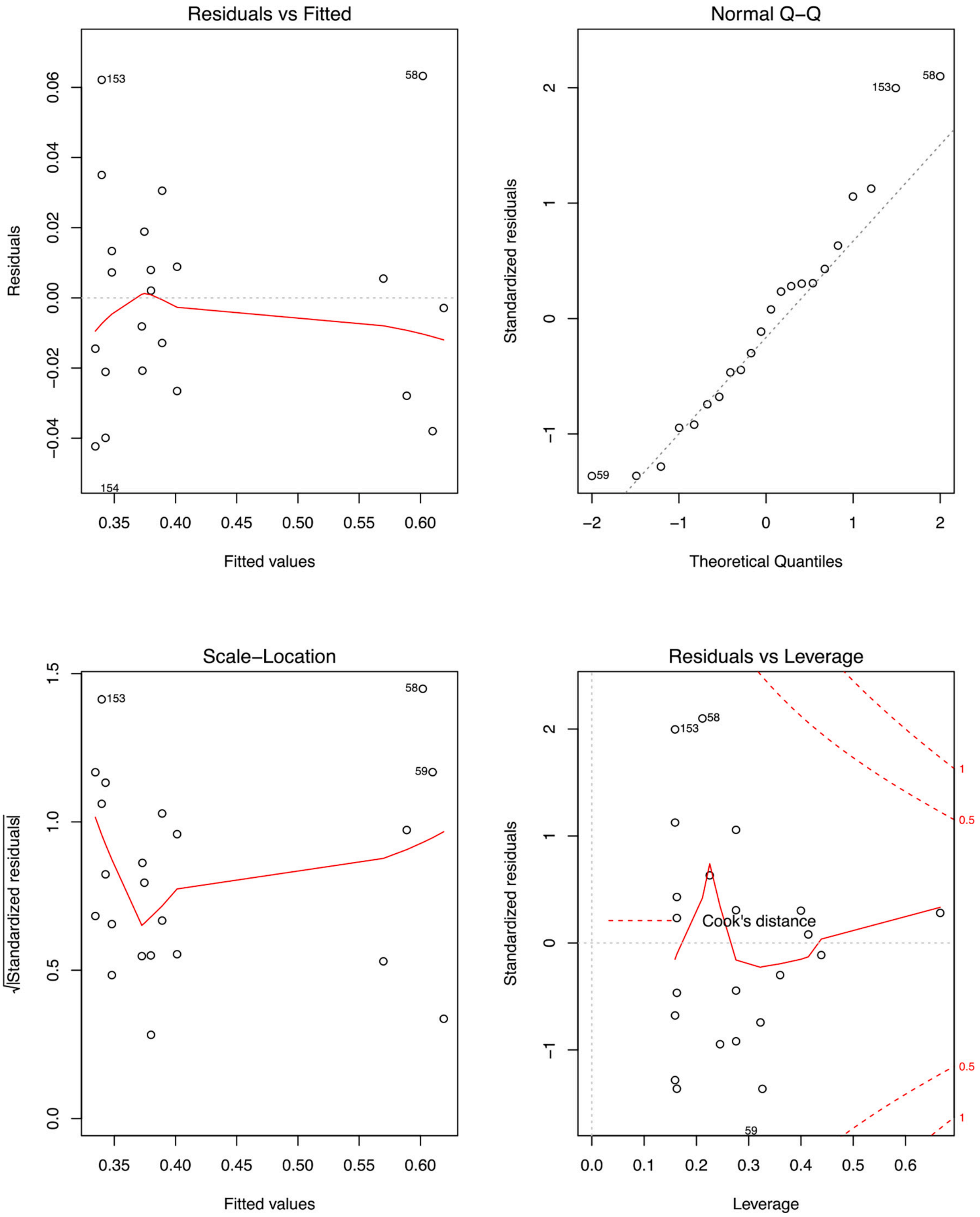
Annex 1. Correlation matrix of the variables of the systematic review on organic mulching in maize in the tropics, $n = 66$.



Annex 2. Distribution of the maize grain yield ratio of the 148 treatments (the ratio is the maize yield of the mulched treatment divided by the maize yield of the control treatment).



Annex 3. Distribution of the total maize biomass ratio of the 70 treatments (the ratio is the total biomass of the mulched treatment divided by the total biomass of the control treatment).



Annex 4. Visual assumptions check for the maize biomass model.
Plot "Residuals vs Fitted "shows the linearity of the relationship between the depending and explaining variables; plot "Normal Q-Q "shows the normal distribution of residuals; plot "Scale-Location "shows the equal variance of variables; plot "Residuals vs Leverage "shows the outliers and high leverage data points.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crsust.2022.100194.

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