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Impacts of plastic film mulching on crop yields, soil water, nitrate, and organic carbon in Northwestern China: A meta-analysis

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ABSTRACT

In order to increase crop yield in semi-arid and arid areas, plastic film mulching (PFM) is widely used in Northwestern China. To date, many studies have addressed the effects of PFM on soil physical and biochemical properties in rain-fed agriculture in Northwestern China, but the findings of different studies are often contradictory. Therefore, a comprehensive review of the impacts of PFM on soil water content, soil nutrients and food production is needed. We compiled the results of 1278 observations to evaluate the overall effects of PFM on soil water content, the distribution of nitrate and soil organic carbon, and crop yield in rain-fed agriculture in Northwestern China. Our results showed that PFM increased soil moisture and nitrate concentration in topsoils (0–20 cm) by 12.9% and 28.2%, respectively, but slightly decreased (1.8%) soil organic carbon (SOC) content in the 0–10 cm soil layer. PFM significantly increased grain yields by 43.1%, with greatest effect in spring maize (79.4%). When related to cumulative precipitation during the crop growing season, yield increase from PFM was greatest (72.8%) at 200–300 mm, which was attributed to the large increase for spring maize and potato, implying that crop zoning would be beneficial for PFM in this region. When related to N application rate, crop yields benefited most from PFM (80.2%) at 200–300 kg/ha. A cost-benefit analysis indicated that PFM increased economic return by an average of 29.5%, with the best improvement for spring maize (71.1%) and no increase for spring wheat. In conclusion, PFM can significantly increase crop yield and economic return (especially for spring maize) in rain-fed agriculture areas of Northwestern China. Crop zoning is recommended for PFM to achieve the largest economic benefit. However, full account needs to be taken of the environmental impacts relating to N loss, SOC depletion and film pollution to evaluate the sustainability of PFM systems and further research is required to quantify and mitigate these impacts.

1. Introduction

As the human population increases, the global demand for food is expected to double by 2050 (Tilman et al., 2012). With decreasing availability of well-watered agricultural lands, existing cropland with limited water supply such as those in rain-fed arid and semiarid areas will need to be used more effectively to attain the required food production levels, (Fischer and Turner, 1978; Haddad et al., 2010). In China, approximately one third of the dryland farming is in the arable land areas, of which about 40% are situated on the Chinese Loess Plateau (Li et al, 2004). Thus the Chinese Loess Plateau has the potential to be a major food production area of China in the 21st century if appropriate agricultural technologies can be applied to solve the water stress issue.

Since plastic film mulching (hereafter refer to “PFM”) can increase the water content of shallow soils, protect soil water from evaporation and improve soil temperature (Ravi and Lourduraj, 1996; Huang et al., 1999), it has been widely applied in areas of the Chinese Loess Plateau to increase crop yields and ensure a sufficient food supply for the growing population (Deng et al., 2006). Many studies have assessed the influence of PFM on the yield of various crops (e.g., maize and wheat) through impacts on soil water content, soil temperature, soil nutrients, and even soil microbes (Cook et al., 2006; Subrahmaniyan et al., 2006). However, the findings of these studies are often contradictory or inconsistent in relation to PFM application in semiarid areas. For example, while PFM is often shown to increase crop yield, reductions in yield have also been observed (Du et al., 2004). Li et al. (1999) reported that PFM reduced spring wheat yield due to low antecedent soil

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moisture and nutrient depletion during the mulching period. Even where increases in crop yield with PFM have been reported, the reason for the increase or underlying mechanism may differ for different crops or different climatic regions. Some studies have suggested that the mechanism for yield increase under PFM is an improvement in soil water and temperature conditions and an enhancement of soil nutrient availability; although also associated with the consumption of soil organic carbon (Wilson and Jefferies, 1996; Gao et al., 2009). Several studies have observed a decrease in soil organic carbon under PFM due to enhanced soil mineralization (Li et al., 2009; Li and Li, 2015), raising questions regarding sustainability. On the other hand, Liu et al. (2014) and Gao et al. (2014) reported that PFM increased crop root growth and root exudates, thus promoting soil organic carbon accumulation. These differences could be related to different crops with different root systems, differences in the number of years that mulching has been practiced (short vs long-term) or different management practices (i.e. high N input could stimulate soil organic matter mineralization). Therefore, PFM may have negative effects if applied inappropriately, not only decreasing crop yield, but also promoting soil degradation. Wang et al. (2006) showed that PFM resulted in nitrate accumulation in the top soil, potentially decreasing N leaching during storms but increasing greenhouse gas (nitrous oxide) emission. Liu et al. (2014) found that the nitrate accumulation under PFM had a positive relationship with N input. Hence, the effects of PFM on crop yields and agricultural ecosystems are variable, considering the different factors, such as climate (precipitation and temperature), crops, soils, and agricultural management practices (e.g. N input levels), and a comprehensive assessment based on all available data is needed to evaluate the economic and environmental sustainability of the practice for arid and semiarid regions.

The objectives of this study, therefore, were to comprehensively evaluate through meta-analysis the effects of PFM on crop yield, soil water content, and soil nutrients (i.e., soil nitrate and soil organic carbon) under a range of conditions, and the economic benefit of PFM in the rain-fed agriculture areas of Northwestern China.

2. Materials and methods

2.1. Data

The Web of Science and China National Knowledge Internet were used to find peer-reviewed studies published before January 2017. Search terms included ‘plastic film mulch’ or ‘mulching’, ‘nitrogen’, ‘nitrate’, ‘water content’ or ‘soil organic carbon’ in the article title, abstract, and keywords. The following five criteria were defined for a study to be included in the analysis: i) the field experiment and the experimental sites were located in rain-fed agriculture areas of Northwestern China (Shaanxi; Gansu; Qinghai; Xinjiang; northwest Inner Mongolia); ii) the crop grain was harvested at the physiological mature stage; iii) in addition to the treatment; a control group without the application of PFM was included in the experiment design; iv) reported averages of observational data were based on at least three replicates; v) the application rates of nutrient inputs (fertilizer N; P and K) were reported; for inclusion in the cost–benefit analysis. Accordingly; a total of 1278 observations from 83 peer-reviewed studies were included in our analysis.

2.2. Effect size

To quantify the impacts of PFM on a given variable, the response ratio (R) was determined according to Hedges et al. (1999):

$$\ln R = \ln\left(\frac{Xt}{Xc}\right), \tag{1}$$

where X_t and X_c are the treatment value (i.e. under PFM) and corresponding control value, respectively, for the given variable. The results were presented as the percentage change ((R-1) × 100) under PFM, with a positive percentage change denoting an increase in variable value due to PFM and a negative value denoting a decrease.

Effect sizes can be weighted using the inverse of the pooled variance (Yang et al., 2016) or the number of replications (Lam et al., 2012), depending on the integrity of the reported standard deviations in the database. Over 50% of the studies included in our meta-analysis did not report the standard deviations of the mean values. In addition, extreme weights may be generated using variance-based weighting functions, but not when using replication-based approaches (Van Groenigen et al., 2011). Therefore, the replication based weighting was adopted in our analysis using the following equation (Lam et al., 2012):

$$\text{weight} = \frac{nt \times nc}{nt + nc}, \tag{2}$$

where n_t and n_c represent the numbers of replicates of the treatment and control groups, respectively. Mean effect sizes and the 95% confidence intervals (CIs) were generated by a bootstrapping procedure with 4999 iterations, using METAWIN 2.1 (Rosenberg et al., 2000). Effects of PFM were considered significant if the 95% CIs did not overlap with zero. Similarly, means of categorical variables were considered significantly different from each other if their 95% CIs did not overlap (Xia et al., 2017).

2.3. Cost-benefit analysis

Cost-benefit analysis included assessment of the input costs, income from yield sales and net economic benefit (NEB). The input costs included the cost of agricultural materials such as seed, fertilizer, pesticides, and plastic film (http://www.npcs.gov.cn/and http://china.guidechem.com/), and labor cost associated with fertilizer/pesticide applications and mechanical operations (Table S1). Yield income refers to income from grain yield. The NEB was calculated by subtracting the input cost from the yield income (Xia et al., 2017).

3. Results

3.1. Effect of PFM on soil water content

On average, PFM increased soil water content by 9.0% across all soil layers (Fig. 1), compared with traditional cultivation. The effect decreased with increasing soil depth; for example, soil water content at 0–20 cm depth was increased by 12.9%, more than twice of that at

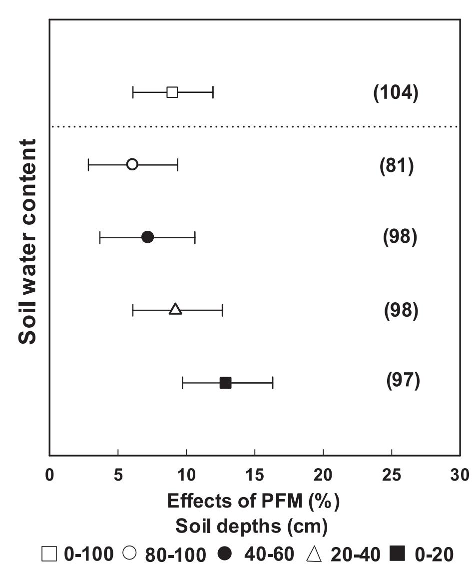

Fig. 1. Changes in soil water content affected by PFM at different soil depths. The numbers in parentheses indicate the number of observations.