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RESEARCH ARTICLE

The status and distribution characteristics of residual mulching film in Xinjiang, China

ZHANG Dan[1], LIU Hong-bin[1], HU Wan-li[2], QIN Xiao-hui[3], MA Xing-wang[4], YAN Chang-rong[5], WANG Hong-yuan[1]

[1] *Key Laboratory of Nonpoint Source Pollution Control, Ministry of Agriculture/Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing 100081, P.R.China*
[2] *Institute of Agricultural Environment and Resources, Yunnan Academy of Agricultural Sciences, Yunnan 650205, P.R.China*
[3] *Protection Station of Agricultural Resources and Environment, Xinjiang Agricultural Department, Urumqi 830001, P.R.China*
[4] *Institute of Soil Fertilizer and Water Saving, Xinjiang Academy of Agricultural Sciences, Urumqi 830091, P.R.China*
[5] *Institute of Environment and Sustainable Development in Agriculture, Chinese Academy of Agricultural Sciences, Beijing 100081, P.R.China*

Abstract
Pollution of residual plastic film in arable lands is a severe problem in China. In this study, the status of residual film and influential factors were investigated using the methods of farm survey in combination with questionnaires and quadrat sampling at a large number of field sites in Xinjiang Uygur Autonomous Region, China. The results showed that the amount of film utilization increased largely and reached to 1.8×10^5 t in 2013. Similarly, the mulching area also substantially increased in recent decades, and reached to 2.7×10^5 ha in the same year. According to the current survey, 60.7% of the sites presented a greater mulch residue than the national film residue standard (75 kg ha^{-1}), and the maximum residual amount reached 502.2 kg ha^{-1} in Turpan, Xinjiang. The film thickness, the mulching time and the crop type all influenced mulch residue. The thickness of the film had significantly negative correlation with the amount of residual film ($P<0.05$), while the mulching years had significantly positive correlation with it ($P<0.05$). The total amount of residual film in Xinjiang was 3.43×10^5 t in 2011, which accounted for 15.3% of the cumulative dosage of mulching. Among all the crops, the cotton fields had the largest residual amount of mulch film (158.4 kg ha^{-1}), and also the largest contribution (2.6×10^5 tons) to the total amount of residual film in Xinjiang.

Keywords: Xinjiang, residual mulching film, influential factor, agricultural resources, agricultural pollution

1. Introduction

Plastic films have been used extensively as mulching for crops in the modern agriculture. Worldwide, the annual consumption of mulching plastic film has reached as high as 0.5–1.5 million t (Yang *et al.* 2015). China is the largest consumption country of the mulching film, accounting for 60% of the world agricultural film demand (Yang *et al.* 2015).

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ZHANG Dan, Mobile: +86-13126535516, E-mail: zhangdan0630@126.com; Correspondence WANG Hong-yuan, Tel: +86-10-82108763, E-mail: wanghongyuan@caas.cn

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Film mulching technology has been reported to remarkably improve crop yields and economic benefits by effectively maintaining soil moisture and thus conserving water resource (Lamont 2005; Li *et al.* 2005; Anikwe *et al.* 2007; Yang *et al.* 2011; Zhang *et al.* 2011; Briassoulis *et al.* 2013). This technology is of particular importance and of wide use in the arid and semi-arid regions of China (Schimel 2010; Yan *et al.* 2014). Without rational management measures, however, a large amount of plastic mulching film can reside and accumulate in the field and cause a series of agronomic and environmental problems due to its nature of resistance to degradation (Briassoulis *et al.* 2015; Makhijani *et al.* 2015). It has been observed that residual mulching film can block water, nutrient and heat transfer in the soil, disrupt soil environment, and thus decline soil quality and reduce crop production (Huang 2012; Shen *et al.* 2012; Makhijani *et al.* 2015; Yang *et al.* 2015).

In China, the wide use and high residual ratio of mulching film has made its associated problems more serious than any other country of the world. In the past decades, recovery rate of the plastic film in China was very low, because of high demand for labor, inefficiency of recovery machinery, and especially lack of mandatory recycle policy. In the beginning of year 2015, the Ministry of Agriculture, China set the environmental goals of "one control, two reductions, and three basics" by 2020. One major goal is to realize pollution-free disposal of agricultural film and to achieve more than 80% recovery of the plastic film. To achieve the goal of improved film recovery rate, the first necessary step is to find out the present situation of residual film in the major film mulching areas.

Most of the previous investigations on the residual film have been conducted at a small number of field sites within a relatively small region. Moreover, there was a general lack of consideration of various factors such as climate characteristics, crop types, film thickness, mulching years, film utilization amount, covering ratio and etc., which all influence film residue (Mi *et al.* 1998; Chen 2008; Ma 2008; He *et al.* 2009; Hu *et al.* 2013; Picuno 2014). As a result, significant different results have been reported in the previous studies. For example, the regional mulch residual amount (301 kg ha^{-1}) of Yan *et al.* (2008) was obviously higher than the value (209 kg ha^{-1}) reported by He *et al.* (2009), even though both studies were conducted in Shihezi, Xinjiang. In both studies, only 3 or 4 field sites were investigated, which is probably the reason for the great difference of the results. There is an urgent need to more accurately assess mulching film use based on a large number of datasets, with consideration of different categories such as crop types.

This study aims to assess the status and distribution characteristics of residual mulching film in Xinjiang Uygur Autonomous Region, Northwest China, where use of mulching film has been reported (Yan *et al.* 2008; Wang *et al.* 2012) to be several times higher than in South China (Cai *et al.* 2013; Kang *et al.* 2013; Zeng *et al.* 2014). To our best knowledge, this study is the first to investigate the mulch residue status and analyze its influential factors by combining the farm survey method with the quadrat sampling method. To obtain a fair assessment, a large set of questionnaires and quadrat samples were collected. This study will eventually contribute to promoting effective control and management of residual mulch pollution in China.

2. Materials and methods

2.1. Study site

This study was conducted in Xinjiang (73°40´–96°18´E, 34°25´–48°10´N, Fig. 1), Northwest China. Xinjiang is the largest land area in China's provinces and regions, spanning over 1.6 million km^2, and it is an important Chinese agricultural production base for several crops including cotton, maize, fruits and vegetables. For example, in 2013, the planting area of cotton in Xinjiang was 1.7×10^6 ha, which accounted for 39.5% of the nationwide area (Rural Social and Economic Investigation Department, National Bureau of Statistics 2014). This region has a typical arid continental climate with a mean annual precipitation of 150 mm. Mulching is an extremely important farming practice to maintain soil moisture content. Thus, most of the crops are covered with film during growth, and particularly almost all cottons are film-mulched (Liu *et al.* 2010).

2.2. Farm survey method

To obtain a thorough picture of mulching plastic film using, a total number of >700 copies of the questionnaires were sent out to the farmers covering all the main agricultural production regions across Xinjiang. By the end of the survey, 672 copies of the questionnaires were returned by farmers, and 593 copies of them were valid. The questionnaire was designed (Appendix A) to include as much information related to mulching film use and site-specific factors as possible, such as the information on the survey location, soil type, crop type, irrigation type, film thickness, mulching years, film mulching dosage, recycling methods, amount and etc. Since the distribution of arable land is scattered in Xinjiang, the field sampling sites located quite unevenly (Fig. 1). What's more, the survey was conducted comprehensively as possible. The survey covered a wide range of major crops in this region, including cotton, maize, wheat, vegetables, potato, as well as minor crops such as sunflower, soybean, flowers, melon, etc. The minor crops were grouped in one category in the survey due to their

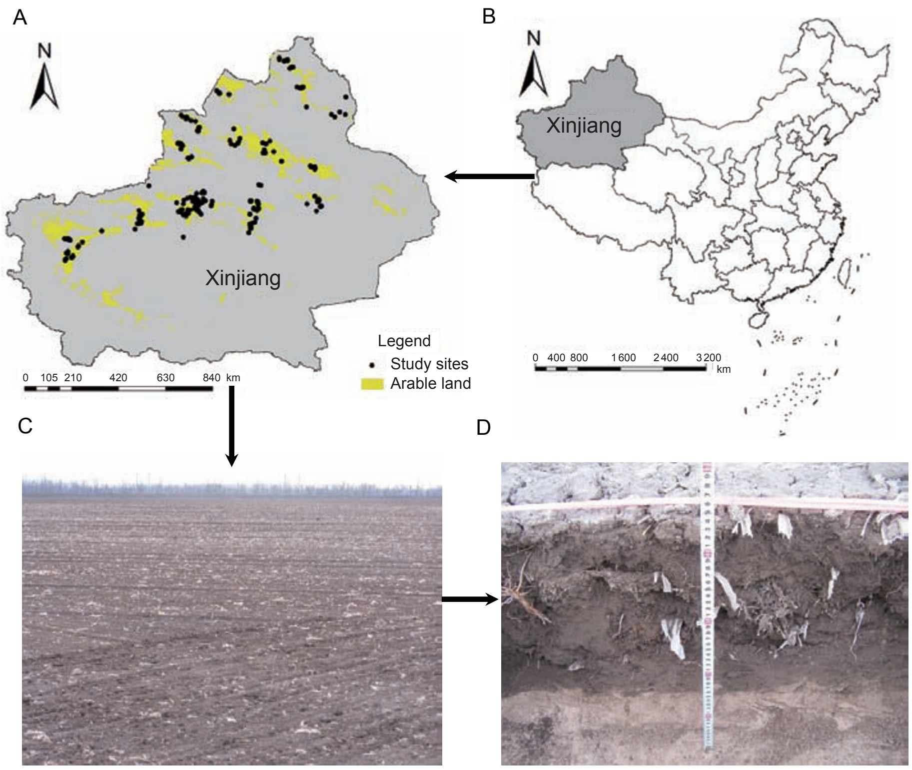

Fig. 1 The distribution of study sites and the apparent residual film situation in Xinjiang, China. A, the distribution of study sites. The yellow areas represent the arable land, the rest were residential areas, forests, deserts, etc. B, the location of Xinjiang. C, the distribution of residual film on the soil surface. D, the distribution of residual film in soil profile.

individual small planting areas, and this group is hereafter referred as 'Others'.

2.3. Quadrat sampling method

In connection to the survey conducted, residual film in soil was sampled and quantified by quadrat sampling method. Specifically, for each of the 593 survey sites across Xinjiang (Fig. 1), five quadrats with the size of 200 cm in length, 100 cm in width, and 30 cm in depth were randomly sampled and the residual film was manually collected. Thereafter, the film was cleaned by ultrasonic apparatus, and the moisture on the film surface was sopped up by blotting paper. Following spreading the curly residual film carefully, the air-dried residual films were weighed.

The amount of film residual at each site was calculated as follows:

$$Q=\overline{M}/S_a\times 10\,000$$

Where, Q is the amount of film residual (kg ha^{-1}); $\overline{M}$ is the mean mulching residual amount of five quadrats (kg); S_a is the area of each quadrat (m^2); 10 000 is conversion coefficient from m^2 to ha.

The total film residual amount for each crop was calculated as follows:

$$A_i=\overline{Q}_i\times S_i/1\,000$$

Where, i represents the cotton, maize, wheat, vegetables, potato and other crop types; A_i is the total residual film amount of the ith crop (t); $\overline{Q}_i$ is the mean film residual amount of the ith crop (kg ha^{-1}); S_i is the mulching area of the ith crop (ha); 1 000 is conversion coefficient from kg to t.

The total film residual amount (ton) for the entire Xinjiang was calculated as:

$$A=\sum_{n=1}^{n}A_i$$

2.4. Data analysis

SPSS 19.0 software was used for statistical analysis. Bivariate correlation method was used for correlation analysis, and one-way ANOVA was used for comparing significant differences.

3. Results and discussion

3.1. Residual film status

According to *China Agricultural Statistical Yearbook* (Rural Social and Economic Investigation Department, National

Bureau of Statistics 2014), both the mulching film utilization amount and mulching area in Xinjiang significantly increased from 1993 to 2013 (Fig. 2). Specifically, the film utilization amount increased by 5.5-fold from 3.3×10^4 t in 1993 to 1.8×10^5 t in 2013. Its annual growth rate was 7.0×10^3 t, and the accumulated utilization amount during the 20 years was up to 2.2×10^6 t. Accordingly, the total mulching area increased from 6.2×10^5 ha in 1993 to 2.7×10^6 ha in 2013, with the growth rate of 1.0×10^5 ha yr^{-1}. The total mulching film utilization amount and mulching area in China reached 1.4×10^6 t and 1.8×10^7 ha in 2013, respectively. Xinjiang has become the largest region for both film utilization amount and mulching area, accounting for 12.9 and 15.0% of the national total values, respectively.

The amount of residual mulch film in the arable land was calculated using the quadrat sampling method. The residual film volume ranged widely from 0 to 502.2 kg ha^{-1}. North of Xinjiang region presented slightly pollution, the residual amount of some fields were 0 kg ha^{-1}; whereas the maximum residual amount occurred in Turpan. According to the Chinese Standard of "Limit and test method for residual quantity of agricultural mulch film" (GB/T 25413-2010 2010), 75 kg ha^{-1} was regulated as the threshold residual mulch film in the topsoil of the farmland. In hence, the range of 75 kg ha^{-1} was selected to divide the whole scope of residual volume in Xinjiang to indicate the mulch residual distribution at different ranges (Fig. 3). According to the current survey, 60.7% of the areas had a residual film amount above the national film residue standard (75 kg ha^{-1}), although 72% of the areas had a residual film amount smaller than 150 kg ha^{-1}. This indicates that residual film pollution has become a serious issue in many areas of Xinjiang, and this issue is urgent to be addressed from aspects of policy, regulation and technology in an all-round manner (Yan *et al.* 2008; Liu *et al.* 2014).

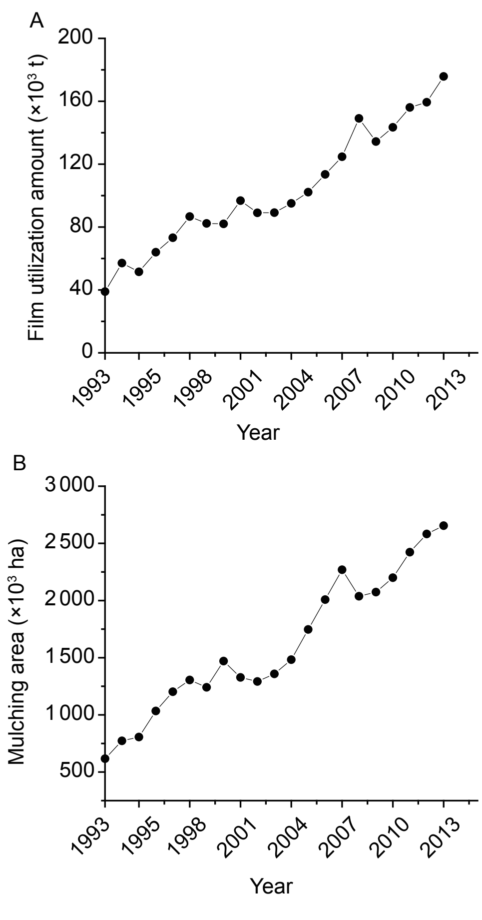

Fig. 2 The trends of the total film utilization amount (A) and mulching area (B) in Xinjiang from 1993 to 2013 (data source: Rural Social and Economic Investigation Department, National Bureau of Statistics 1994–2014).

3.2. The main factors influencing mulch film residue

The mean amount of residual mulch film across the entire Xinjiang was 121.5 kg ha^{-1}, and the median was 92.8 kg ha^{-1}. Due to the large spatial variability factor (CV) of 80.8%, the mean and the median values of the residual film amount may not well represent all the aspects of film residue in Xinjiang. It has been reported that clime, sunshine time, crop type, film thickness, mulching years, film utilization amount and recovery method could all influence the quantity of residual films (Chen 2008; He *et al.* 2009; Hu *et al.* 2013; Picuno 2014). In the present study, three major factors (film thickness, mulching years and crop type) were chosen to analyze their correlations with the quantity of residual film.

The thickness of the film had significantly negative correlation with the amount of residual film ($P<0.05$). In general,

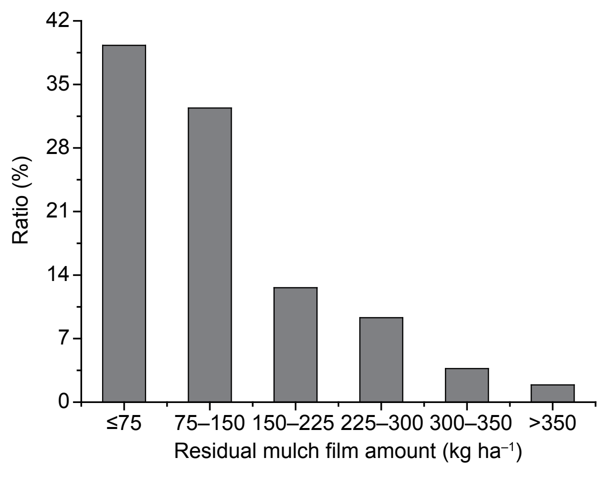

Fig. 3 The distribution of residual mulch film amount at different ranges.

the durability and tensile resistance of plastic film are associated with the film thickness, and the thinner the film is, the more film resides. Taking the film of 0.006 and 0.008 mm thicknesses as examples (Fig. 4), >90% of the regions mulched with the 0.006 mm film had a residual film volume higher than 75 kg ha^{-1}, while the percentage was only 48.8% for the 0.008 mm film mulching regions. Chen *et al.* (2008) found that the strength of tensile resistance can be improved by 25%, when the film thickness increased from 0.008 to 0.010 mm. The thin films are very easy to be broken up into small pieces during recycling by human or machines, and the buried part are likely fractured and then retained in the soil. On the contrary, the thick films with good durability and tensile resistance are easier to keep for big pieces, and thus are good for recycling. Therefore, increasing the thickness of plastic film mulch would facilitate its recycle, effectively reduce the amount of residual film and eventually control the while pollution. On the other side, the thick film owning the same cover area with the thin equivalent will increase the film amount, and cause more residues in the case of no recycling. In hence, the areas without recycling action will accumulate smaller residual films when using thin film; inversely the areas will depict higher residues when using thin films. Since most of the fields in Xinjiang perform mulch collection by human or machines, there were smaller residues using thick film.

According to the continuous mulching years, the average residual time of the film in Xinjiang fields was divided into 4 phases, namely, ≤5, 5–10, 10–20 and >20 years (Fig. 5), and the amounts of the residual film were 38.0, 101.1, 123.8, and 190.1 kg ha^{-1}, respectively. The mulching years would significantly raise the residual film amount (P<0.05), which is consistent with the results of Kang *et al.* (2013) and Ma *et al.* (2008). The volume of residual film with >20 mulching years was 5 times larger than that those with ≤5 years, and the same pattern was observed when comparison was made for individual crops. Take cotton as an example, the film residues increased from 84.0 kg ha^{-1} with mulching for ≤5 years to 210.3 kg ha^{-1} with mulching for >20 years (Fig. 6). Previous studies also indicated that the residual film amount in cotton fields linearly increased by 11.2 to 13.7 kg ha^{-1} yr^{-1} in Xinjiang (Liu *et al.* 2010; Dong *et al.* 2013). The residual volume in maize, vegetables, potato and the other crop fields also presented the same increasing trend with the prolongation of mulching time in Xinjiang.

The agricultural film residues pollution in Xinjiang was most serious in cotton fields, with the average of the residual volume reaching 158.4 kg ha^{-1} (Fig. 7). Cotton fields presented the highest film residues among all the crops, mainly because drip irrigation was applied under film during cotton growth, which did not allow removal of the plastic film (Chen 2008). Furthermore, the cotton fields with long-term plastic film mulch cover (over ten years) accounted for 74.9% of all the surveyed fields. The film residues were 142.1 kg ha^{-1} when mulching for 10–20 years and 210.4 kg ha^{-1} when mulching for >20 years. These values are considerably lower than those reported in the previous study, i.e., 259.7 kg ha^{-1} after continuing mulching for 10 years and 307.9 kg ha^{-1} after mulching for 20 years (Yan *et al.* 2008). However, the values in our study are likely to be more reliable, because our data were based on a much larger datasets.

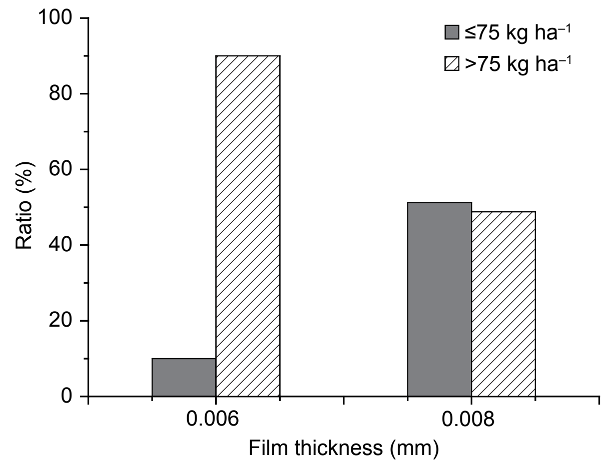

Fig. 4 Effect of film thickness (e.g., 0.006 and 0.008 mm) on the amount of residual mulching film.

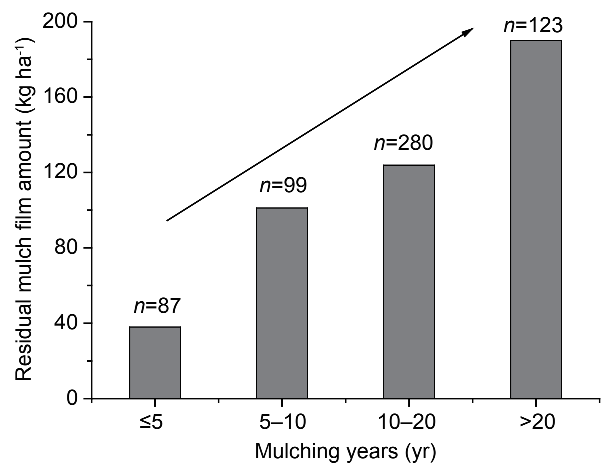

Fig. 5 Effect of mulching years on residual mulching film amount.

Following cotton, maize fields had the second greatest film residue volume. The ratio with a mulching time of more than 10 years for maize was less than that for cotton, although much higher residual quantity (279.2 kg ha^{-1}) was observed for continuous >20 years mulching. The residual

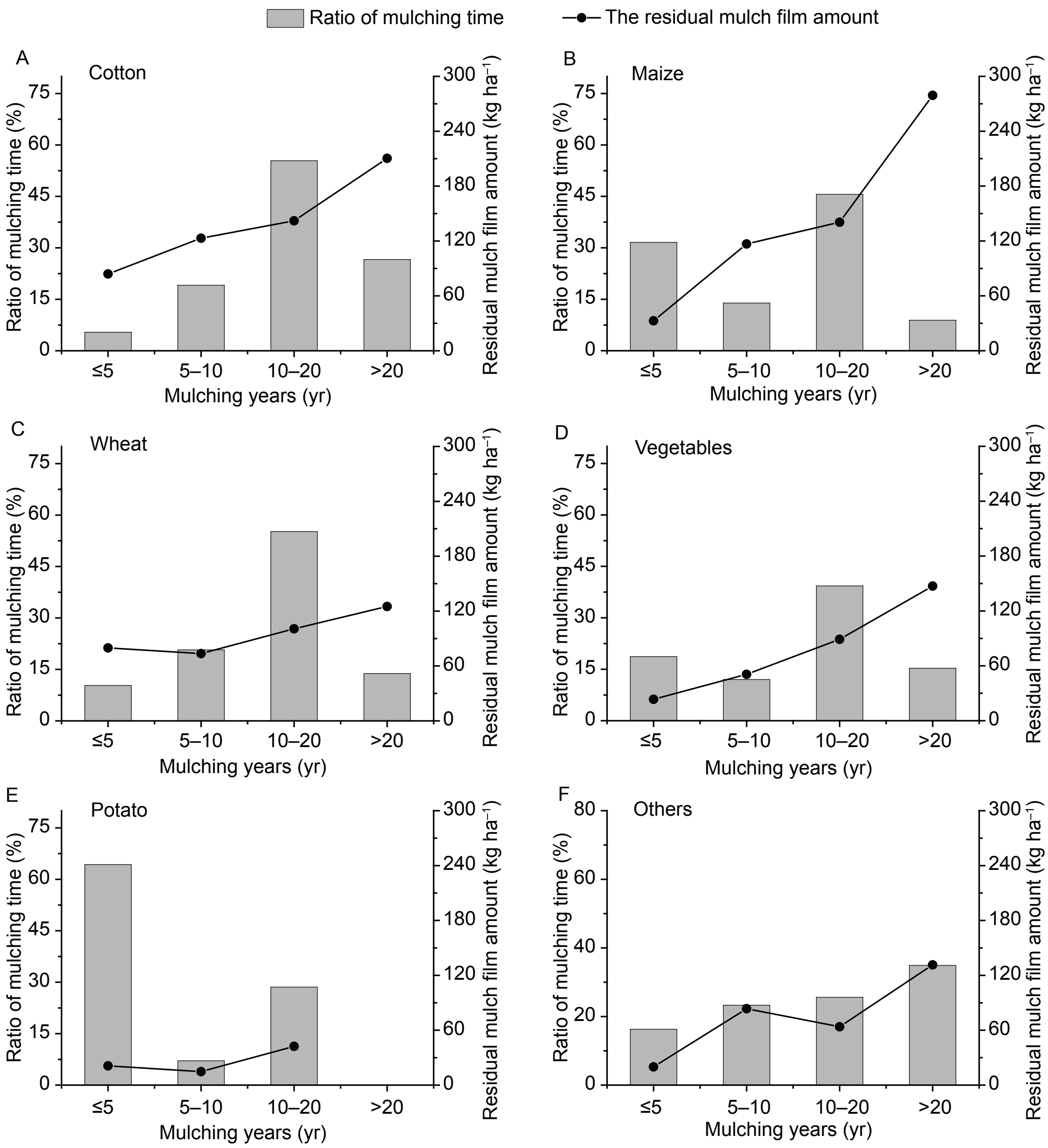

Fig. 6 Ratios of mulching and amount of residual film at different mulching years of each type of crop (cotton, maize, wheat, vegetables, potato and others, others include sunflower, soybean, flowers, melon and etc.).

mulch of wheat, vegetable and the other crops was of the similar volume to maize, *ca*. 90 kg ha^{-1}. The potato fields had the smallest residual mulch (26.7 kg ha^{-1}) and potato was the only crop that had the mulching residue smaller than the regulated threshold value of 75.0 kg ha^{-1}. That is because of two reasons. One reason is that the seasonal residue of potato fields was very low, and its accumulation effect was not obvious. The other reason is that the dominant mulching time of potato is relatively short, and 64.3% of the fields had mulching time <5 years, with a residual quantity of 21.1 kg ha^{-1}.

3.3. Total residual amount of plastic film

The mulching area in Xinjiang was 2.4×10^6 ha in 2011, which accounted for 49.1% of the total planted area of this region (5.0×10^6 ha). As shown in Table 1, the total amount of residual film in Xinjiang was 3.4×10^5 t in 2011, which accounted for 15.3% of the cumulative dosage of mulching (2.2×10^6 t). Among all the crops, cotton and maize fields had the largest contribution to the total amounts of residual film, because of their large mulching area and residual film levels. Mulching ratio of cotton reached as high as 100%, the same

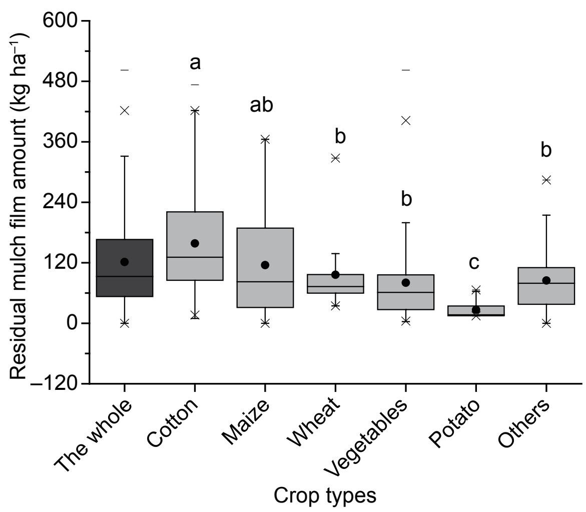

Fig. 7 Residual mulching film amount of different crop types in Xinjiang. The whole include all crops, which was the level of overall. Bars labeled with the same letter do not differ significantly with different crop types. The upper and the bottom – represent the maximum and the minimum of the residual film, respectively; the upper and the bottom × represent the 99th and the 1th percentiles of it, respectively; the solid dot represents the mean of it.

as observed by Liu *et al.* (2010). The area of plastic film mulching for cotton was 1.6×10^6 ha, and the mulching area of maize was 5.5×10^5 ha, accounting for 67.0 and 22.3% of the total mulching area of Xinjiang, respectively. The residual mulch levels of cotton and maize were 158.4 and 115.4 kg ha^{-1}, respectively. As a result, the cotton fields (2.6×10^5 t) accounted for 75.7% of the total residual amount of the entire region, and the maize fields (6.3×10^4 t) accounted for 18.4% of the total residual amount.

4. Conclusion

In the recent two decades years, residual film dramatically increased as the application of agricultural plastic film grows in Xinjiang. Until 2011, the total amount of residual film in Xinjiang was 3.43×10^5 t, which accounted for 15.3% of the cumulative dosage of mulching. In which, 60.7% of the regions had a residual film amount greater than the national film residue standard (75 kg ha^{-1}), and even up to 502.2 kg ha^{-1}. These results indicated that the prevention of the residual plastic film pollution was imperative. The residual film amount was increased with the mulching years prolonged. Conversely, the residual film was found to respond negatively to increased thickness of film, suggesting that increasing the film thickness is an effective means to reduce the amount of residual film. Moreover, the residual film amount closely related with the crop type. Among all the crops, the cotton fields had the largest contribution to the total amount of residual film in Xinjiang, which should be listed as the key control regions.

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Appendix associated with this paper can be available on http://www.ChinaAgriSci.com/V2/En/appendix.htm

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Table 1 The total plastic film residual amount of each crop in Xinjiang[1)]

Crop type	Planting area ($\times10^3$ ha)	Mulching area ($\times10^3$ ha)	Mulching ratio (%)	Residual film quantity ($\times10^3$ t)
Cotton	1638.1	1638.1	100	259.5
Maize	728.0	546.7	75.1	63.1
Wheat	1078.0	–	–	–
Vegetables	322.6	213.3	66.1	17.1
Potato	45.4	13.3	29.3	0.3
Others	1171.4	35.3	3.0	3.0
Total	4983.5	2446.7	49.1	343.0

[1)] The data of planting area and the mulching area were for 2011.
–, mulching areas of wheat was too small to be included in statistics, resulting in no data here.

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