An Opportunity for Regenerative Rice Production: Combining Plastic Film Cover and Plant Biomass Mulch with No-Till Soil Management to Build Soil Carbon, Curb Nitrogen Pollution, and Maintain High-Stable Yield

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Abstract: China has attained rice sufficiency with the increased use of nitrogen (N) fertilizer, but this has led to serious N pollution. China has the world’s highest use of N with the lowest N use efficiency (NUE). Including livestock production, China’s agriculture sector has surpassed industry as the greatest polluter of water. Using plastic film on raised-beds, combined with improved agronomic practices, can boost rice yield by 50% with 36% less N fertilizer use, 30% higher NUE, and stabilized the yield of 9.75 t ha\(^{-1}\). It also counters the effects of drought and low ambient temperature. A six-year study was conducted combining no-tillage, crop-residue mulch, and plastic cover, alternating organic rice and rapeseed production. All the treatments, fertilized with biogas slurry and rapeseed meal, gave rice yields of 7.0 to 10.7 t ha\(^{-1}\), well above China’s average of 6.5 t ha\(^{-1}\). In this time, soil organic matter increased from 1.6% to 4.2%. In the first four years, the combination of crop-residue mulch with plastic cover had a slightly higher yield than mulch alone. In the fifth and sixth years, the latter treatment surpassed the use of plastic cover with crop-residue mulch. Trials with a biodegradable film show that plastic pollution can be dealt with.

Keywords: conservation agriculture; no tillage; residue return; plastic cover; biodegradable plastic film; sustainable crop intensification; rice cropping system; soil organic carbon; system of rice intensification; China

1. Introduction

Over the past 50 years, China’s agricultural improvement efforts have sought to increase food production to meet the demand of a large and still growing population, with the objective of attaining grain self-sufficiency despite the country’s very limited arable land area, less than 0.1 hectare per capita [1,2]. This area has been shrinking, due to rapid industrialization and urbanization while the population continues growing. With limited arable area available, food production has been raised mostly by increasing the use of nitrogen (N) fertilizer in conjunction with the introduction of new rice varieties, particularly hybrids that have greater production potential.

In general, China has been successful with this strategy, increasing domestic grain production from 132 Mt in 1950 to 607 Mt in 2014 [3]. Average paddy rice yield in China is now 6.5 t ha\(^{-1}\), which is
significantly higher than the averages for the world, 4.6 t ha\(^{-1}\), and for Southeast Asia, 4.4 t ha\(^{-1}\) [2]. With just 8% of the world’s arable land [4], China is feeding 18% of the global population [4]. Between 1980 and 2008, per-capita grain production increased by 22%, from 326 kg to 399 kg, while per-capita meat production went from 9 kg to 42 kg, more than quadrupling availability. In this same period, population increased by 35%, from 987 million to 1.33 billion. Hunger significantly decreased in China, while it increased in other parts of the developing world [1].

1.1. Nitrogen Fertilizer Overuse and Livestock Waste are the Main Causes of Pollution in China

The prevailing crop intensification strategy led to heavy use of N fertilizer which increased nitrogen discharge into water bodies, resulting in serious environmental pollution affecting groundwater supplies [3]. China now accounts for 28% of the world’s consumption of nitrogen fertilizers [2], and it has the highest fertilizer N application rate in the world. At 328 kg ha\(^{-1}\) yr\(^{-1}\), this is more than 2.7 times the world average [5]. Nitrogen use efficiency (NUE) in China fell by about 300% between 1979 and 2010 [6], and China’s average NUE is currently only 25%, about 60% of the world’s average [7]. Agricultural systems are responsible for almost 60% of current nitrogen discharge from human activities (35% from croplands, 24% from livestock). The other sources of N discharge are domestic waste (13% urban sewage, 8% rural sewage, 18% organic garbage), with the remaining 2% from industrial waste [3].

In absolute terms, meat consumption in China increased sevenfold over the past three and a half decades. In the 1980s, the average Chinese person ate around 14 kg of meat per year. Today, with an additional 380 million people, per capita consumption is 63 kg per year, an increase of 350%. Currently, China consumes 28% of the world’s meat—twice as much as the United States in terms of total volume [8]. Such an expansion of intensive livestock production, of course, generates a massive amount of manure. Up to the 1970s and early 1980s, China was a model country for nutrient recycling. However, decreasing labor availability for processing and applying organic materials and the relatively low cost of inorganic fertilizers has led to substantial reductions in the use of manure and other organic waste for supporting crop production [9].

The overuse of N fertilizer and diminished recycling of organic wastes have become major sources of soil and water pollution in China. The country’s Ministry of Water Resources has reported that water from over 80% of the wells monitored was classified as not fit for human consumption [10]. Yu et al. have estimated that the current anthropogenic nitrogen discharge rates to freshwater are 2.7 times above a ‘safe’ nitrogen-discharge threshold [3]. China’s agriculture contributes around 20% of the nation’s total greenhouse gas (GHG) emissions, which are now the largest in the world, most of the agricultural emissions coming from synthetic N fertilizer use and from the livestock sector [11,12].

Conventional agricultural practices and corresponding nutrient mismanagement are responsible for some 80% of the economic costs associated with environmental degradation [1]. Hence, the concept of ‘sustainable intensification’ is now being advanced to reduce the negative environmental impacts of excessive N fertilizer use, recognizing the importance of maintaining high levels of food self-sufficiency [13]. With certain policy changes in recent years, China had been able to increase NUE in the production of its three major food crops (rice, corn and wheat) from 28% in 2005 to 33% in 2015 [5]. However, further improvements are needed.

1.2. Drought and Low Temperature are the Major Constraints of Rice Production in Sichuan

In the hilly areas of Sichuan, frequent droughts combined with highly inadequate irrigation infrastructure limit overall rice production in the province [14]. In northern Sichuan, where paddy fields occupy 44% of the total cultivated area, meteorological records show that in 49 of the 52 years between 1957 and 2008, there was some or even widespread drought. In northeast Sichuan, drought is experienced in nine years out of ten [15]. This makes developing a technology to combat the effects of drought in rice-producing areas a priority.
A second major constraint is a low temperature, which especially affects the establishment of the rice crop. It results in transplanting shock to seedlings that are put into the field when the soil is still cold, making the leaves yellow, stunting plant growth, and reducing the plants’ potential to produce more tillers and large root systems. These two factors of drought and low temperature together result in unstable and unpredictable rice yields that are easily depressed by adverse weather conditions. Some Sichuan farmers have shifted their field operations to other crops, but the majority persist in planting rice because, for them, rice represents food security.

1.3. Plastic Cover on Raised-Beds Counters the Effects of Drought and Low Temperature, Resulting in High-Stable Rice Yields with Substantially Reduced N Inputs

Opportunely, a highly innovative integrated rice management system has been developed by Lu et al. [16] in Sichuan that addresses these two major production constraints of frequent drought and low temperature. It can boost rice yields even with a 36% reduction in the N fertilizer application rate [15]. Most importantly, it supports high yield even during drought years and reduces the risks of rice production failures, due to bad weather [17].

The plastic cover integrated technology (PCIT) reported on here combines the use of plastic film to cover the raised beds with improved agronomic practices from the System of Rice Intensification (SRI) [18] (Figure 1). SRI is a methodology of rice production developed in Madagascar in the 1980s. This methodology recommends growing seedlings in an unflooded nursery seedbed and transplanting them singly while still young, at the 2–3 leaf stage, with wide spacing between plants to encourage more tillering and greater root growth.

Figure 1. Plastic-covered raised beds irrigated only in the ditch, with triangular geometry of transplanting.

Wider spacing, it is observed, allows more sunlight to reach the base of the seedlings, which contributes to sturdier plants, better able to withstand the stresses of wind and rain from storms. Higher numbers of tillers per hill compensate for the wider spacing between plants because these tillers also produce more grain. Many of the late tillers produced by the plant are unproductive under Sichuan conditions, but a triangular transplanting method developed in this province minimizes the number of unproductive tillers associated with wide spacing [19]. Young seedlings are transplanted singly in a triangular pattern; the hills are spaced 40 × 40 cm in a square grid pattern across the field, with three seedlings planted in each hill 10–12 cm apart, forming a small equilateral triangle, as seen in Figure 2a. Figure 2b shows how three seedlings planted this way in a single hill with more distance between them grow more tillers compared to three seedlings being planted together in one hill, an insight from experience with the System of Rice Intensification.
Figure 2. (a) Sparse, triangular transplanting pattern seen after harvest; (b) On the left side, three seedlings planted in one hill in triangular pattern spaced 10–12 cm apart. The tillers are more profuse compared to the right with three seedlings planted in a bunch in one hill. The roots of the plants on the right, being close together, have less space to grow and spread.

The plastic-covered raised-beds have furrows between them that permit furrow irrigation which replaces flood irrigation and economizes on water. Since the raised beds are never submerged by flooding, their soil remains in mostly aerobic condition, keeping plant roots from suffocating and degrading, and supporting more abundant beneficial aerobic organisms in the soil. Weeds on the beds are not a problem because the plastic cover smothers them [20,21]. Also, by reducing surface evaporation and conserving soil moisture, the plastic cover significantly improves the crop’s drought-resistance [22–24], as can be seen in Figure 3. This methodology results to more vigorous plants compared to rice under traditional flooded conditions [25]; it saves water [15,22]; and it reduces the labor required for irrigation and weeding [15].
Figure 3. Rice plants on plastic-covered beds on left growing normally despite drought.

These integrated techniques can increase yield from 6.0 t ha\(^{-1}\) to 9.75 t ha\(^{-1}\) with a fertilizer application rate of only 120 kg N ha\(^{-1}\), which is two-thirds of what farmers usually use in Sichuan [26]. A seven-year study by Dong et al. in hilly areas of Sichuan [17], using the same integrated technology with plastic cover in raised beds, reported that an N fertilizer rate of 120 kg ha\(^{-1}\) was enough to ensure a reliably stable rice yield of 9 t ha\(^{-1}\). Fertilizer recovery efficiency is 32%, and the rate of N fertilizer loss is reduced by 40%.

While it is true that applying increased fertilizer enabled China to attain grain self-sufficiency, the standard recommended practices have been inefficient and have harmed the environment. Under China’s current nitrogen management, N discharge from croplands already exceeds acceptable thresholds in 14 out of 31 provinces [3]. Moreover, this excessive application of N fertilizer is not needed to support high yields of hybrid rice under conditions of moderate to high soil fertility [27]. Huang et al. propose that improving and maintaining soil fertility should be a prime focus for efforts to utilize the productivity of hybrid rice.

Results from long-term fertilization experiments (> 20 years) in China have indicated that combining manure with synthetic fertilizers can improve soil quality, while generating higher yields of rice, maize, and wheat, by 8.2–9.9% more than the yields obtained by using synthetic fertilizer alone [28]. Based on trials across six provinces in China, an International Rice Research Institute (IRRI) study concluded that the optimum rate for applying N fertilizer on rice crops is in the range of 60–120 kg ha\(^{-1}\)—Much less than was being widely used, i.e., over 300 kg ha\(^{-1}\) [29].

The PCIT offers a means to move the rice sector rapidly toward the goal of sustainable intensification by reducing such excessive N fertilizer use while maintaining high rice yields. It can also, as have seen below, decrease farmers’ costs of production and also labor input. The latter has become a serious constraint on agricultural production in China as much rural labor force has relocated or is relocating to cities. The contribution that PCIT can make to more sustainable agriculture will be enhanced by returning more plant biomass to the soil in combination with recycling animal manure to increase soil organic matter further.

These alterations in rice production methods build up the carbon in the soil rather than deplete it, thereby enhancing soil fertility. This process has the further benefit of reducing CO\(_2\) in the atmosphere, which is driving climate change. Carbon sequestration in the soil countervails the current momentum for global warming and reduces the environmental pollution caused by the current agricultural practice. The adoption of PCIT already on over 78,800 ha in Sichuan province—with 1200 ha of this area in fully-organic production, giving rice yields that exceed 7.5 t ha\(^{-1}\)—indicates that this methodology is ready to be scaled-up with multiple beneficial effects for China and indeed for other parts of the world.
1.4. Mode of Action of the Plastic Film Cover with Raised-Bed Technology

In cold regions, the soil temperature is critical during the early growth stage of rice. Using plastic cover can make the soil’s temperature in the early spring around 4.5 °C warmer than with traditional flooded-rice cultivation [15,17,30,31]. Warmer soil temperatures minimize the usual transplanting shock that occurs when seedlings are taken from their nursery and transplanted into the cold open field. The higher soil temperature enhances the vitality of rice roots [32] and supports more vigorous growth and a higher rate of tiller production [17,33]. Transplanting young seedlings at the 2–3 leaf stage as recommended with SRI methodology also increases tiller production [15]. Plastic film cover has been seen to result in 12% higher average yield, while using wheat straw as mulch led to a 14% lower average yield, compared with the results from lowland rice under traditional flooding [31]. These studies have shown that a higher soil temperature during the early stage of rice growth in the early spring is critically important for achieving high and stable yields in cold rice-producing regions.

Evidence also suggests that plastic film cover accelerates the rate of soil mineralization, increasing the release of nutrients into the soil and resulting in significantly higher soil N concentrations [34,35]. Plastic cover likewise increases the absorption of nutrients from the soil [25,36]. This is corroborated by a report by Li et al. [33] that plants under plastic cover experience no serious water stress and absorb nitrogen more actively. Dong et al. [17] reported that plastic cover increased the number of productive tillers by 33%, the rice grain yield by 33%, and NUE by 8%, showing simultaneous improvements in nitrogen use and rice production.

In addition to suppressing weeds, the plastic cover also is seen to inhibit crop diseases and insect pests [37,38]. It is worth noting that Chinese farmers increased their use of pesticides by 120% between 1991 and 2008 [39]. This has adverse effects on the soil biota and on water quality. So, lowering the incidence of pests and diseases, with a concomitant reduction in biocide applications will have positive implications for the health of the environment and also of human beings. In summary, the soil warming effect, the soil moisture retention, the acceleration of soil nutrient release, the increased absorption of nutrients, and the reduced incidence of pests and weeds, all brought about by using a plastic cover on permanent (no-till) raised beds, play tangible roles in improving and stabilizing rice yield.

1.5. Possibilities for Biodegradable Film Cover

The main drawback of this integrated technology is the collateral effect of some amount of plastic pollution. The plastic film made with new polyethylene (PE) materials (0.004 mm thick) is relatively intact after rice harvest, so it is fairly easy to peel off the raised bed for recycling, and farmers do collect and recycle it. This film costs 750 RMB ha⁻¹ (a little over $US 100 per hectare or $US 40 per acre, and about 7 RMB per mu). However, when the plastic sheets are removed, some small pieces can be torn off and remain in the field unless collected. It is not advisable to buy and use cheaper, thinner films as they are more difficult to remove thoroughly from the field.

Recognizing this as a problem, for the past several years, biodegradable film (black in color) has been tested at different locations. It has a programmable rate of degradation that satisfies the temperature requirement needed during the early rice-growing stage. So far, the results have been promising. The all-natural plant materials from which this film is made add to the soil’s organic matter when they decompose and supplement the nutrients in the plant residues [40,41]. Solving the “white pollution” issue associated with the white non-biodegradable plastic film will be essential for the spread of this technology.

There is an economic dimension to be considered. Biodegradable films can be manufactured in China and any country, but at present their cost, and thus, price is higher than for plastic made from fossil fuel materials, at least until large-scale production levels for plant-based plastics are attained. Currently, there are government subsidies for the purchase and use of inorganic N fertilizer. Because of the multiple benefits that PCIT offers, including less need for applying fertilizer, some or possibly much of the current fertilizer subsidies could be redirected to reduce the cost to farmers of buying.
biodegradable plastic film because it is in the public interest to reduce both the pollution of soil and water.

A lot is at stake. The costs of establishing nutrient recycling systems and pollution abatement are small relative to the current annual costs of water pollution, not considering the additional costs of soil and air pollution. It was estimated in 2010 that water pollution-imposed costs on China equal to 1.5% of its national GDP: US$ 20 billion for treating polluted water supplies plus US$ 71 billion to account for the adverse effects of environmental degradation [3]. As seen above, the excessive agricultural use of nitrogen is the largest contributor to this water pollution and to this cost. This subject will be discussed further in Section 3.6 below.

1.6. Issue of Long-Term Soil Sustainability with an Increase in Soil Mineralization Rate

Several studies have reported that plastic cover accelerates the rate of soil mineralization and increases the release of nutrients into the soil [30,31,42]. The improved hydrothermal conditions in soil under mulch increase microbial activity which can diminish soil organic carbon [43]. One of the major issues raised regarding the PCIT is its effect on the long-term sustainability of soil systems. In conservation agriculture (CA), the practice of no-tillage combined with continuous plant-biomass mulch increases soil organic matter, and over time it improves the physical, chemical and biological properties of the soil [44]. PCIT includes mulching with crop residues as the plant biomass more than compensates for any reduction in SOM attributable to the plastic cover.

In China, rice straw and other plant residues are still usually burned after harvest. As in many parts of the world, farmers burn their fields to eliminate stubble and weeds before they sow a new crop. This practice may be fast and economical, but it is undesirable and unsustainable. Open burning is the single largest source of black carbon in the air, accounting for more than a third of all black carbon emissions. So, this practice is a health hazard, as well as unpleasant and unsightly. While this air pollutant is short-lived compared to greenhouse gas emissions, it does contribute to air pollution, to climate change, and to increased melting in the cryosphere regions of snow and ice [45].

The village where this field experiment was conducted had been using PCIT for its organic rice production for six years. Rice straw was used for mulching the rapeseed (Brassica napus L.) crop that is planted after rice with no-till crop-establishment practices, seeding through mulch. The rapeseed production is intensified by intercropping Irish potatoes (Solanum tuberosum L.) and honey peas (Pisum sativum L.), both planted under the mulch without tillage. In the following rice season, however, the rapeseed residue is not returned to the soil because its bulky, woody stems impede rice planting. This is being changed, however, by introducing the use of a shredder that can chop up the rapeseed residue and return it to the soil in small, more easily decomposable pieces.

Would the continuous return of the residual plant biomass from both rice and rapeseed production further increase soil organic matter (SOM) and rice yield? What would be the combined effect of no-tillage, plant-biomass mulching, and plastic cover? Further, will a shift to fully-organic rice management, particularly the use of biogas slurry and rapeseed meal as organic fertilizers, be enough to increase and maintain soil organic matter and yield? A six-year experiment to address these questions was conducted combining plastic film cover with the Conservation Agriculture practices of no-tillage and crop-residue return in a rotation system of organic rice and rapeseed, also using appropriate crop management practices of SRI. The results are reported here.

2. Materials and Methods

2.1. Site Description

This on-farm experiment was conducted for six years in Shuanghe Village, Dongxi town, Jianyang City (E 104°36’, N 30°24’; 423 m.a.sl) in the Sichuan basin of southwest China. Mean annual temperature there is 17.1 °C, with annual precipitation of 830 mm/year [46]. The soil texture of the paddy fields
is mostly clay, with a 24.0% sand and 41.5% clay fractions; with 9.4 g kg\(^{-1}\) of organic carbon and 1.42 g kg\(^{-1}\) of total nitrogen concentration.

### 2.2. Experimental Design and Trial Management

The field experiment was conducted in an organic rice-rapeseed rotation system with four respective treatments, as shown in Table 1:

- **CT**—conventional tillage without plastic cover and without plant residue return
- **NTPC**—no tillage with only plastic cover in the rice season (no rice straw mulch in the rapeseed season).
- **NTCM**—no tillage with rapeseed plant residue mulch in the rice season and rice straw mulch in the rapeseed season (no plastic cover in the rice season).
- **NTCMPC**—no tillage with straw mulch and plastic cover in the rice season and straw mulch in the rapeseed season.

| Code   | Treatment                                      | No Tillage | Rice Season Mulch | Rapeseed Season Mulch |
|--------|------------------------------------------------|------------|-------------------|-----------------------|
| CT     | Conventional tillage                           |            | ✓                 | ✓                     |
| NTPC   | No-till with plastic cover                     | ✓          |                   |                       |
| NTCM   | No-till with crop mulch (rapeseed plant residue in rice, and rice straw in rapeseed) | ✓          | ✓                 | ✓                     |
| NTCMPC | No-till with both crop mulch and plastic cover (rapeseed plant residue for rice, and rice straw for rapeseed crop) | ✓          | ✓                 | ✓                     |

The treatments were all evaluated on raised beds with no-till practices. In the NTCM and NTCMPC treatments, after the rice was harvested, all the rice straw from the plot was left in the field. After the rapeseed was harvested, rapeseed plant residues were shredded into small pieces of 20–25 cm and left in the field. In the NTCMPC treatment, the middle of the beds had a furrow 10 cm depth and 10 cm wide, and the rapeseed residue was put back into these furrows; then the raised beds’ surface was flattened and covered with plastic film. In the NTPC and NTCMPC treatments, after making the soil soft with irrigation, raised beds were constructed and the surface flattened. Then the raised bed plot was covered with plastic film as previously described by Reference [16].

The raised beds were 145 cm wide, and the ditches on either side of the raised beds were 15 cm deep and 20 cm wide. There was no water layer above the surface of the raised beds; instead, irrigation water was distributed in the ditches between the raised beds. The raised beds were covered with transparent plastic film 0.004 mm thick and 175 cm wide. All the treatments had the same transplanting density (1.8 × 10^6 plant ha\(^{-1}\)).

The field experiment was a randomized complete block design with three replications. The size of all plots was 30 m\(^2\). In the rice season, each plot was supplied with 250 kg biogas slurry and 2.5 kg rapeseed meal. In the rapeseed season, only biogas slurry (350 kg) was applied. The average nutrient content of the organic fertilizer applied from 2012–2017 is shown in Table 2. In the rice season, each treatment received 113.7 kg N ha\(^{-1}\), 79.8 kg P\(_2\)O\(_5\) ha\(^{-1}\), and 100.5 kg K\(_2\)O ha\(^{-1}\); and in the rapeseed season, each received 93.3 kg N ha\(^{-1}\), 81.7 kg P\(_2\)O\(_5\) ha\(^{-1}\), and 122.5 kg K\(_2\)O ha\(^{-1}\). All the organic fertilizers were applied as basal fertilizer. The rice variety used was the local hybrid variety Chuanxiang 8108, and the rapeseed variety used was Nongyou No.1, supplied by the Institute of Crop Science, Sichuan Academy of Agricultural Sciences.
Table 2. Average nutrient content of biogas slurry and rapeseed meal of 2012 to 2017.

| Organic Fertilizer | Total N (g kg\(^{-1}\)) | Total P\(_2\)O\(_5\) (g kg\(^{-1}\)) | Total K\(_2\)O (g kg\(^{-1}\)) | pH |
|--------------------|--------------------------|--------------------------------------|---------------------------------|----|
| Biogas slurry      | 0.8                      | 0.7                                  | 1.05                            | 7.4 |
| Rapeseed meal      | 56.4                     | 25.8                                 | 15.6                            | 5.6 |

2.3. Crop Yield Measurements

At maturity, nine rice plants were collected at random from each plot to count the number of productive tillers. The grain yield was determined by harvesting the whole plot, excluding the outer two border rows, and weighing the grain, with yield calculated accordingly.

2.4. Soil Analyses

Surface soil was sampled randomly every season in all treatments at 0–5 cm depth. The sampling for soil organic carbon (SOC) was done after six years when the rapeseed crop was harvested. Soil texture was determined by using the pipette method [47]. Soil pH was measured in 1: 2.5 soil: water slurry using a combined electrode pH meter. The air-dried soil samples were pretreated with 0.5 mol L\(^{-1}\) HCl to remove carbonate and were then ground into powder in a ball mill (MM200, Retsch, Haan, Germany). Analyses for SOC and total N concentration (TN) content were performed using an EA1108 CHN elemental analyzer (Fisons Instruments, Germany) [24,48]. Total P concentration (TP) content in the soil was determined with Mo-Sb-Vc colorimetry, and total K concentration (TK) content in the soil was determined by flame photometry [49]. The total N content of rice and rapeseed straw was measured using the Kjeldahl method. The available N content of all soil samples was determined in a 1 mol L\(^{-1}\) NaOH extract, according to the method described by Bao [49], the available P content was determined in a 0.5 mol L\(^{-1}\) NaHCO\(_3\) extract, via spectrophotometer; the available K content was determined by flame photometry following extraction with 1 mol L\(^{-1}\) \(\text{NH}_4\)OA\(_C\) [49].

2.5. Statistical Analyses

Multiple comparisons of means were made with the Tukey-Kramer HSD at a 0.05 probability level. Analyses of variance were performed with the statistics analysis system (JMP10, SAS Institute, 2012). The statistical model used included sources of variation, due to year (containing the rainfall and temperature conditions in the year), tillage method, plastic cover, rice straw return, and rapeseed residue return. The level of statistical significance for figures is indicated by ns, *, **, *** indicating, respectively, not significant, significant at \(p < 0.05\), \(p < 0.01\) and \(p < 0.001\). The figures were made with SigmaPlot12.5 (Version 12.5, Systat Software, San Jose, CA, USA).

3. Results and Discussion

3.1. Effect of Biogas Slurry and Rapeseed Meal on Organic Rice Yield

As stated in the methodology, all the treatments during rice season received the same basic organic fertilizer application of 250 kg/plot biogas slurry (83.3 t ha\(^{-1}\)) and 2.5 kg/plot of rapeseed meal (0.83 t ha\(^{-1}\)). The rice yields of the different organic treatments from 2012 to 2017 are presented in Figure 4. These yields ranged from 7034 kg ha\(^{-1}\) with conventional tillage (CA) in 2016, to 10,672 kg ha\(^{-1}\) from no-tillage with crop mulch (NTCM) in 2017, with a mean of 8703 kg ha\(^{-1}\).
As expected, the CT which received only the basic organic fertilizer without any plant residue return and plastic cover registered the lowest six-year average yield of 8.3 t ha$^{-1}$. What is interesting in this average result is that the yield approximated the five-year average yield of 8.3 t ha$^{-1}$ reported by Dong et al. [17] when using the same PCIT but applying the recommended inorganic N fertilizer rate (120 kg ha$^{-1}$). These trials were conducted in the adjacent city of Ziyang with similar climatic and soil conditions.

The recommended N rate of 120 kg ha$^{-1}$ gives a stable high yield, while increasing NUE and reducing the pollution effects of N fertilizer overuse. Common applications of N are often 50% to 100% higher than 120 kg ha$^{-1}$, or even more. In this same study, the five-year average yield from farmers’ traditional practice when applying 180 kg N ha$^{-1}$ and not using the PCIT was 6.5 t ha$^{-1}$. The yield from all the organic treatments was higher than China’s national average of 6.5 t ha$^{-1}$ [50]. This is also much higher than the average rice yields for the world and for Southeast Asia noted above, 4.6 and 4.4 t ha$^{-1}$, respectively [2]. Our results indicate that the use of biogas slurry combined with oilcake meal can offer a satisfactory alternative to N fertilizer, which is widely overused at present. In the absence of biogas slurry, ordinary manure slurry combined with highly reduced amounts of N fertilizer could be another alternative, not assessed in this study. Replacing oilcake meal with chemical N fertilizer is cheaper in terms of N content, but the latter will not have as beneficial effects on the structure and functioning of soil systems. At any rate, in our trials, the amount of basic organic fertilizer (biogas slurry and rapeseed meal) applied in the rice season was the equivalent of 113.7 kg N ha$^{-1}$, 79.8 kg P$_2$O$_5$ ha$^{-1}$, and 100.5 kg K$_2$O ha$^{-1}$. The amount of N received approximates the 120 kg ha$^{-1}$ recommended by Dong et al. for sustainable and satisfactory rice production. This could be why organic management attained such an acceptable level of yield.

### 3.2. Effect of Plant Residue Return and Plastic Cover on Organic Rice Yield

An increasing yield trend was observed in all treatments, except for 2016, when the yield of all the treatments dropped because of rice blast disease during that year. The mean yield of all treatments in 2016 was 7531 kg ha$^{-1}$, i.e., 1202 kg ha$^{-1}$ lower than the five-year mean. NTCMPC (no-till with crop mulch and plastic cover) yielded the best among all treatments overall, at 9067 kg ha$^{-1}$, while CT (conventional tillage) had the lowest average yield, 8298 kg ha$^{-1}$. The overall lower yield of CT suggests that tillage might have a negative effect on rice yield because this was significantly lower than from the no-tillage treatments in 2012 and 2015.
The treatments of no-till with plastic cover (NTPC) and no-till with crop mulch and plastic cover (NTCMPC) were significantly higher than those treatments without plastic cover, i.e., CT and NTCM, only in the first year (2012). In the second, third, and fifth year (2013, 2014, and 2016), the combination of no-tillage and crop mulching practices (NTCM and NTCMPC) yielded similarly, and both were significantly higher than CT and NTPC. With a combination of the three practices—no tillage, crop residue return, and plastic cover—NTCMPC yielded highest among all practices in the first four years (2012 to 2015), but it was significantly higher than NTCM only in 2015.

Starting in the fifth year (2016), combining no-tillage and crop mulching practices without plastic cover application (NTCM) outperformed all of the other treatments and achieved the highest yield among the treatments with 10,673 kg ha\(^{-1}\) in 2017. NTCM yield was significantly higher than NTCMPC in the final year (2017), suggesting that the additional effect of plastic cover on top of the other two treatments might not be necessary to attain high rice yield after five years of returning plant residues to the soil.

This is an interesting result because in previous studies (1999 to 2001) of several researchers on the effects of plastic cover vs. wheat straw mulch on the yields of rice-wheat rotational cropping systems [15], it was reported that compared with traditional flooding of fields, non-flooded plastic cover resulted in a 12% higher average rice yield, while non-flooded wheat straw mulching decreased average rice yield by 14%. This trend was consistent over the years. Further analysis found that these yield differences were associated with increases in soil temperature under plastic cover, while there was a lower temperature under wheat straw mulch. In the PhD dissertation of Dong in 2019 (unpublished) [51], one of the authors of this article who studied the water retention and warming effect of the plastic cover, concluded that the key factors for the increase and stability of rice yield throughout the seven years were the water retention capability of plastic cover in drought years and its warming effect in rainy years (cold), particularly during the tilling stage. The major reason for the high adoption of this technology by farmers in Sichuan, China is the stable high yields despite severe weather fluctuations.

NTCM had a significantly higher yield than NTCMPC in the final year (2017) was surprising because the plastic cover is meant to counter the negative effects of low soil temperature and drought. Huang et al. [52] and Zhang et al. [32] found that the plastic cover exerted little effect on rice yield when water and temperature conditions were not the limiting factors. Might the continuous return of plant residues somehow modify soil conditions enough to modulate temperature effects and retain more soil moisture? Did the plastic cover exert little effect because water and temperature in 2017 were not limiting? That was not covered in this study. Does this mean that the plastic can eventually be eliminated? Alternatively, would the direction be for the correct management of plant residues in combination with biodegradable film to also be able to deal with the weeds? These questions deserve evaluation, also considering the effects of soil biology. If the soil biota is enhanced by changes in crop, soil, water and nutrient management practices, this might offset the effect of colder ambient temperatures, at least within a moderate range.

An analysis of the effects of introducing System of Rice Intensification practices in Sichuan between 2004 and 2010, when SRI use expanded from 1123 hectares to 301,067 hectares [53], showed that in the two years when the province had severe drought stress, 2006 and 2010, the yield advantage of SRI management was greater than in the other five years when precipitation was more normal. In the water-stressed years, average SRI yield was 20% greater than the yields of farmers who used conventional cultivation methods in the non-stressed seasons. This indicated that the effects of SRI practices, such as transplanting young seedlings and widely-spaced hills with single plants, complement and can add to the impact of plastic cover, no-till raised beds, and organic fertilization.
3.3. Effect of Biogas Slurry and Rapeseed Meal as Basic Organic Fertilizer, Return of Plant Residues, and Plastic Cover on Soil Organic Carbon (SOC)

After six years of annually applying as the basic organic fertilization, 250 kg/30 m^2 of biogas slurry (83.3 t ha\(^{-1}\)) plus 2.5 kg/30 m^2 of rapeseed meal (0.83 t ha\(^{-1}\)) during the rice season, and 350 kg/30 m^2 of biogas slurry (116.7 t ha\(^{-1}\)) during the rapeseed season, the results showed that the soil organic carbon with all the treatments was significantly increased (Figure 5), with a mean SOC of 25.2 g kg\(^{-1}\) compared to the baseline of 9.4 g kg\(^{-1}\) that was recorded in 2012 before the trials were started. SOC rose by 1.7 times the baseline SOC.

![Figure 5. Soil organic carbon (SOC) of the different treatments after six years compared with the baseline SOC and with the conventionally-managed chemical-applied field.](image)

The significantly higher SOC of all the treatment plots that received the biogas slurry and rapeseed meal indicates that biogas slurry application could be a good method to improve soil fertility sustainably, being also a practical and beneficial way to manage (dispose of) livestock wastes. Treatment 1, which received only the base organic fertilizer under conventional tillage with an organic rice-rapeseed rotation, reached a SOC level of 22.9 g kg\(^{-1}\), 144% above the baseline. This indicates that the application of biogas slurry and rapeseed meal is able to increase SOC substantially.

The treatments that received the basic organic fertilizer in combination with crop-residue mulch from rice straw and rapeseed (NTCM and NTCMPC) reached SOC levels of 28.0 g kg\(^{-1}\) and 25.9 g kg\(^{-1}\), respectively. Three and two-point-eight times compared to the baseline SOC. The plastic cover is well known to increase soil temperature [17,54], and consequently, to increase the rate of soil mineralization [43]. This would be the most likely explanation for why NTCMPC treatments registered lower SOC compared to NTCM. The SOC with NTCM trials was significantly higher than with the conventional tillage treatment (CT) that had received only the basic organic fertilizer. This confirms that the return of crop residues as mulch can significantly contribute to improving SOC, which is not surprising. That the SOC in the plastic-covered NTPC and NTCMPC plots showed no significant difference suggests that the plastic cover could even lessen the effect of crop residue in increasing SOC, which warrants further study.

NTCM, which had the highest SOC and available N, also registered the highest rice yield in 2017 when the soil samples were taken.
3.4. Effect of Biogas Slurry and Rapeseed Meal as Base Organic Fertilizer, Return of Plant Residues and Plastic Cover on Available NPK

Figure 6 shows that the treatments with plant residue return without plastic cover (NTCM) significantly increased available K but had no significant difference in terms of available N and P. NTCM had the highest available K (501.7 mg/kg). All organic treatments had significantly higher available N, P and K compared with the adjacent conventional chemical field as seen below.

Figure 6. Comparison of soil-available N, P, K associated with different treatments after six years. Same letters indicate that they are not significantly different.
In terms of total NPK (Figure 7), the organic treatments, including the return of plant residues significantly increased total N and P, but have no significant difference in terms of total K. Apparently the total K in the experimental site is inherently high. However, the return of plant residues significantly increased available K.

**Figure 7.** Comparison of total N, P, K associated with different treatments after six years. Same letters indicate that they are not significantly different.

The findings of this study showed that the use of biogas slurry and application of a more concentrated organic fertilizer in the form of rapeseed meal is sufficient to both attain high yield and to
increase the soil organic matter and soil nutrients compared to conventional chemical-based practice. Moreover, by combining the use of biogas slurry and rapeseed meal with the return of crop residues and plastic cover, rice yield and soil properties can be enhanced even more. The results of the practices evaluated demonstrated that by properly managing the agricultural waste that has become a serious source of non-point pollution in China, three objectives can be concurrently achieved: Maintaining high rice yield, improving soil fertility sustainably, and reducing the negative environmental effects of excessive nitrogen fertilizer. A fourth objective is discussed next, making good use of animal wastes so that they become an asset rather than a liability.

### 3.5. Management of Crop Residue and Livestock Waste for Sustainable Rice Intensification

Livestock manures in China are a significant source of nitrogen, phosphorus and potassium. Chadwick et al. [9] estimated the value of this manure resource to be 216 billion Yuan per year (over $US 30 million) at 2012 prices for N, P$_2$O$_5$ and K$_2$O. It is therefore prudent that this source of nutrients is used to enhance crop production, while reducing the overuse of N fertilisers, improving farmers’ incomes, and curbing the overall emissions of greenhouse gases associated with fertilizer production, distribution, and use [55].

There were in 2011, around 40 million rural household biogas plants and 4658 large biogas plants in China [56]. The use of biogas slurry offers a practical and productive way to manage livestock wastes, but the lack of appropriate machines and equipment for this is a constraint on its application. Applying the slurry with use of a water pump in a truck-mounted tank that can spray the slurry onto the mulch requires less labor than needed for the application of compost, and it gives quick, visible results for plant growth compared to the application of compost, although the application of inorganic N gives even more immediate results. Compost making, particularly the repeated turnings of the pile, requires a lot of working-days, which even some hard-core organic practitioners complain about. In a related project in Chongqing, China, where mulch was used with no-till vegetable production, the use of biogas slurry in combination with rice straw mulch was much preferred by farmers over the usual organic practice of compost making and application.

Biogas slurry may even prove to be a better organic fertilizer than compost. Abubaker et al. [57] reported that fertilization with biogas residues gave higher crop yield than inorganic NPK, and that biogas residues increased soil microbial activity. This is corroborated by the study of Pascual et al. [58] where the addition of fresh types of wastes (municipal solid waste or sewage sludge) had a more favourable effect on soil biological activity than did compost. These claims of the superiority of biogas slurry merit further study.

For non-organic rice production, replacing rapeseed meal with much-reduced amounts of N fertilizer in combination with the use of biogas slurry, returning plant residue, and using plastic cover could predictably result to high yields with lower cost compared to just providing rapeseed meal in terms of the N content.

### 3.6. Gene-Centered Rice Intensification vs. Improvement in Cultural Practices

Hybrid rice varieties are bred to be more responsive to high levels of N fertilization. Hence, the current crop intensification strategy combines planting hybrid varieties with high levels of N application. It appears that the emphasis given to promoting hybrid varieties in China may have unintentionally contributed to the greater use of N fertilizer to the point where it has become a source of soil and water pollution and greenhouse gas emissions.

The results of related experiments conducted by the authors in the same site and in a neighboring city in Sichuan (Table 3) show that the PCIT applied with a traditional (unimproved) rice cultivar could out-yield a popular hybrid variety grown with farmers’ conventional practices in both sites. However, when both traditional and hybrid varieties were cultivated under PCIT, the hybrid out-yielded the traditional variety at both sites. This showed, however, that gene-based rice intensification is not the only way to attain higher yields. Improvements in cultural practices can make significant contributions
to yield improvement, and this pathway can provide China with an opportunity to conserve in situ its dwindling genetic diversity of its rice. The much-awarded research in Yunnan province which showed that mixed planting of 2–4 rice varieties could reduce losses from the dreaded blast disease [59] is a reminder to both farmers and researchers of the value of maintaining rice genetic diversity.

### Table 3. Rice yield of traditional and hybrid varieties under conventional and plastic cover integrated technology (PCIT) cultivation methods.

| Experimental Site | Rice Variety          | Conventional Method (tons/ha) | Integrated Plastic Cover (tons/ha) |
|-------------------|-----------------------|------------------------------|----------------------------------|
| 1. Ziyang, Sichuan| Guiyu no.7 (traditional variety) | 6.30                         | 7.65                             |
|                   | Chuanxiang 8108 (hybrid)         | 6.52                         | 8.80                             |
| 2. Jianyang, Sichuan| Guiyu no. 7 (traditional variety) | 5.50                         | 6.75                             |
|                   | Chunaxiang 8108 (hybrid)         | 5.85                         | 8.00                             |

### 3.7. Use of Biodegradable Film Cover to Solve the Plastic-Cover Pollution Issue

Plastic film cover can boost crop yields and is increasingly becoming more popular in many countries. However, even with judicious recycling efforts, small plastic fragments are left in the field, contributing to environmental pollution [60,61]. Environmental concerns over plastic pollution have led to the development of biodegradable film cover that can be used instead of polyethylene film. The technology is now mature in other parts of the world, with programmable rates of degradation controlled by varying the starch content of the material. In China, the biodegradable film is available on the market, but its use is still very limited. Like biomass, biodegradable plastic film is decomposed by microbial activity in the soil and converted into carbon dioxide, water, and natural substances [62]. Hence, this is an environmentally-friendly alternative to the plastic cover.

Multi-location testing of degradable film cover under PCIT in rice has shown that it can fulfill the functions of the plastic film without resulting pollution. This alternative eliminates the cost of labor for removing the plastic film after harvest, which takes about 10 working-days ha$^{-1}$. However, there is still a substantial disadvantage of the higher current cost of biodegradable film, which is three to four times more expensive than polyethylene. That cost should come down substantially as the demand for biodegradable film increases, and it is produced on a much larger scale. The multiple benefits from this material which were discussed in Section 1.5 above could reasonably justify some subsidization by the government.

### 3.8. Ecological Footprint and Pollution Reduction

One consideration in favor of using plastic film cover is that it reduces the amount of greenhouse gas emissions which result from the production of fertilizer and pesticides (aggregating all greenhouse gases in terms of their CO$_2$ equivalence). The emissions saved (diminished) by reducing fertilizer and pesticide use by the introduction of plastic film to increase rice production will be substantial compared with present practice. Moreover, if the additional income from increased rice yield is considered, along with the value of having reduced pollution when less nitrogen and pesticides are used, the use of plastic cover becomes quite justifiable economically.

To make an estimate of the value of PCIT’s environmental impact, the carbon footprint of N fertilizer reduction with the new technology is presented in Table 4. The computation was based on the CO$_2$ emission rate for producing 1 kg N in the form of urea as derived by Wood and Cowie [63]. Rice farmers in China currently apply 215 kg of N fertilizer ha$^{-1}$ season$^{-1}$ on average, so this was used as the basis of calculation, although in rice-producing areas in southeast China, normal practice applies 240 to 280 kg/ha N [64,65].
### Table 4. Carbon footprint comparison of N fertilizer saved per season: Conventional chemical, chemical PCIT, and organic PCIT.

| Cultivation Method | N Fertilizer Used (kg/ha) | N Fertilizer Saved (kg/ha) | CO₂ Emissions Saved from N/ha * (kg/ha) | Adoption Area (ha) | N Fertilizer Saved (tons) | CO₂ Emissions Saved from N (tons) |
|--------------------|---------------------------|---------------------------|----------------------------------------|-------------------|--------------------------|----------------------------------|
| Conventional       | 215                       | 0                         | NA                                     | NA                | NA                       | NA                               |
| Chemical PCIT      | 0                         | 215                       | 8644                                   | 1200              | 258,000                  | 1037                             |
| Organic PCIT       | 120                       | 95                        | 382                                    | 77,600            | 7,372,000                | 29,643                           |
| Total              |                           |                           |                                        |                   |                          | 7,630,000                        |

* Note: 1 kg N from urea is equivalent to 4.0189 kg CO₂ emission as derived by Reference [64].

PCIT as currently practiced requires only about 56% of the N fertilizer input of conventional chemical-dependent practice. An application rate of 120 kg N ha⁻¹ is enough to achieve a reliably stable rice yield of 9 t ha⁻¹ with N fertilizer recovery efficiency of 32%. This would reduce the N fertilizer loss rate by 40% [17]. The area of PCIT adoption in Sichuan with reduced, but still some N fertilizer utilization reached more than 77,600 ha in 2019, while fully-organic PCIT (which discontinues N fertilizer use) is 1200 ha. By these changes, the carbon footprint for this area is reduced by 30,680 tons of CO₂ per season. In addition, there would be reductions not considered here from reduced use of agrochemicals for crop protection.

The reduction of N fertilizer’s carbon footprint is, thus, already, with the limited spread of PCIT use, making a contribution to climate-change mitigation. At the current price of N from urea fertilizer (US$ 517/ton) [66], the savings from PCIT for farmers who still use some (but reduced) N fertilizer has reached US$ 3.94 million per crop season. This is a substantial benefit for farmers, augmenting the financial gains that they get from increased yield because it reduces their input costs. Moreover, these numbers do not take account of the value of the irrigation water that is saved by using plastic film. In the decades ahead, with greater water scarcity, the value of water that does not need to be devoted to rice production to meet basic food needs will keep rising for society even if it is not an economic cost to farmers.

For organic PCIT, the biogas slurry application is 33.3 tons/ha. For the 1200 ha of organic PCIT, 39,960 tons of biogas slurry would be utilized. This is a by-product of producing biogas which already brings great value to households and communities. With the increasing demand for livestock products coming from a burgeoning population, and with changing dietary preferences for animal protein, greater quantities of manure will be generated in the years ahead [9]. This represents a real cost to society even if it is not calculated in financial terms. Disposing of manure without utilizing its nutrients represents an opportunity cost that should be considered and recouped by policy-makers. Proper and productive handling of animal wastes will have both health and aesthetic benefits for the human population.

Combining biogas slurry with much-reduced amounts of inorganic N can maintain high rice yields, while improving NUE. It will dispose of animal waste products in a beneficial way rather than having them add to environmental pollution. If these nutrients seep into the water supply and cause nutrient gluts in lakes, rivers and waterways, this imposes environmental harm and costs that should be avoided. Scaling up the combined use of organic and inorganic nutrients could turn the great and growing amount of livestock waste into a resource. The lack of appropriate implements and facilities at the farm level for handling and applying digestate is a major impediment at present, however, and we will consider this below.
4. Conclusions and Recommendations

The excessive use of N fertilizer in rice production combined with the mismanagement of livestock waste has led to severe N pollution problems in China. Using the innovative PCIT for rice production counteracts the constraints of drought and low temperature to achieve high and stable rice yields with lower use of N fertilizer. The effects of using both crop residues and plastic film on no-till raised beds with System of Rice Intensification practices were studied for six years.

Organic fertilization with biogas slurry and rapeseed meal for all the treatments significantly increased yield, as well as soil organic matter (SOM), and available soil N compared to the baseline SOM. This combination of practices under organic management consistently attained yields higher than the current China average yield of 6.5 t ha\(^{-1}\). The combination of no-tillage and both plastic cover and crop-residue mulch registered an average yield of 9.07 t ha\(^{-1}\), 8.4% more than with conventional rice management.

With positive results in using biodegradable film, which avoids plastic pollution, this multi-faceted technology could holistically address the goals of higher rice yields that are stable even in drought years, while decreasing the use of N fertilizer without any yield penalty, indeed with gains in yield. This technology provides a practical means to productively manage the problem of increasing livestock waste, while at the same time raising the levels of soil organic matter and soil nutrients, bringing degraded rice lands back into higher production. It can also help farmers to cope with the water shortages that are expected to increase, due to climate change. The shortage of appropriate equipment for applying slurry is a constraint for the spread of this methodology. Designing and producing such equipment to be sold at reasonable prices should be a policy priority for both economic and environmental reasons. This should be part of a larger strategy for formulating and implementing policies that support sustainable crop intensification, particularly in the rice sector, but also for the agricultural sector as a whole. In China and elsewhere, it will be important to move agricultural policy beyond a narrow view of crop intensification as just optimizing N fertilizer applications with an emphasis on introducing more N-responsive new varieties. A broader strategy would aim to make better use of under-utilized and polluting agricultural resources, making them into an asset rather than a liability, with far-reaching economic and environmental implications.

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References
1. Lu, Y.; Chadwick, D.; Norse, D.; Powlson, D.; Shi, W. Sustainable intensification of China’s agriculture: The key role of nutrient management and climate change mitigation and adaptation. Agric. Ecosyst. Environ. 2015, 100, 1–4. [CrossRef]
2. FAO Statistics Division FAOSTAT. Available online: http://www.fao.org/faostat/en/ (accessed on 15 June 2019).
3. Yu, C.; Huang, X.; Chen, H.; Godfray, H.C.J.; Wright, J.S.; Hall, J.W.; Gong, P.; Ni, S.; Qiao, S.; Huang, G.; et al. Managing nitrogen to restore water quality in China. Nature 2019, 567, 516. [CrossRef] [PubMed]
4. United Nations; Department of Economic and Social Affairs; Population Division. World Population Prospects: The 2017 Revision, Data Booklet. ST/ESA/SER.A/401. 2017. Available online: https://population.un.org/wpp/Publications/Files/WPP2017_DataBooklet.pdf (accessed on 30 March 2019).
5. Ministry of Agriculture of the People’s Republic of China. Action Plan for Zero Growth in the Application of Fertilizer by 2020. Available online: http://jiuban.moa.gov.cn/zwlml/tzgg/tz/201503/20150318_4444765.htm (accessed on 30 March 2019). (In Chinese)

6. Ma, L.; Zhang, W.F.; Ma, W.Q.; Vethof, G.L.; Oenema, O.; Zhang, F.S. An analysis of developments and challenges in nutrient management in China. J. Environ. Qual. 2013, 42, 951–961. [CrossRef] [PubMed]

7. Zhang, S.; Gao, P.; Tong, Y.; Norse, D.; Lu, Y.; Powolson, D. Overcoming nitrogen fertilizer over-use through technical and advisory approaches: A case study from Shaanxi Province, northwest China. Agric. Ecosyst. Environ. 2015, 209, 89–99. [CrossRef]

8. The Chinese Are Eating More Meat than ever before, and the Planet Can’t Keep up. Available online: https://www.motherjones.com/environment/2018/07/the-chinese-are-eating-more-meat-than-ever-before-and-the-planet-cant-keep-up/ (accessed on 31 July 2018).

9. Chadwick, D.; Jia, W.; Tong, Y.; Yu, G.; Shen, Q.; Chen, Q. Improving manure nutrient management towards sustainable intensification in China. Agric. Ecosyst. Environ. 2015, 209, 34–46. [CrossRef]

10. Ministry of Water Resources of China. Groundwater Monthly Bulletin: January 2016 (P2). Available online: http://www.mwr.gov.cn/sj/tjgb/dxsdtlyb/201702/t20170214_860969.html (accessed on 12 April 2019).

11. Zhang, F.; Cui, Z.; Chen, X.; Ju, X.; Shen, J.; Chen, Q.; Liu, X.; Zhang, W.; Mi, G.; Fan, M.; et al. Integrated nutrient management for food security and environmental quality in China. In Advances in Agronomy; Sparks, D.L., Ed.; Academic Press: Cambridge, MA, USA, 2012; Volume 118, pp. 1–40.

12. Improved Nutrient Management in Agriculture—a Neglected Opportunity for China’s Low Carbon Growth Path. Available online: http://www.sainonline.org/SAIN-Website(English)/download/PolicyBrief%20No1final.pdf (accessed on 12 April 2019).

13. Qin, Y.; Yan, H.; Liu, J.; Dong, J.; Chen, J.; Xiao, X. Impacts of ecological restoration projects on agricultural productivity in China. J. Geogr. Sci. 2013, 23, 404–416. [CrossRef]

14. Xu, F.X.; Xiong, H. Gene-Pool Structure and High-Yield Cultivation of Hybrid Rice High-Yield Species; China Agricultural Science and Technology Press: Beijing, China, 2015; Volume 1, pp. 1–20. (In Chinese)

15. Lu, S.; Dong, Y.; Yuan, J.; Lee, H.; Padilla, H. A high–yielding, water–saving innovation combining SRI with plastic cover on no-till raised beds in Sichuan, China. Taiwan Water Conserv. 2013, 61, 94–109. (In English)

16. Lu, S.H.; Zeng, X.Z.; Ren, G.J.; Zhang, F.S. Water-saving high yield integrated film mulching technology on paddy. Sci. Technol. Sichuan Agric. 2009, 20, 25. (In Chinese)

17. Dong, Y.J.; Zeng, F.W.; Yuan, J.; Zhang, G.B.; Chen, Y.X.; Liu, X.J.; Hilario, P.; Ren, T.S.; Lu, S.H. Integrated rice management to simultaneously improve rice yield and nitrogen use efficiency in various paddy field environments. Pedosphere 2019, accepted.

18. Uphoff, N. The System of Rice Intensification (SRI): Responses to Frequently-Asked Questions; SRI-Rice, Cornell University: Ithaca, NY, USA, 2015; Available online: http://sri.cals.cornell.edu/aboutsri/SRI_FAQs_Uphoff_2016.pdf (accessed on 21 June 2019).

19. Fan, M.; Lu, S.; Jiang, R.; Liu, X.; Zhang, F. Triangular transplanting pattern and split nitrogen fertilizer application increase rice yield and nitrogen fertilizer recovery. Agron. J. 2009, 101, 1421–1425. [CrossRef]

20. Zhao, X.; Lin, C.; Xu, M.; Huang, J.; Chen, Y.; Li, C.; Cai, Q. Effect of film-mulched treatment on weed diversity in rice field. Biodivers. Sci. 2009, 19, 195–200.

21. Dong, Y.; Yuan, J.; Lu, S. Effect of long-term different cultivation modes and N applications on diversity of weed communities in oilseed rape fields under rice-oilseed rape rotation system. Southwest China J. Agric. Sci. 2015, 28, 1027–1032. (In Chinese)

22. Liu, X.; Ai, Y.; Zhang, F.; Lu, S.; Zeng, X.; Fan, M. Crop production, nitrogen recovery and water use efficiency in rice–wheat rotation as affected by non-flooded mulching cultivation (NFMC). Nutr. Cycl. Agroecosys. 2005, 71, 289–299. [CrossRef]

23. Zhang, L.; Lin, S.; Bouman, B.A.M.; Xue, C.; Wei, F.; Tao, H.; Yang, X.; Wang, H.; Dittert, K. Response of aerobic rice growth and grain yield to N fertilizer at two contrasting sites near Beijing, China. Field Crops Res. 2009, 114, 45–53. [CrossRef]

24. Tao, Y.; Zhang, Y.; Jin, X.; Saiz, G.; Jing, R.; Guo, L.; Liu, M.J.; Shi, J.C.; Zuo, Q.; Tao, H.B.; et al. More rice with less water-evaluation of yield and resource use efficiency in ground cover rice production system with transplanting. Eur. J. Agron. 2015, 68, 13–21. [CrossRef]
25. Lu, X.; Wu, L.; Zheng, Z.; Kong, X.; Zhang, F. Physiological characteristics of nitrogen nutrition and stress-resistance of film-mulched rice in various ecological regions of Zhejiang Province. *J. Appl. Ecol.* 2005, 16, 273–278. (In Chinese)

26. Fan, M.S.; Jiang, R.F.; Zhang, F.S.; Lu, S.H.; Liu, X.J. Nutrient management strategy of paddy rice-upland crop rotation system. *J. Appl. Ecol.* 2008, 19, 424–432. (In Chinese)

27. Huang, M.; Jiang, P.; Shan, S.; Gao, W.; Ma, G.; Zou, Y.; Uphoff, N.; Yuan, L.P. Higher yields of hybrid rice do not depend on nitrogen fertilization under moderate to high soil fertility conditions. *Rice* 2017, 10, 43. [CrossRef]

28. Li, Z.; Xu, M.; Zhang, H.; Zhang, W.; Gao, J. Grain yield trends of different food crops under long-term fertilization in China. *Sci. Agric. Sin.* 2009, 42, 2407–2414.

29. Peng, S.B.; Buresh, R.J.; Huang, J.L.; Zhong, X.H.; Zou, Y.B.; Yang, J.C.; Wang, G.H.; Liu, Y.Y.; Tan, Q.Y.; Cui, K.; et al. Improving nitrogen fertilization in rice by site-specific nutrient management: A review. *Agron. Sustain. Dev.* 2010, 30, 649–656. [CrossRef]

30. Li, Y.S.; Wu, L.H.; Zhao, L.M.; Lu, X.H.; Fan, Q.L.; Zhang, F.S. Influence of continuous plastic film mulching on yield, water use efficiency and soil properties of rice fields under non-flooding condition. *Soil Tillage Res.* 2007, 93, 370–378. [CrossRef]

31. Liu, M.; Lin, S.; Dannenmann, M.; Tao, Y.; Saiz, G.; Zuo, Q.; Sippel, S.; Wel, J.; Gao, J.; Cai, X.; et al. Do water-saving ground cover rice production systems increase grain yields at regional scales? *Field Crops Res.* 2013, 150, 19–28. [CrossRef]

32. Zhang, Y.; Liu, M.; Saiz, G.; Dannenmann, M.; Guo, L.; Tao, Y.; Shi, J.; Zuo, Q.; Butterbach-Bahl, K.; Li, G.; et al. Enhancement of root systems improves productivity and sustainability in water saving cover rice production system. *Field Crops Res.* 2017, 213, 186–193. [CrossRef]

33. Li, S.; Zuo, Q.; Jin, X.; Ma, W.; Shi, J.; Ben-Gal, A. The physiological processes and mechanisms for superior water productivity of a popular ground cover rice production system. *Agric. Water Manag.* 2018, 201, 11–20. [CrossRef]

34. Wang, J.K.; Zhang, J.H.; Xu, X.C.; Zhang, X.; Cheng, F.; Sun, X.W.; Lin, L.P.; Chen, E.F. Effect of long-term covering with plastic film on characteristics of nitrogen in soil. *Plant Nutr. Fertil. Sci.* 1996, 2, 125–130.

35. Chen, Z.; Lin, S.; Yao, Z.; Zheng, X.; Gschwendtner, S.; Schloter, M.; Liu, M.; Zhang, Y.; Butterbach-Bahl, K.; Dannenmann, M. Enhanced nitrogen cycling and N2O loss in water-saving ground cover rice production systems (GCRPS). *Soil. Biol. Biochem.* 2018, 121, 77–86. [CrossRef]

36. Zheng, L.; Pei, J.; Jin, X.; Schaeffer, S.; An, T.; Wang, J. Impact of plastic film mulching and fertilizers on the distribution of straw-derived nitrogen in a soil-plant system based on 15N-labeling. *Geoderma* 2018, 317, 15–22. [CrossRef]

37. Summers, C.G.; Stapleton, J.J. Use of UV reflective mulch to delay the colonization and reduce the severity of Bemisia argentifolii (Homoptera: Aleyrodidae) infestations in cucurbits. *Crop Prot.* 2002, 21, 921–928. [CrossRef]

38. Ngouajio, M.; Auras, R.; Fernandez, R.T.; Rubino, M.; Counts, J.W.; Kijchavengkul, T. Field performance of aliphatic-aromatic copolyester biodegradable mulch films in a fresh market tomato production system. *HortTechnology* 2008, 18, 605–610. [CrossRef]

39. Sun, B.; Zhang, L.; Yang, L.; Zhang, F.; Norse, D.; Zhu, Z. Agricultural non-point source pollution in China: Causes and mitigation measures. *Ambio* 2012, 41, 370–379. [CrossRef] [PubMed]

40. Feuilloley, P.; Cesar, G.; Benguigui, L.; Grohens, Y.; Pillin, I.; Bewa, H.; Lefaux, S.; Jamal, M. Degradation of polyethylene designed for agricultural purposes. *J. Polym. Environ.* 2005, 13, 349–355. [CrossRef]

41. Zumstein, M.T.; Schintlmeister, A.; Nelson, T.F.; Baumgartner, R.; Woebken, D.; Wagner, M.; Kohler, H.; McNeill, K.; Sander, M. Biodegradation of synthetic polymers in soils: Tracking carbon into CO2 and microbial biomass. *Sci. Adv.* 2018, 4, eaas9024. [CrossRef]

42. Liu, X.J.; Wang, J.C.; Lu, S.H.; Zhang, F.S.; Zeng, X.Z.; Ai, Y.W.; Peng, S.B.; Christie, P. Effects of non-flooded mulching cultivation on crop yield, nutrient uptake and nutrient balance in rice-wheat cropping systems. *Field Crops Res.* 2003, 83, 297–311. [CrossRef]

43. Liu, X.E.; Li, X.G.; Hai, L.; Wang, Y.P.; Fu, T.T.; Turner, N.C.; Li, F.M. Film-mulched ridge–furrow management increases maize productivity and sustains soil organic carbon in a dryland cropping system. *Soil Sci. Soc. Am. J.* 2014, 78, 1434–1441. [CrossRef]
44. Palm, C.; Blanco-Canqui, H.; DeClerck, F.; Gatere, L.; Grace, P. Conservation agriculture and ecosystem services: An overview. *Agric. Ecosyst. Environ.* **2014**, *187*, 87–105. [CrossRef]

45. International Cryosphere Climate Initiative. Open Burning. Available online: [http://iccinet.org/open-burning/](http://iccinet.org/open-burning/) (accessed on 12 April 2019).

46. China Meteorological Data Service Center. Dataset of Annual Surface Observation Values in Individual Years (1981–2010) in China. Available online: [http://data.cma.cn/en/?r=data/detail&dataCode=A.0029.0005](http://data.cma.cn/en/?r=data/detail&dataCode=A.0029.0005) (accessed on 25 March 2019).

47. Gee, G.W.; Bauder, J.W. Particle-size analysis. In *Methods of Soil Analysis, Part 1: Physical and Mineralogical Methods*; Klute, A., Ed.; Soil Science Society of America Book Series; American Society of Agronomy and Soil Science Society of America: Madison, WI, USA, 1986; pp. 404–410.

48. Liu, M.; Dannenmann, M.; Lin, S.; Saiz, G.; Yan, G.; Yao, Z.; Pelster, D.E.; Zhang, Y. Ground cover rice production systems increase soil carbon and nitrogen stocks at regional scale. *Biogeosciences* **2015**, *12*, 4831–4840. [CrossRef]

49. Bao, S. *Analysis of Soil and Agricultural Chemistry*; Chinese Agricultural Press: Beijing, China, 2008. (In Chinese)

50. International Rice Research Institute. China and IRRI. Available online: [https://www.irri.org/where-we-work/countries/china](https://www.irri.org/where-we-work/countries/china) (accessed on 12 April 2019).

51. Dong, Y.J. *Rice production systems increase soil carbon and nitrogen stocks at regional scale*. *Agric. Sustain. Dev.* **2019**, *32*, 50–62. [CrossRef]

52. Huang, X.Y.; Xu, Y.C.; Shen, Q.R.; Zhou, C.L.; Yin, J.L.; Dittert, K. Water use efficiency of rice crop cultivated under waterlogged and aerobic soil mulched with different materials. *J. Soil Water Conserv.* **2003**, *17*, 140–143. (In Chinese)

53. Zheng, J.G.; Chi, Z.Z.; Li, X.Y.; Jiang, X.L. Agricultural water saving possible through SRI for water management in Sichuan, China. *Taiwan Water Conserv.* **2013**, *61*, 50–62.

54. Sintim, H.Y.; Bandopadhyay, S.; English, M.E.; Bary, A.I.; DeBruyn, J.M.; Schaumann, G.E. Plastic mulching in agriculture: Trading short-term agronomic benefits for long-term soil degradation? *Sci. Total Environ.* **2016**, *550*, 690–705. [CrossRef]

55. Kasirajan, S.; Ngouajio, M. Polyethylene and biodegradable mulches for agricultural applications: A review. *Agron. Sustain. Dev.* **2012**, *32*, 501–529. [CrossRef]

56. Abubaker, J.; Risberg, K.; Pell, M. Biogas residues as fertilisers—effects on wheat growth and soil microbial activities. *Appl. Energy* **2012**, *99*, 126–134. [CrossRef]

57. Steinmetz, Z.; Wollmann, C.; Schaefer, M.; Buchmann, C.; David, J.; Tröger, J.; Muñozac, K.; Frör, O.; Schaumann, G.E. Plastic mulching in agriculture: Trading short-term agronomic benefits for long-term soil degradation? *Sci. Total Environ.* **2016**, *550*, 690–705. [CrossRef]

58. Pascual, J.A.; Garcia, C.; Hernandez, T.; Ayuso, M. Changes in the microbial activity of an arid soil amended with urban organic wastes. *Biol. Fertil. Soils* **1997**, *24*, 429–434. [CrossRef]

59. Zhu, Y.; Chen, H.; Fan, J.; Wang, Y.; Li, Y.; Chen, J.; Fan, J.; Yang, S.; Hu, L.; Leung, H.; et al. Genetic diversity and disease control in rice. *Nature* **2000**, *406*, 718. [CrossRef] [PubMed]

60. Liu, E.K.; He, W.Q.; Yan, C.R. ‘White revolution’ to ‘white pollution’—Agricultural plastic film mulch in China. *Environ. Res. Lett.* **2014**, *9*, 091001. [CrossRef]

61. Kasirajan, S.; Ngouajio, M. Polyethylene and biodegradable mulches for agricultural applications: A review. *Agron. Sustain. Dev.* **2012**, *32*, 501–529. [CrossRef]

62. Wood, S.; Cowie, A. A review of greenhouse gas emission factors for fertiliser production. Report for International Energy Agency (IEA) Bioenergy Task 38, June 2004. Research and Development Division, State Forests of New South Wales. Available online: [http://www.scientheearth.com/uploads/24/6/5/24658156/2004_wood_a_review_of_greenhouse_gas_emission_factors.pdf](http://www.scientheearth.com/uploads/24/6/5/24658156/2004_wood_a_review_of_greenhouse_gas_emission_factors.pdf) (accessed on 12 April 2019).

63. Wood, S.; Cowie, A. A review of greenhouse gas emission factors for fertiliser production. Report for International Energy Agency (IEA) Bioenergy Task 38, June 2004. Research and Development Division, State Forests of New South Wales. Available online: [http://www.scientheearth.com/uploads/24/6/5/24658156/2004_wood_a_review_of_greenhouse_gas_emission_factors.pdf](http://www.scientheearth.com/uploads/24/6/5/24658156/2004_wood_a_review_of_greenhouse_gas_emission_factors.pdf) (accessed on 12 April 2019).

64. Li, Y.; Yang, L.Z.; Wang, C. Evaluation of fertilizing schemes for direct-seeding rice fields in Taihu Lake Basin, China. *Turk. J. Agric. For.* **2010**, *34*, 83–90.

65. Qiao, J.; Yang, L.Z.; Yan, T.M.; Xue, F.; Zhao, D. Nitrogen fertilizer reduction in rice production for two consecutive years in the Taihu Lake area. *Agric. Ecosyst. Environ.* **2012**, *146*, 103–112. [CrossRef]
66. Yang, Y.; Ni, X.; Zhou, Z.; Yu, L.; Liu, B.; Yang, Y.; Wu, Y. Performance of matrix-based slow-release urea in reducing nitrogen loss and improving maize yields and profits. *Field Crops Res.* **2017**, *212*, 73–81. [CrossRef]

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