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# Costs and benefits of crop residue retention in a Chinese subsistence farming system

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## Costs and benefits of crop residue retention in a Chinese subsistence farming system

### 1. Introduction

The use of conservation agriculture (CA) as a paradigm for broader livelihood development in developing countries initially started in Africa, and has recently spread into parts of Asia.

The supply of CA advice and adoption incentives doesn't appear to be matched by farm household demand. One potential reason for this mismatch is that the enthusiasm of CA adoption is often based on agronomic plot-level studies, and rural households generally operate in a broader environment with farm-level constraints, objectives and non-agronomic factors all entering household decision-making processes.

Cropping systems that use reduced tillage and crop residue retention often increase grain yields and improve environmental outcomes (Knowler and Bradshaw, 2007; Giller *et al.*, 2009; Giller *et al.*, 2011). Numerous field experiments have analysed the production effects of either full residue removal or retention (Fischer *et al.*, 2002; Malhi and Lemke, 2007; Huang *et al.*, 2008; Bakht *et al.*, 2009; Aulakh *et al.*, 2012) or using different amounts of crop residue as mulch (Maskina *et al.*, 1993; Govaerts *et al.*, 2005; Mupangwa *et al.*, 2012).

Trade-offs exist in the role of residues in a) boosting grain yields b) providing a resource for livestock feed, home heating and cooking and c) providing ground cover to reduce erosion potential. These trade-offs are more critical in areas of lower net incomes, high livestock dependence, cold climates, or highly erodible soils, for example large areas of western China. Evidence from other regions suggests that not all residues need to be retained to gain the benefits of residue retention. For example, zero tillage treatments with 30% residue retention produced the same grain yields as treatments with full residue retention in

Mexico (Govaerts *et al.*, 2005). However, even if no grain yield penalties exist, grain and crop residues have different economic values.

Questions remain regarding whether mulching is the most sensible, efficient or profitable use of crop residues (Giller *et al.*, 2009), and the role of residues in influencing economic returns appears an open question with implications for agricultural development. From a broader perspective, Erenstein (2011) and Valbuena *et al.* (2012) used comprehensive survey data to highlight that many different typologies of rural households rely heavily on residues to feed livestock, with demand being especially strong when biomass production is limited. More generally, the attractiveness of using residues as a mulch for rural households will be related to the aggregate costs and benefits of residue retention (Erenstein, 2002). In this article we examine economic, production and environmental trade-offs that exist in relation to different crop residue retention practices in western China. To achieve this we simulate long-run field-level yields and economic returns associated with different levels of crop residue retention in the Dingxi Prefecture, Gansu Province, northwest China.

## **2. Methodology**

### *2.1. Study site*

Rural households in the Dingxi Prefecture are mainly subsistence oriented, reliant on off-farm income and have income levels well below those observed in local urban centres (Nolan *et al.*, 2008). Predominate crops grown among these households include spring wheat (*Triticum aestivum* L.), field pea (*Pisum arvense* L.) and potatoes (*Solanum tuberosum* L.), with households also raising small ruminants (Nolan *et al.*, 2008). The climate is semi-arid, with median annual rainfall between 1970 and 2010 being 384 mm, ranging from 246

mm in 1982 to 565 mm in 2003. Approximately two-thirds of annual rainfall is received between May and August. Temperatures range from a maximum average in July of 26 °C to a minimum average of -13°C in January. On average there are 157 days per year with a minimum below 0 °C.

A survey conducted by Nolan *et al.* (2008) in 2003 provides data on the basic structural characteristics of 46 rural households in the Dingxi Prefecture. Over the 46 farms interviewed the median population density was five people per hectare, this was calculated as the median number of people in a household divided by the median farm size in hectares (total land including uncultivated). The median farm livestock density was 0.8 tropical livestock units (TLU) per hectare. This was calculated as the median farm's TLU divided by the median farm size, with one TLU being equivalent to a 250 kg live weight animal. Based on the general classification described in Valbuena *et al.* (2012), this relatively low human population and livestock density places the research site as a low-density location.

Li *et al.* (2011) observe that current farmer practice in the study region is to remove all residues from the field after harvest. Households in western China value crop residues as a livestock feed source as grazing bans restrict pasture grazing and alternative feed sources are limited. In addition, households often own draught livestock and to capture an increased demand for meat consumption a recent government policy shift has been to foster additional livestock production in western China. Crop residues are also a valuable source of heating (minimum temperatures often fall below -15°C during winter) and are used as a source of cooking fuel (electricity, coal and methane generating units are expensive and

timber is scarce). The above factors suggest that households may wish to retain some crop residues as mulch and to remove some for other uses.

## *2.2. Simulating production*

The rotation examined here is observed local practice of growing spring wheat followed by field pea, with crop sowing generally occurring in March and harvest occurring in July. This is followed by a fallow period over winter until the following March when the next crop is planted (i.e. one year spring wheat is grown and the next year field pea is grown).

Experimental trials conducted in 2002-2010 for this rotation provided production data associated with four different treatments related to tillage and crop residue retention. The four treatments were: tillage with full crop residue removal (current farmer practice), no-till with full crop residue removal, tillage with full crop residue retention and no-tillage with full crop residue retention. Details of the experimental design, including soil, water and nitrogen data and management practices are available in Huang *et al.* (2008).

As variable residue retention rates were not examined in the experiment, the practice of variable crop residue retention was simulated using APSIM over a 40 year period from 1970 to 2010. Different simulations were set up where the amount of crop residue removed after harvest changed incrementally from 0% to 100% (using increments of 10%). APSIM simulates crop, forage and soil-related processes and the influence of climate and management activities on these processes using local climate and soil data (Keating *et al.*, 2003). The APSIM simulations used observed daily climate data, observed soil, nitrogen and water characteristics and observed agronomic management practices (Huang *et al.*, 2008). Key model outputs from the simulations included grain yields, biomass, water balance, soil

nitrogen, runoff and ground cover. To validate the APSIM model, observed and predicted yields for no-till with residue retention were compared, as were the treatment effects between no-till with and without residue retention.

### *2.3. Economic assessment of simulated production*

In order to determine the economic impacts of crop residue retention practices the net annual value of the spring wheat-field pea rotation is calculated using equations 1-5 on a per hectare basis, with fixed parameters provided in Table 1. Grain is valued as the total value of all grain produced minus production costs per hectare (Eq. 2). The net value of livestock has three components (Eq. 3). The first is the economic return associated with removing residues from the field and using these residues to feed goats (the most common local small ruminant). Standard livestock feed requirements and growth data are used to determine the number of goats that the residue could feed (NRC, 1981; Sahlu *et al.*, 2004). To achieve a daily live weight gain of 50 grams and reach 16 kg at sales a goat requires an average of 45 grams of crude protein (and 400g of dry matter) per day for 320 days. In the region, field pea and spring wheat dry matter is approximately 16% and 6% crude protein (Zhang *et al.*, 2010). Based on these calculations one weaner goat requires 14,400 grams of crude protein to grow from birth to 16 kg, in addition a breeder goat requires 15,420 grams of crude protein for maintenance each year. At 80% residue removal 2314 kg/ha of wheat residue and 1202 kg/ha of field pea residue is available. This amount of residue is equivalent to 331,284 grams of crude protein and is sufficient feed for approximately 12 weaner goats and their mothers (assuming a 120% lambing rate). Full details of the livestock calculations are available in the online materials.



The second component of livestock returns is the labour cost associated with removing variable amounts of crop residue. Based on fieldwork observations, to carry residues from the field to the house and feed to livestock requires 20 man-days per hectare (based on 3500 kg of residues), and this requirement will vary as the amount of residue retained changes. The third component is the cost to purchase crop residues associated with household heating and cooking demand. Households first decide on the portion of residues to retain, and then use the removed residues to meet family heating and cooking requirements. Residues in excess of these family requirements are fed to livestock. If production is too low or residue retention rates are at a level that doesn't provide enough residues for household needs, residues need to be purchased at the market price.

$$\text{rotation net value} = \text{grain net value} + \text{livestock net value} \quad (1)$$

$$\text{grain net value} = \sum_{g \in w, p} G_g P_g - C_g \quad (2)$$

$$\text{livestock net value} = (N \times Lw \times Pl) - LC - \sum_{r \in wr, pr} RC_r \times P_r \quad (3)$$

$$N = CPA / CPD \quad (4)$$

$$CPA = \sum_{r \in wr, pr} (RP_r - RH_r) \times CPC_r \quad (5)$$

where :

$g$  = grain,  $w$ = spring wheat grain,  $p$ =field pea grain;

$r$  = crop residue,  $wr$ = spring wheat residue,  $pr$ =field pea residue;

$G$  = grain (kg/ha),  $P$  = price (RMB/kg),  $C$  is production cost (RMB/ha);

$N$ = livestock weaner inventory (number),  $Lw$  = weaner live weight (kg);

$Pl$  = liveweight price for weaners (RMB/kg);

$LC$  = labour costs to remove residues from field, and feed to livestock (RMB/ha);

$RC$  = crop residue purchased to meet household heating and cooking demand (kg);

$CPA$ = crude protein available (grams/ha);

$CPD$ = crude protein demand per weaner (grams to reach  $Lw$ );

$RP$  = crop residue produced (kg/ha);

$RH$  = crop residue required to meet household heating and cooking demand (kg/ha); and

$CPC$  = crude protein content of crop residue (% dry matter).

**Table 1****Fixed parameters in economic model**

Parameter	Unit and comments	Value	Source
Household residue demand	Kg/ha, based on 5 people/ha	1500	Field work
Wage rate	RMB/day	40	Field work
Labour demand	Days to remove one ha of crop residue	20	Field work
Production costs (wheat, pea)	RMB/ha	2482, 2142	Huang <i>et al.</i> (2008) and field work
Meat price	RMB/kg	16	Field work
Grain prices (wheat, pea)	RMB/kg	2, 2.9	Field work
Residue prices (wheat, pea)	RMB/kg	0.2, 0.3	Field work
<i>Lw</i>	Kg, live weight of weaner at selling	16	Field work
<i>CPC</i> (wheat, pea)	Grams crude protein/kg dry matter	60, 160	Zhang <i>et al.</i> (2010)
Weaner goat energy demand	Grams crude protein/day	45	NRC (1981) and Sahlu <i>et al.</i> (2004)

Notes: These parameters are fixed in each year. The amount of grain and crop residue used in Eq. 1-5 is generated in APSIM. 1 \$US = 6.4 Chinese Yuan Renmimbi, RMB.

Grain, residue and livestock price data are sourced from field observations and Gansu government official sources (CSP, 2009). The overall trend for major agricultural commodity prices in Gansu between 2004 and 2011 has been a modest rise in grain prices and a strengthening of meat prices, with real grain prices rising 38% and real meat prices by 90%. Despite sizeable price fluctuations in the global grains market in 2006-2008, domestic grain prices in China have been somewhat insulated from global market variations. For example, the increase in wheat prices from 2006-2008 within Gansu was 23%, compared to a 71% in the global wheat price during the same period (Lu and Yu, 2011). Carter *et al.* (2012) and Lu and Yu (2011) attribute this insulation to government grain self-sufficiency policies.

In order to assess if different price structures change how residue retention influences economic returns, results are generated for three different price series:

1. Base case prices. These are the prices observed in 2011 within the study site. At observed prices the livestock to grain price ratio is 7.
2. Medium run prices. These are 2011 prices + (2011 prices × percentage change in real prices between 2004 and 2011). At these prices the livestock to grain price ratio is 9. This price series is an attempt to assess what would happen if the current Chinese trend of livestock prices rising faster than grain prices continued.
3. Falling meat prices. Meat prices fall by 40%, and grain prices do not change. At these prices the livestock to grain price ratio is 4.

### **3. Results**

### 3.1. Production results

Observed climatic, soil, water and crop management data were used to simulate a wheat-field pea rotation from 1970 to 2010. All the APSIM simulation files and results are available in the online materials. The median yield gap over the nine years between APSIM simulated grain yields and grain yields observed in the experiment was 12% for spring wheat and -8% for field pea. Despite APSIM under and over predicting absolute yields, APSIM predicted similar yield gaps to those observed in the experiment for no tillage with and without residue retention. In the experiment, the average grain yield gap over the nine years for no tillage with and without residue retention was 31% for spring wheat and 37% for field pea, compared to APSIM simulated differences of 28% and 39%, respectively. Observed biomass gaps between no tillage with and without residue retention were 27% for spring wheat and 31% for field pea, compared to APSIM simulated differences of 24% and 39%, respectively.

Retaining residues can improve long-run production; residue retention has a positive effect on average biomass (Table 2). In addition, retaining residues can stabilise the relative variability of production. For example, the coefficient of variation for the field pea biomass (CV, i.e. standard deviation divided by mean of 40 simulated years) falls by 7% when 30% of residues are retained, relative to zero residue retention (Table 2). This is because residue retention stabilises soil water balances (Figure 1). This ability of crop residue mulching to assist in smoothing long-run production has also been observed by Erenstein (2002) and Govaerts *et al.* (2005).

**Table 2**

Average annual simulated biomass (kg/ha), grain yield (kg/ha) and crop residue yield (kg/ha) in a wheat-field pea rotation with different residue retention practices from 1970-2010.

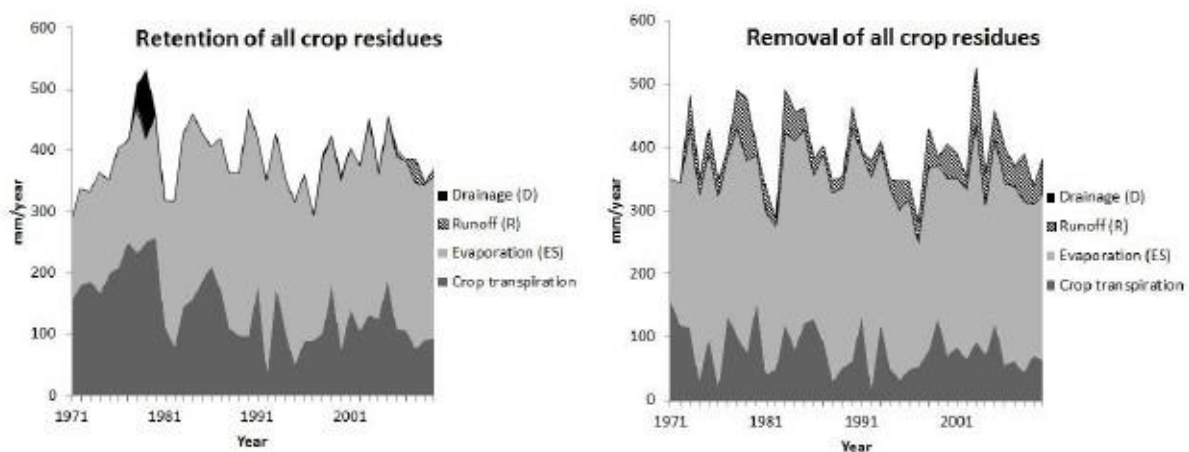
Crop	% of crop residue retained	Biomass	grain	Crop residue	Crop residue removed	Crop residue retained
Wheat	100	8482 (0.36)	3126 (0.36)	5356 (0.36)	0	5356
Wheat	70	7690 (0.36)	2858 (0.36)	4832 (0.36)	1449	3383
Wheat	30	6443 (0.37)	2432 (0.37)	4011 (0.37)	2807	1204
Wheat	0	5330 (0.36)	2003 (0.36)	3327 (0.37)	3327	0
Field pea	100	5758 (0.48)	2065 (0.52)	3693 (0.46)	0	3693
Field pea	70	4687 (0.51)	1661 (0.57)	3026 (0.48)	908	2118
Field pea	30	3937 (0.53)	1377 (0.59)	2560 (0.50)	1792	768
Field pea	0	2792 (0.60)	965 (0.67)	1827 (0.57)	1827	0

Note: CV is in parenthesis.

Crop growth is primarily a function of limiting conditions related to water and nutrients. Our APSIM results are in broad agreement with the key biophysical concepts underpinning crop residue mulching; for example, retaining residues has a positive influence on the soil water balance as it reduces evaporation (Fig. 1) and runoff (Fig. 1 and Fig. 2). This reduced runoff increases infiltration, thus increasing available soil water at sowing (Fig. 3).

In order to examine the effect of crop residue retention on soil water we simulated the components of the soil water balance. The water balance of a point (a field in this situation) is written as:  $P = ET + R + D + \partial S$  (Zhang *et al.*, 2001). Where P is precipitation, ET is

evapotranspiration (comprised of evaporation (ES) and crop transpiration), R is runoff, D is drainage below the root zone, and  $\partial S$  is the change in soil water storage. The simulated water balance for the rotation differed depending on how residues were used (Fig. 1). Variable rainfall is the key driver of water balance variation, with in-crop rainfall variability (CV of 0.35) exceeding total annual rainfall variability (CV of 0.18). Runoff is higher when no residues are retained (Fig. 1 and Table 3). The majority of this runoff occurs in the fallow period as ground cover is less or non-existent. The average runoff is 35 mm over the whole year when all crop residues are removed (min=0, max=99), with 1.7 mm of this occurring within the crop growing season (min=0, max=16). Evaporation is also higher when crop residues are removed (Fig. 1 and Table 3).



**Fig. 1.** Simulated terms in the water balance for a wheat-field pea rotation with full crop residue retention and with all crop residues removed from the field.

**Table 3**

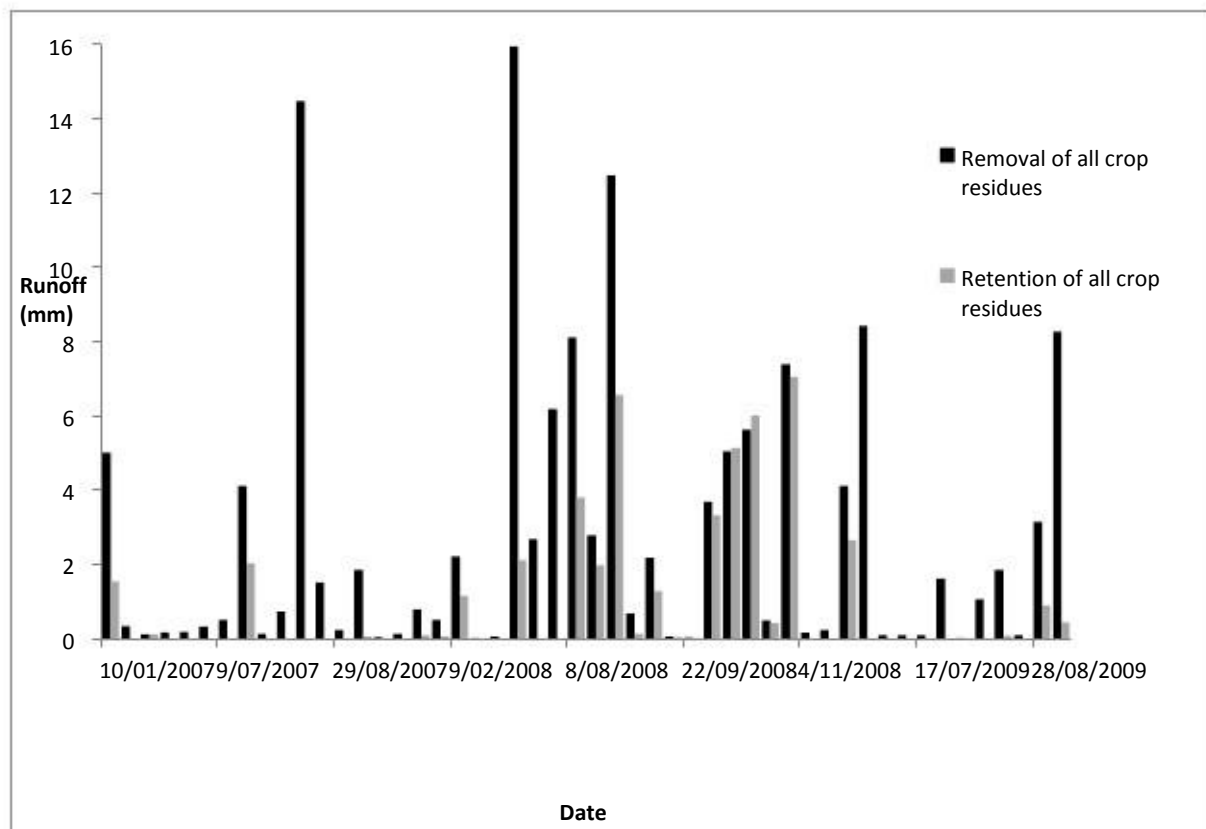
Simulated components of the water balance at a point (inferred here to represent a field) in the average year (over 1970-2010).

Component of the water balance	Retain all crop residues	Remove all crop residues
Precipitation	391	391
Crop transpiration	144	80
Evaporation	241	276
Runoff	2	35
Drainage below the root zone	4	0
Change in soil water storage	0	0

Note: all values are expressed in mm.

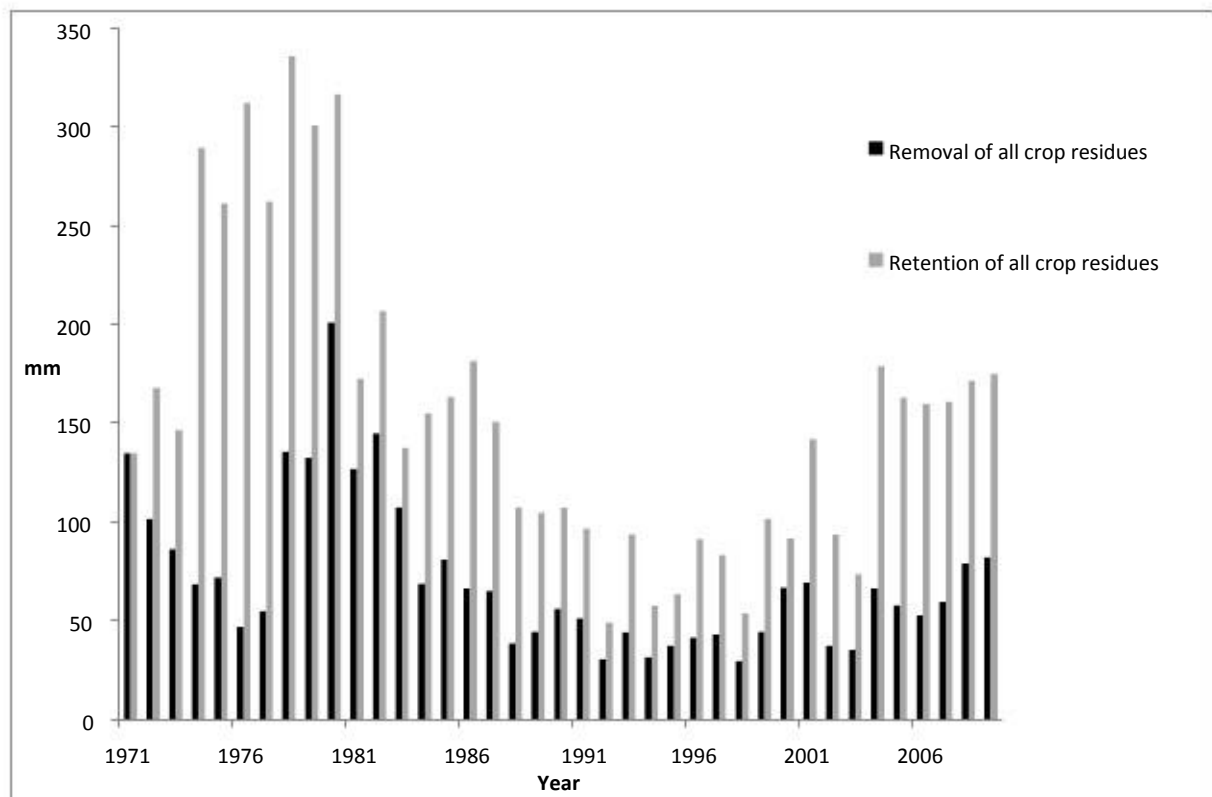
Runoff is strongly associated with the duration and intensity of rainstorm events. In order to gauge the effect of crop residue retention on daily runoff, runoff over two seasons is examined (Fig. 2). A large number of the bigger runoff events are shortly after harvest in August and September, rainfall in these months accounts for 35% of the annual average.





**Fig. 2.** Simulated 2007-2009 daily runoff in a wheat-field pea rotation with different residue retention practices.

As a result of reduced evaporation and reduced runoff available soil water at sowing increases when residues are retained (Figure 3). This in turn influences biomass (Table 2).



**Fig. 3.** Simulated available soil water at sowing in a wheat-field pea rotation with different residue retention practices.

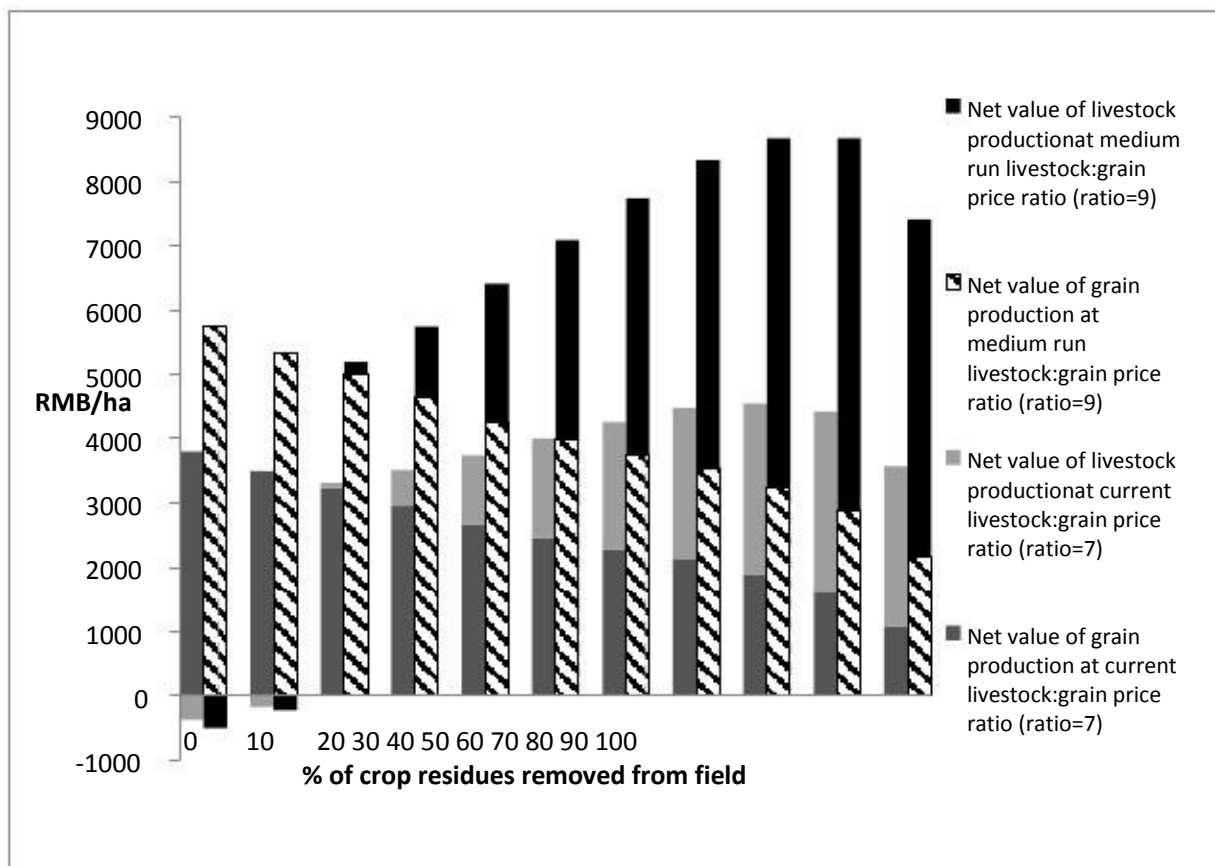
Cereal crop residues typically have a high C:N ratio and this may be detrimental to plant nitrogen uptake as temporary N-immobilisation can occur in the early years of residue retention. In the long run, crop residue retention is believed to increase soil N mineralisation (Erenstein, 2002). This concept appears true for our case study, with residue retention having lower levels of soil nitrogen in earlier years, and then higher levels of soil nitrogen as the cumulative effects of residue retention occur. The average kg/ha of total soil inorganic nitrogen (nitrate) ( $\text{NO}_3$ ) at crop sowing between 1971-1980, 1981-1990, 1991-2000, and 2001-2010 was 81, 72, 114 and 94 when no crop residues were retained, and was

72, 74, 183 and 239 when all crop residues were retained. Increased organic matter when residues are retained is one reason explaining these different nitrogen levels at crop sowing.

Although the grain yield effects of conservation agriculture can be positive, negative or insignificant and the results can be highly site-dependant (Govaerts *et al.*, 2005; Giller *et al.*, 2009), in this study, using crop residues as mulch (in conjunction with no-tillage) increases soil water and soil nitrogen content, and this translates into higher production (Table 2). Maximum production occurs when all residues are retained; however, maximum production does not necessarily translate into maximum economic value.

### 3.2. Economic results

Overall, we find that retaining a small portion of crop residues as mulch is beneficial to economic returns, with the maximum economic return occurring when 20% of residues are retained in the field (Fig. 4). Clear trade-offs exist between using residues as a mulch to increase grain yields and using residues as a source of livestock feed and household heating and cooking fuel. The value of grain production falls as residue retention declines, and the net value of livestock production rises until 90% of residues are removed. Current farmer practice is full residue removal (Li *et al.*, 2011); and in this study, similar returns could be obtained by removing 30% of residues (average economic return is 3505 RMB/ha at 30% removal and 3573 RMB/ha at 100% removal). Higher returns are available if 30-90% of residues were removed.



**Fig. 4.** Simulated net annual average economic value of grain production and livestock production in a wheat-field pea rotation with different residue retention rates and different price scenarios from 1970-2010.

There are three noticeable changes in total net economic returns as the amount of residue removed from the field rises (Fig. 4). As residue removal commences (from a case of retaining all residues) total net economic returns fall, and returns are lowest at approximately a 20% removal rate. This is because in this zone of low levels of residue removal (0-20% removal) households purchase residues from the market to meet their heating and cooking requirements. As residue removal increases fewer residues need to be purchased to meet household heating and cooking requirements, and at the same time

grain production declines. At 10% removal, the lost value of grain production (relative to full residue retention) exceeds the savings made from reductions in residue purchasing costs.

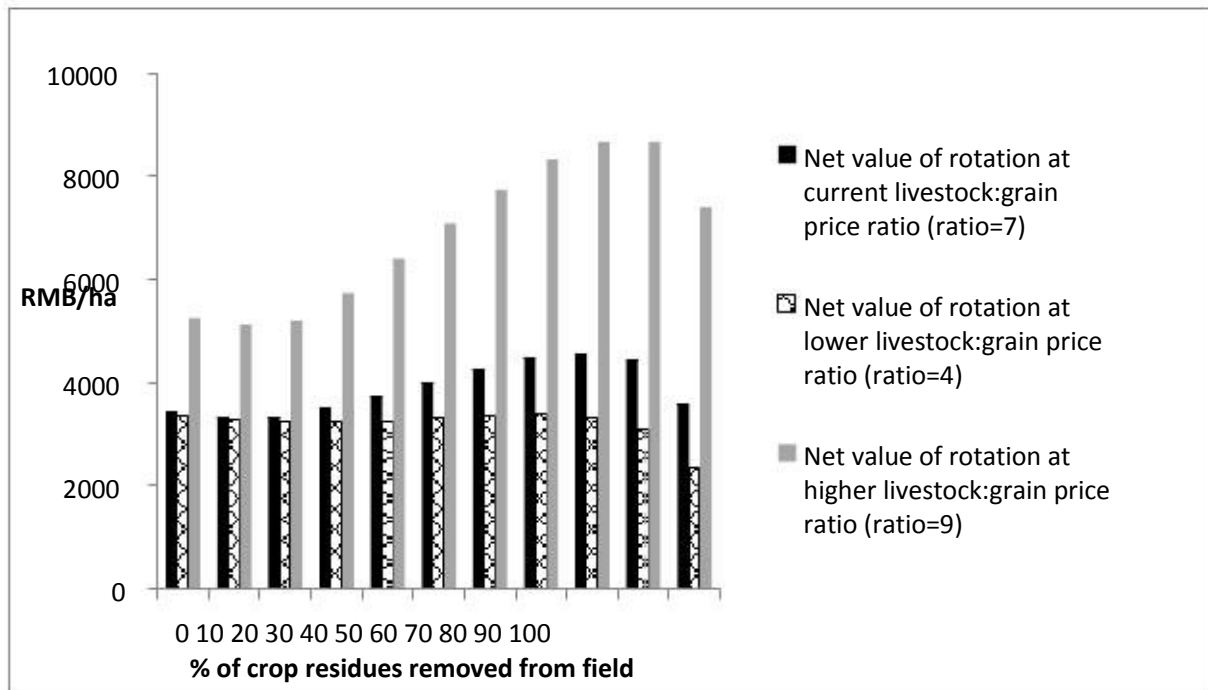
Once greater than 20% of residues are removed, household residue production is sufficient to cover household cooking and heating requirements, and all additional residues removed from the field are used to feed livestock. Economic returns rise from 20% removal until their maximum at 80% removal. In this zone, the value of extra residue in increasing livestock production exceeds the value of lost grain production.

Economic returns fall once removal rates exceed approximately 80%. This is because at very high rates of residue removal livestock production falls due to lower biomass production. At 100% removal there is 1823 kg/ha of field pea residue produced and 1823 kg removed from the field, but at 90% removal 2273 kg/ha is produced, and 2045 kg is retained. The reduction in residue produced when moving from 90% to 100% removal is 20%, as a result removing a larger percentage of total residues produced (i.e. 10% more) doesn't actually increase available residues to feed livestock as it does at lower residue retention rates.

If prices follow medium run trends, then residue removal will continue to increase returns (Fig. 4). However, if grain prices stay constant and livestock prices fall by 40%, the negative income effect of reduced grain and the positive income effect of increased livestock feed counterbalance each other, and changes in residue retention have a limited influence on net profitability (Fig. 5). Alternatively stated, if livestock prices fall by less than 40%, relative to grain prices, removing between 0 and 90% of residues provides similar economic outcomes.

Regardless of the price series used, retaining a small amount of residue always increases

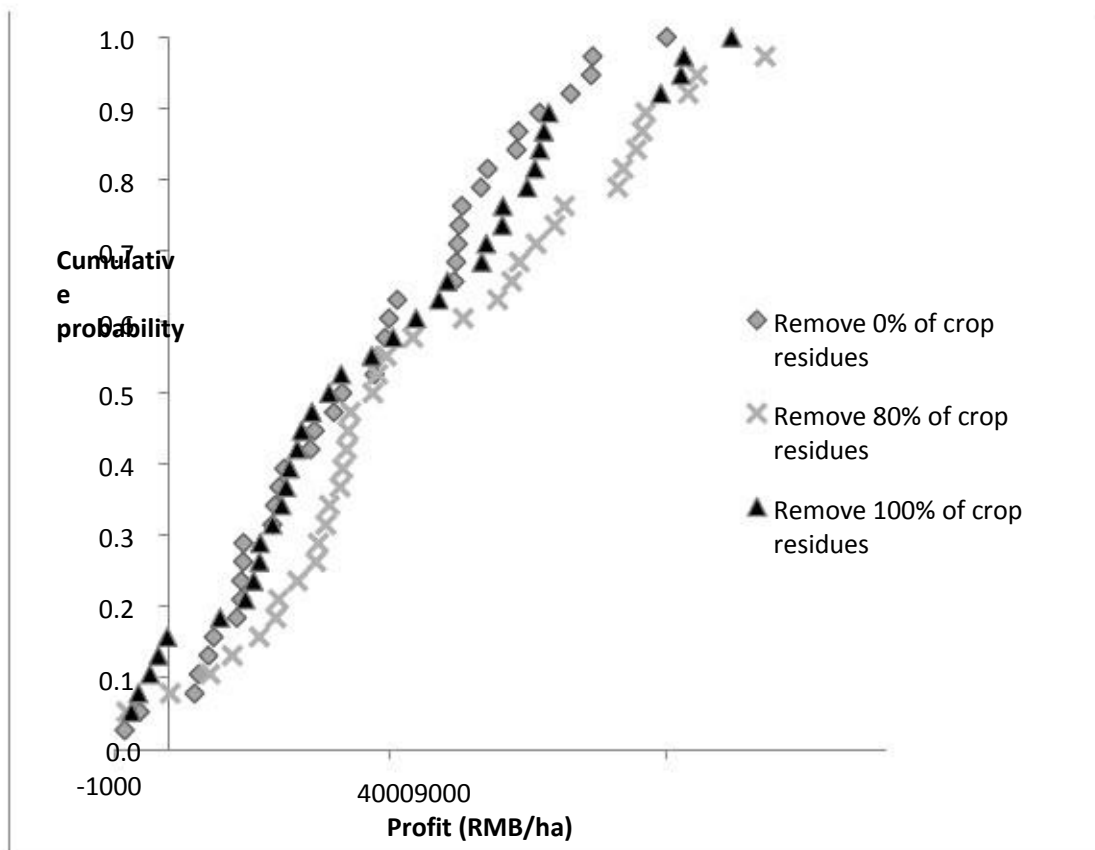
average economic returns, with an increase of residue retention from 0 to 20% increasing average economic returns by at least 15% in each of the three price series (Fig. 5).



**Fig. 5.** Simulated net annual average economic value of rotation with different residue retention rates and different price series from 1970-2010.

Variability in grain and residue yields exists (Table 2), and this translates into variable economic returns (Fig. 6). The CV of returns was 0.76 at 0% removal, 0.76 at 80% removal and 0.87 at 100% removal. Although, crop residue retention has some a modest positive impact on stabilising returns (13% fall in CV), compared to no residue retention, as the amount retained increases there is no fall in relative variability until over 80% is removed. In low and higher income years returns are more extreme when 100% of residues are removed (Fig. 6). At 100% residue removal returns are higher than at zero removal, so although removing all residues increases variability it also increases expected returns. Removing 80% of residues increases expected returns (relative to removing zero % of residues) without a

shift in CV. More promising is that removing 80% of residues increases expected returns (relative to removing 100% of residues) and also reduces CV.



**Fig. 6.** Cumulative probability of annual profit/ha over 40 years of model simulations using base case prices and different residue retention rates.

### 3.3. Ground cover results

High levels of groundcover can reduce the susceptibility of soil to wind and water erosion. Groundcover (live and dead plant cover) was simulated in APSIM and results are expressed as the mean percentage of days in the year when groundcover fell below a nominated threshold of 50%. When all residues are removed, in the average year, there are 75 days where ground cover exceeds 50%. On the contrary, when all residues are retained there are

287 days when ground cover exceeds 50%. When only ground cover after harvest, prior to the next season's crop is considered (i.e. ignoring standing biomass, living cover) there are zero days and 249 days where ground cover exceeds 50% when all residues are removed and when all residues are retained, respectively. These differences in ground cover influence both runoff (Fig. 2) and wind erosion potential.

## **Conclusions**

In the article we offer some modest insights into the production, economic and environmental consequences of retaining crop residues. Major findings of this study are that (1) residue retention improves and stabilises production and reduces erosion potential, and (2) removing 30-80% of crop residues increases economic returns (relative to full removal or zero removal) as the value of additional residues for livestock feed and heating exceeds the value of lost grain production. Current farmer practice in the study site is to remove all crop residues, and the uptake of conservation agriculture practices in China has been minimal (Li *et al.*, 2011). Promoting full removal or retention of crop residues should be carefully considered as mixed farming systems often rely on both grain and residues for income and household consumption needs. Advocating retaining a small portion of residues as mulch may assist in lifting incomes and stabilising the relative variability of incomes, as in this study retaining 20% of residues as mulch leads to economic returns greater than the current practice of full residue removal, and reduced the CV of economic returns. In addition, developing alternative forage resources for livestock feed, for example lucerne (*Medicago sativa* L.), may encourage using crop residues as mulch.



Tensions exist between farmers improving their economic situation and reducing environmental stress, like water and wind erosion. China's Sloping Land Conversion Program aims to reduce environmental stress by providing farmers with financial incentives to plant trees and perennial grasses (Qu *et al.*, 2011). Although monitoring could prove challenging, the idea of providing financial incentives to retain crop residues should be further canvassed as crop residues have an ability to reduce erosion potential, and this is critical in fragile environments like western China. A complicating factor is that residue retention can increase herbicide and fertiliser runoff (Erenstein, 2002), and this should also be properly factored into decisions regarding payments of residue retention.

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