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Whole-farm economic and risk effects of conservation agriculture in a crop-livestock system in western China

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ABSTRACT

Researchers advocate using conservation agriculture as a tool to improve farmer livelihoods, with crop residue retention being an integral component of conservation agriculture. Crop residues are used for mulch, livestock feed, and fuel material in crop-livestock farming systems. In this article, we conducted long-term simulation modelling to compare the economic effects of different crop residue retention practices for a crop-livestock agricultural household in semi-arid China. We calculated the average profit and net present value (and associated variability) of different crop residue retention practices using planning horizons of 3, 6, 10, and 20 years. Crop residue retention increased grain production, reduced forage production leading to smaller livestock flock sizes, and increased family heating and cooking costs. The net effect was that retaining minimal crop residues gave the highest profits using the three year planning horizon.

Full crop residue retention provided the highest profit when the planning horizon exceeded 10 years. Relatively flat economic payoffs associated with changing crop residue usage around the maximum economic payoff existed. Calls for comprehensive crop residue retention are unlikely to be attractive when farmers discount future profits, and when crop residues have significant value as a fuel and feed source. The economic benefits of crop residue retention can take numerous years to eventuate and retaining crop residues also increased simulated ground cover and this positive environmental impact extends beyond individual farm boundaries. Because of these time lags and external environmental benefits, providing financial incentives to retain crop residues during the initial transition years could be a policy option.

1. Introduction

Conservation agriculture has three main principles: zero or minimal soil disturbance, a permanent soil cover provided by a growing crop or a dead mulch of crop residues, and diversified crop rotations (FAO, 2008). Questions remain regarding whether leaving crop residues in the field is the most sensible, efficient or profitable use of crop residues (Giller et al., 2009). This is because crop residues (a) improve soil fertility and soil moisture thus boosting grain yields, (b) provide a resource for livestock feed, household heating and cooking demands and (c) provide ground cover to reduce erosion potential. These trade-offs become more pronounced when markets for goods that are substitutes for crop residues are incomplete, as often occurs in developing countries. For example, if access to alternative sources of livestock feed or household heating materials is not feasible, households will use crop residues for these purposes. This creates tensions with retaining crop residues as mulch, even though the alternative sources of livestock feed or heating are more efficient. Crop residues often have significant value in developing country farming systems. For example, Magnan et al. (2012) estimated that crop residues removed from the field comprise approximately 25% of the value of cereal production on a sample of mixed farms in Morocco. Hellin et al. (2013) raise the idea that partial residue retention could reduce trade-offs in Mexican farming systems.

Cropping systems that use reduced tillage and crop residue retention often increase grain yields and improve environmental outcomes (Giller et al., 2009, 2011; Knowler and Bradshaw, 2007). The production effects of either full crop residue removal or retention (Aulakh et al., 2012; Bakht et al., 2009; Fischer et al., 2002; Huang et al., 2008; Malhi and Lemke, 2007) or using different quantities of crop residues as a mulch (Govaerts et al., 2005; Maskina et al., 1993; Mupangwa et al., 2012) have been analysed in numerous field experiments and results are highly context specific. A positive grain yield effect has been found using simulation models in Mexico (Hartkamp et al., 2004) and Ghana (MacCarthy et al., 2009). Erenstein (2011) and Valbuena et al. (2012) used survey data to highlight that many rural households rely on crop residues to feed livestock. We are interested in complementing these

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agronomic-focused studies by examining the economic effects of crop residue retention over time.

The aim of this article was to assess the economic outcomes associated with different crop residue management patterns at the whole-farm level. We attempted to illustrate principles and trade-offs associated with crop residue usage rather than directly model household decision-making. In this article we simulated crop production using different levels of crop residue retention. We based our simulations on agronomic and climatic data from a field experiment conducted in Dingxi Prefecture, Gansu Province, P.R. China (Huang et al., 2008). We then calculated the average net economic value and the net present value of retaining different amounts of crop residues across multiple time periods from 1970 to 2010 using a planning horizon of 3, 6, 10 and 20 years. We captured issues related to the planning horizon of resource-poor farmers and the trade-offs between using crop residues for mulch or for raising livestock and meeting household heating and cooking requirements; however, we did not cover all aspects of the conservation agriculture debate (Appendix S1). All the materials required to replicate our results are in the Appendix.

2. Methodology

2.1. Study site

Farm households in the Dingxi Prefecture are mainly subsistence oriented, reliant on off-farm income and have income levels well below their urban counterparts (Nolan et al., 2008). These farm households typically grow spring wheat (*Triticum aestivum* L.), field pea (*Pisumarvense* L.) and potatoes (*Solanum tuberosum* L.), and often raise 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 to 565 mm. Approximately two-thirds of annual rainfall occurs between May and August. On average, there are 157 days per year with a minimum daily temperature below 0 °C.

A survey conducted by Nolan et al. (2008) provided data on the basic structural characteristics of 46 farm households in the Dingxi Prefecture. The median population density of surveyed households 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 had one hectare of arable land. 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 Dingxi as a low-density location.

Li et al. (2011) observe that current farmer practice in the study site involves the removal of all crop residues from the field after harvest. Households in western China value crop residues as a livestock feed source as grazing bans restrict pasture grazing (Dong et al., 2007) and alternative feed sources are limited. To capture an increased demand for meat consumption a recent government policy shift has focused on developing livestock production in western China (Brown et al., 2009; Komarek et al., 2012). Crop residues are a valuable household resource for heating and cooking. Electricity, coal and methane generating units are expensive and timber is scarce. These factors all provide incentives to remove crop residues from the field.

2.2. Simulating crop production

To gauge how different crop residue management practices influence household livelihoods, we simulated crop production based on the typical crop rotation used by farmers in Dingxi. The simulated rotation followed the observed local practice of growing one year of spring wheat followed by one year of 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 (spring) when the next crop is planted. Experimental trials conducted in 2002–2010 for this rotation provided data associated with four different treatments related to tillage and crop residue usage. Huang et al. (2008) provides a description of the experiment. 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.

As Huang et al. (2008) only examined two crop residue retention practices, we used APSIM to simulated additional crop residue retention practices. The cropping systems model APSIM simulates, on a daily time step, 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). We used observed data related to daily climate, soil and water characteristics and agronomic management practices from Dingxi to calibrate the model. In the case study region, APSIM has been previously developed and tested for wheat-lucerne rotations (Chen et al., 2008b), and specifically for the spring wheat-field pea rotation in Dingxi (Chen et al., 2008a) using the same data as in this article. Chen et al. (2008b) simulated crop biomass over time with a root mean squared deviation of 208 kg/ha, 12% of the observed mean. We extrapolate this previously tested model to examine crop residue retention issues. Predicted outputs from the APSIM model were compared with observed data from the experimental trial (Section 3.1 and Appendix S1, Figs. 4A–5A). In addition, we conducted "sensibility testing" (Holzworth et al., 2011). This involved assessing model output against common sense to determine if the model captured key biophysical processes associated with crop residue retention. Examples of this "sensibility testing" included comparing modelled soil water, ground cover and soil nitrogen under different crop residue retention practices (Section 3.1 and Appendix S1, Table 2A and Figs. 1A–3A).

We set up different simulations where the amount of crop residue retained after harvest changed incrementally by 10% from 0% to 100%. To accommodate climate variability, we ran repeat simulations of our model based on different model starting dates. Our model started in every year between 1970 and 2008. We ran the APSIM simulations for the following different time periods: 39 different 3-year periods (1970–1972, 1971–1973, …, 2008–2010), 36 different 6-year periods (1970–1975, 1971–1976, …, 2005–2010), 32 different 10-year periods (1970–1979, 1971–1980, …, 2001–2010) and 22 different 20-year periods (1970–1989, 1971–1990, …, 1991–2010). We used these different 3, 6, 10 and 20 year periods because we were interested in calculating the net present value (NPV) of the crop residue retention practices over different planning horizons.

2.3. Economic assessment of simulated production

In order to determine the economic effect of different crop residue retention practices, we calculated the net economic value of the spring wheat-field pea rotation when different amounts of crop residues were retained on a per hectare basis. Fixed parameters used in the calculations and the structure of the economic model are in the Appendix S1 (Table 1A and eqs. 1A–8A). Commencing different crop residue retention practices can involve fixed costs associated with buying livestock and long-term investments in soil fertility and water that can take numerous years to eventuate. We therefore calculated the NPV associated with retaining different amounts of crop residues using different planning horizons. These calculations were made over all the different simulated time periods. Following this we calculated the range of crop residue retention practices that provided a NPV within 90% of the maximum NPV. Pannell (2006) provides an analysis of how large deviations from optimal decisions often make little difference to the optimal payoff. We also assessed how sensitive the NPV calculations were to changes in commodity prices and discount rates (Appendix S1, Table 3A).

The planning horizons we used for our NPV calculations were 3, 6, 10 and 20 years. Resource-poor farmers often have a short planning horizon regarding farming system management, thus we calculated the NPV over a three year period. The full agronomic benefits of crop residue retention may take numerous years to eventuate (Erenstein, 2002), thus we evaluated a 20 year planning horizon. We also used a 6 year and 10 year planning horizon to capture the medium run. Lynam and Herdt (1989) suggest using a planning horizon greater than 3 to 5 years but less than 20 years when assessing the sustainability of different agricultural production systems. We set the discount rate at 7% to reflect the resource-poor farmer preference for benefits sooner rather than later. We then used discount rates of 4% and 10% to examine the sensitivity of results to changes in discount rates (Appendix S1, Table 3A).

To calculate the NPV over the different time periods we calculated the net economic value of the rotation in each different year on a per hectare basis when different amounts of crop residues were retained. We then discounted these yearly net economic values to arrive at their NPV. The term net economic value was defined as total revenues minus total costs, and included the implicit value of changes in labour requirements. There were three components to the net economic value: net grain value, net livestock value, and costs associated with purchasing crop residues to meet household heating and cooking demands. Details on methodology related to these three components are in the Appendix S1.

Commodity price data came from field observations and official government sources (CSP, 2009). A modest rise in grain prices and a strengthening of meat prices occurred between 2004 and 2011, with real grain prices rising 38% and real meat prices by 90%. We generated NPVs for three different price series to assess how changes in prices altered the profitability of contrasting crop residue retention practices:

1. Base-case prices. These were the prices observed in 2011 within the study site. At observed prices the livestock to grain price ratio is 7.
2. Higher meat prices. These were 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 was an attempt to assess what would happen if the current trend of livestock prices rising faster than grain prices continued.
3. Lower meat prices. Meat prices fall by 40%, and grain prices do not change. At these prices the livestock to grain price ratio is 4. This price series was an attempt to assess what would happen if livestock prices fell relative to grain prices.

3. Results

3.1. Crop production results

Crop residue retention had a positive effect on average biomass and grain yields for both crops over different 10-year simulation periods (Table 1). In this study, average spring wheat and field pea grain yields over the different 10-year simulation periods were 19% and 44% higher, respectively, when all crop residues were retained compared to all crop residues being removed (Table 1). Retaining crop residues also stabilised the relative variability of production; the average coefficient of variation for grain and biomass (CV, i.e. standard deviation divided by the average 10-year simulation period) fell as the proportion of crop residues retained rose (Table 1). Erenstein (2002) and Govaerts et al. (2005) also observe this ability of retaining crop residues in the field to assist in smoothing long-run production.

We compared APSIM simulated production data with data from the experiment described in Huang et al. (2008). For example, we compared the dynamics of APSIM-predicted and field-observed soil water measurements with and without crop residue retention (Appendix S1, Figs. 4A–5A). We used APSIM to capture the production treatment effect of retaining crop residues, rather than trying to predict actual yields. Experiments, in general, can be unintentionally compromised by weeds, pests, nutrient deficiencies, management issues and measurement errors. As these issues are often unobserved it is challenging to account for any discrepancy between observed and simulated yields (Whitbread et al., 2010). Median observed biomass gaps over nine years (2002–2010) between no tillage with and without crop residue retention were 27% for spring wheat and 31% for field pea, compared to APSIM simulated differences over the same period of 19% and 29%, respectively. This indicates that in the experiment, for example, average biomass production for spring wheat was 27% higher when all crop residues were retained in the field, relative to all crop residues being removed. The

Table 1
Average 10-year annual APSIM predicted biomass (kg/ha), grain (kg/ha) and crop residue (kg/ha) production in a spring wheat-field pea no-tillage rotation with different crop residue retention practices over 32 different 10-year simulation periods in Dingxi.

Crop	% of crop residue retained	Biomass	Grain	Crop residue produced	Crop residue removed	Crop residue retained
Spring wheat	100	9787 (0.28)	3305 (0.28)	6482	0	6482
Spring wheat	80	9094 (0.31)	3095 (0.31)	5999	1200	4799
Spring wheat	60	8656 (0.32)	2965 (0.32)	5691	2276	3415
Spring wheat	40	8374 (0.33)	2886 (0.33)	5488	3293	2195
Spring wheat	20	8186 (0.32)	2829 (0.33)	5357	4286	1071
Spring wheat	0	8014 (0.33)	2768 (0.33)	5246	5246	0
Field pea	100	6957 (0.39)	2494 (0.41)	4463	0	4463
Field pea	80	6204 (0.40)	2222 (0.42)	3982	796	3186
Field pea	60	5701 (0.41)	2038 (0.44)	3663	1465	2198
Field pea	40	5341 (0.43)	1899 (0.45)	3442	2065	1377
Field pea	20	5085 (0.44)	1802 (0.47)	3283	2626	657
Field pea	0	4907 (0.44)	1734 (0.47)	3173	3173	0

Note: Each value is the average of 32 different 10-year simulations (1970–1979, 1971–1980, …, 2001–2010). CV is in parenthesis and is defined as the standard deviation divided by mean of 10 simulated years. Here the CV represents the average CV over the 32 simulations.

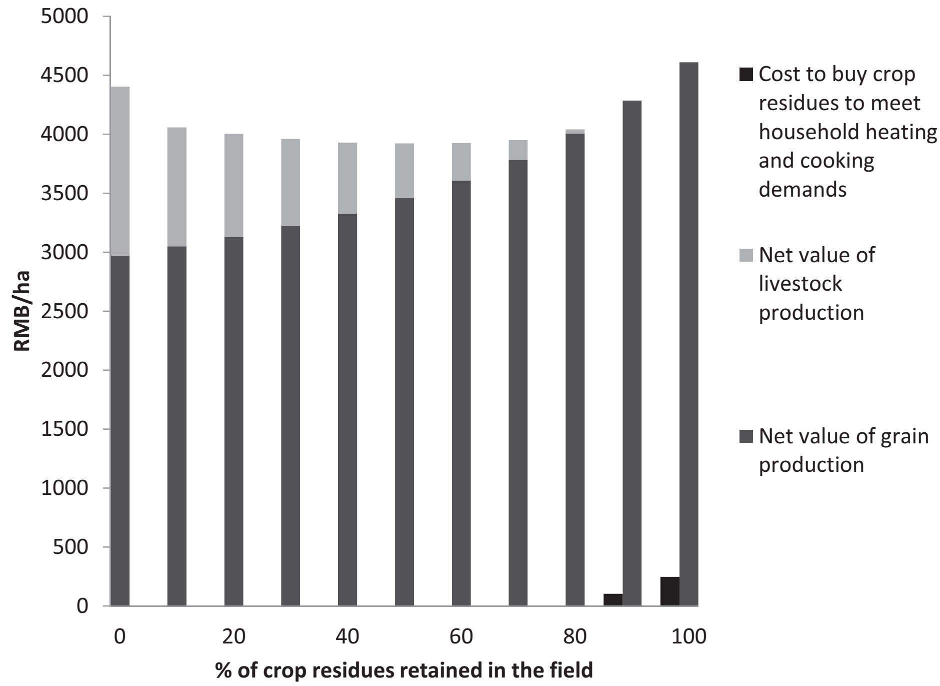

Fig. 1. Simulated average annual net economic value of a spring wheat-field pea no-tillage rotation with different crop residue retention rates over 32 different 10-year simulation periods (1970–1979, 1971–1980, …, 2001–2010) in Dingxi.

simulated difference was 19%, therefore the model underpredicted the treatment effect by 9%.

Our APSIM results agree with the key biophysical concepts underpinning crop residue usage (Erenstein, 2002). For example, retaining crop residues had a positive influence on the soil water balance as it reduced evaporation (Appendix S1, Fig. 1A and Table 2A). This reduced evaporation increased available soil water at sowing (Appendix S1, Fig. 2A), and thus more crop transpiration occurred when crop residues were retained in the field (Appendix S1, Table 2A). Over different 10-year simulation periods, crop residue retention increased average soil nitrogen content at sowing in the long term (Appendix S1, Fig. 3A). In this study, leaving crop residues in the field (in conjunction with no-tillage) increased simulated soil water and soil nitrogen content (Appendix S1, Figs 1A–3A, Table 2A), and this translated into higher average crop production (Table 1). There was minimal runoff observed in the experiment for all the crop residue treatments (Huang et al., 2008); our model also predicted minimal runoff (Appendix S1, Table 2A).

High levels of groundcover can reduce the susceptibility of soil to wind and water erosion (Erenstein, 2002). Groundcover, in the form of crop residues on the soil surface (surface organic matter), associated with different levels of crop residue retention, was simulated in APSIM. Crop residue cover declines as crop residues decompose and this decomposition is mainly a function of moisture, temperature and the C:N ratio of the crop residues. Increased surface organic matter reduced simulated runoff and evaporation (Appendix S1, Table 2A) and this will reduce the susceptibility of soil to wind erosion.

3.2. Economic results

If crop residues are retained soil water and nitrogen balances improve and this has a positive impact on crop production. The trade-off with retaining crop residues in the field is that less crop residues are available for livestock feeding and for meeting household heating and cooking requirements. Our net economic value calculation take these factors into consideration. Retaining no crop residues produced the highest simulated average annual net economic value using 32 different 10-year simulation periods (Fig. 1). The simulated average annual net economic value when 0%, 60% and 100% of crop residues were retained was 4402, 3926 and 4362 RMB/ha, respectively (in 2011, 1 \$US ≈ 6.4 Chinese Yuan Renminbi, RMB). Trade-offs existed between leaving crop residues in the field to increase grain yields and using crop residues as a source of livestock feed and household heating and cooking fuel (Fig. 1). We also solved a constrained optimisation model related to household crop residue management (Appendix S1 and S4). In this optimisation model retaining no crop residues also produced the highest average annual net economic value (same as Fig. 1).

In this study, the length of the planning horizon had an impact on what level of crop residue retention led to the highest net present value (NPV). As the planning horizon increased retaining crop residues increased the NPV, relative to removing crop residues. When the planning horizon was 3, 6, 10 and 20 years the average maximum NPV was achieved when 0%, 0%, 100% and 100% of crop residues were retained, respectively (Fig. 2). When the planning horizon was 3 years all 39 periods resulted in the maximum NPV when 0% of crop residues were retained. When the planning horizon was 6 years, 17 periods had the maximum NPV when 0% of crop residues were retained and 16 periods had the maximum NPV when 100% of crop residues were retained. When the planning horizon was 10 years, in 11 periods the maximum NPV was when 0% of crop residues were retained and in 20 periods the maximum NPV was when 100% of crop residues were retained. When the planning horizon was 20 years, 20 periods had the maximum NPV when 100% of crop residues were retained.

The data in Fig. 2 are the average NPV over different simulation periods and the full range of simulated NPVs for the different planning horizons when 0, 50 and 100% of crop residues are retained are in Appendix S1, Fig. 6A. When the planning horizon was three years full crop residue removal produced the maximum NPV and

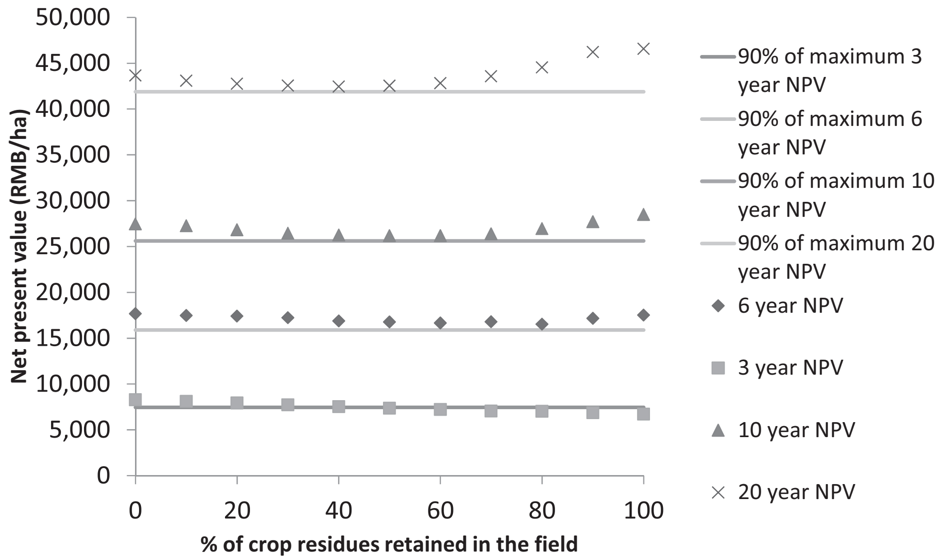

Fig. 2. Average net present value (NPV) of a spring wheat-field pea no-tillage rotation over different simulation periods with different crop residue retention rates and different planning horizons in Dingxi. The 3 year NPVs are the average NPV over 39 different 3-year simulation periods: 1970–1972, 1971–1973, …, 2008–2010. The 6 year NPVs are the average NPV over 36 different 6-year simulation periods: 1970–1975, 1971–1976, …, 2005–2010. The 10 year NPVs are the average NPV over 32 different 10-year simulation periods: 1970–1979, 1971–1980, …, 2001–2010. The 20 year NPVs are the average NPV over 22 different 20-year simulation periods: 1970–1989, 1971–1990, …, 1991–2010.

when the planning horizon was 20 years full crop residue retention produced the maximum NPV. When the planning horizon was 6 and 10 years the distinction between retaining what proportion of crop residues produced the maximum NPV was not as clear, with some periods having full residue retention proving maximum NPV and other periods having zero crop residue retention providing maximum NPV.

The average NPV for the different planning horizons was within 10% of the maximum average NPV for a wide range of crop residue retention practices (Fig. 2). When the planning horizon was 3 years, retaining between 0% and 60% of crop residues resulted in a NPV within 10% of the maximum. When the planning horizon was 6, 10 or 20 years all crop residue retention practices resulted in a NPV within 10% of the average maximum.

Variability in grain and crop residue yields existed (Table 1), and this translated into variable economic returns (Fig. 3). Retaining no crop residues resulted in the highest coefficient of variation (CV) in net economic returns. The CV generally declined as the proportion of residues retained increased (Fig. 3).

In order to gauge how changes in commodity prices influenced the NPV of different crop residue management regimes we calculated the NPVs associated with the three different price series

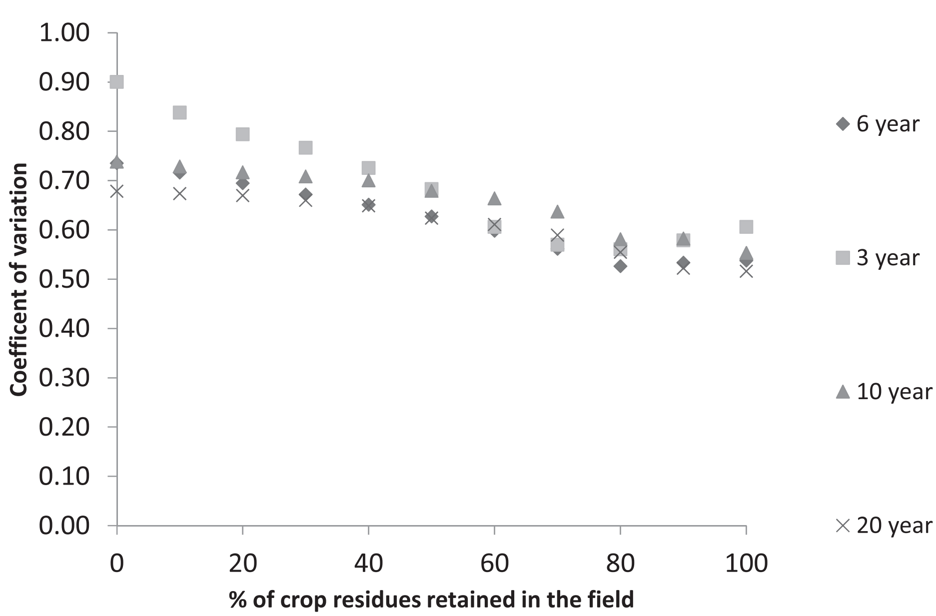

Fig. 3. Average coefficient of variation (CV) for annual net economic value of a spring wheat-field pea no-tillage rotation with different crop residue retention rates over different planning horizons. CV is defined as the standard deviation of net economic values divided by the average annual net economic value over the different simulation periods.

specified in Section 2.3. Changes in commodity prices had an impact on the profitability of crop residue retention practices (Appendix S1, Table 3A). If meat prices fell by 40%, and grain prices did not change, retaining 80% of crop residues produced the highest NPV using the three year planning horizon, respectively, relative to removing all crop residues at current prices. If meat prices rose faster than grain prices, in all planning horizons full crop residue removal produced the highest NPV, compared to full crop residue retention (at based-case prices) if the planning horizon was 10 or 20 years. In addition, using annual discount rates of 4% and 10% (compared to 7% in the original model) did not alter the main conclusion that crop residue retention produced higher NPVs in the 10 and 20 year planning horizons, but crop residue removal produced the highest NPV in the 3 year model (Appendix S1, Table 3A).

4. Conclusion

In this article we offer some modest insights into the economic consequences of retaining crop residues using a simulation model based on data from Dingxi Prefecture. Maximum crop production occurs when all crop residues are retained; however, maximum crop production does not necessarily translate into maximum net economic value (net present value) when different planning horizons are considered. There are two major findings in this study. Firstly, in our case-study, the length of the planning horizon has a strong influence on the net present value (NPV) of different crop residue retention practices. When the planning horizon is three or six years removing all crop residues produces the highest NPV; when the planning horizon is 10 or 20 years full crop residue retention is more profitable. Secondly, in our case-study, the economic payoffs associated with changing crop residue retention rates around the maximum NPV are relatively flat.

These findings have two implications. Firstly, the adoption of full crop residue retention could be challenging for resource-poor farmers as the benefits of crop residue retention take numerous years to eventuate and future benefits and costs are discounted. Secondly, the flat profit payoffs associated with changes in crop residue usage could explain why farmers might be indifferent to crop residue retention. For example, when the planning horizon is 10 years the average NPV is 27,431 RMB when no crop residues are retained, is 28,464 RMB when all crop residues are retained, and is 26,164 RMB when 60% of crop residues are retained. Full crop residue retention results in a 2% and 7% increase in economic returns from the field, compared to full crop residue removal and 60% crop residue retention. These increases translate into a modest 0.5% and 1.9% increase in total household income. This calculation is based on the one hectare rotation representing all agricultural income and 28% of total household income being derived from the farm (Nolan et al., 2008). These marginal income gains might not be sufficient for farmers to change their practices.

Current farmer practice in Dingxi is to remove all crop residues. The uptake of conservation agriculture in China has been minimal (Li et al., 2011). Tensions exist between farmers removing crop residues for improving their short-term economic returns and retaining crop residues to improve long-term economic returns and reducing water and wind erosion potential. When there is a three year planning horizon crop residue retention has a lower NPV, compared with crop residue removal, but crop residue retention delivers the environmental benefits of potentially reducing wind and water erosion, and these benefits extend beyond the farm boundary. The idea of providing financial incentives to retain crop residues should be further canvassed to address these tensions. The idea of providing farmers with financial payments for providing ecosystem services has already been used in the Sloping Land Conversion Program (Qu et al., 2011). Provision of financial incentives to retain crop residues could prove challenging and would require careful monitoring, but if properly administered could provide an entry point for resource-poor farmers into more sustainable agricultural practices.

Addressing incomplete markets is critical when evaluating conservation agriculture issues. Improving access to alternative fuel and livestock feed sources could reduce the implicit value of removing crop residues. Methane units, electricity or renewable energy are examples of alternative fuel sources. Examples of improving livestock systems include better market integration for trading forages and improved maize (*Zea mays*) silage and alfalfa (*Medicago sativa*) production methods. A reduction in the implicit value of crop residues could limit the trade-offs between different crop residue uses. This may encourage farmers to retain crop residues in the field and simultaneously reduce erosion potential. Developing and implementing policies that improve access to alternative fuel and livestock feed sources will prove challenging but could generate worthwhile outcomes if successful.

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Appendix: Supplementary material

Supplementary data to this article can be found online at doi:10.1016/j.agsy.2014.10.013.

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