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Does carbon farming provide a cost-effective option to mitigate GHG emissions? Evidence from China*

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In this study, we apply a whole farm bioeconomic analysis to explore the changes in land use, farm practices and on-farm greenhouse gas (GHG) emission under varying levels of agricultural greenhouse gas abatement incentives in the form of a carbon tax for a semi-arid crop-livestock farming system in China's Loess Plateau. Our results show that the optimised agricultural enterprises move towards being cropping-dominated reducing on-farm emission since livestock perform is the major source of emission. Farmers employ less oats-based and rapeseed-based rotations but more dry pea-based rotations in the optimal enterprise mix. A substantial reduction in on-farm greenhouse gas emission can be achieved at low cost with a small increase in carbon incentives. Our estimates indicate that crop-livestock farmers in China's Loess Plateau may reduce their on-farm GHG emission between 16.6 and 33 per cent with marginal abatement costs <￥100/t CO_2e and ￥150/t CO_2e in 2015 Chinese Yuan. The analysis implies that reducing greenhouse gas emission in China's semi-arid crop-livestock agriculture is potentially a low-cost option.

Key words: agricultural carbon taxation, carbon farming, Loess Plateau, semi-arid crop-livestock farming system, whole farm bioeconomic modelling.

JEL classifications: Q15, Q52, Q54

1. Introduction

China has become the world's largest GHG emitter since 2006 (NCCCC, 2012) and is facing mounting domestic and international pressure to mitigate

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GHG emission. Accordingly, China has committed its GHG emission to peak not later than 2030 and reduce its GHG emission per unit gross domestic production (GDP) 40-45 per cent by 2020 and 60-65 per cent by 2030 compared to the 2005 level (NDRC, 2015). Agriculture contributes significant amounts of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) through, for example, emission from carbon loss caused by arable cropping and changing cultivation and emission from fertiliser application or livestock. In total, agriculture accounts for approximately 15 per cent of China's total GHG emission, 90 per cent of N_2O emission, and 60 per cent of CH_4 emission, which is equivalent to about 2.7 times Australia's entire GHG emission (Tang *et al*. 2016a; Wu *et al*. 2018; Yang *et al*. 2018). As such, agriculture can potentially make a significant contribution to China's compliance with its GHG mitigation targets.

Carbon farming has been widely identified as an essential way to reduce agricultural GHG emission. Carbon farming refers to the land use and farm practices that can sequester carbon in natural sinks such as vegetation and soil, or abate GHG emission from agricultural production (Antle *et al*. 2018). Studies have shown that farmers can enhance the amount of carbon stored in agricultural soils and reduce the amount of carbon released back into the atmosphere through carbon farming practices including conservation tillage, crop stubble management, and conversion from annual to perennial crops or pastures (Thamo *et al*. 2013; Khataza *et al*. 2017). Moreover, farmers can also abate non-CO_2 GHG emission by changing crop-pasture growing structure and optimising livestock management (Fiala 2008; Tang *et al*. 2016a,b; Hawkins *et al*. 2018). However, proper policy incentives are often necessary to induce carbon farming practices (Moran *et al*. 2011; Thamo et al. 2013; Tang *et al*. 2018).

The Chinese government started to take serious action to address climate change during the late 1990s. The Green for Grain program, which started in 1999 was one of the world's most ambitious conservation set-aside programs. Another large-scale national effort was the eco-household program to encourage the adoption of renewable energy and biogas digesters. However, these early stage policies aiming for conservation and agricultural GHG abatement were often outweighed by the pro-production policies motivated by food security targets.

Since the 12th Five Year Plan (FYP, 2011-2015), the Chinese government started to implement more specific measures to reduce agricultural GHG emission as a response to the ambitious national GHG abatement targets. Such measures include improving the formulation and implementation of relevant laws and regulations, adopting agricultural technologies that are more compatible with GHG mitigation, practicing soil test-based fertilisation to reduce the amount of fertilisers and N_2O emission, extending straw mulching and no-tillage farming, feeding cattle with ammoniated straw, and transforming from traditional livestock herding to intensive livestock farming (NCCCC 2012).

In addition to these measures, the Government also set specific targets for the agricultural sector as a response to the national GHG mitigation targets set in the FYPs. For instance, the Ministry of Agriculture (MOA) launched programs to abate agricultural GHG emission by enhancing agricultural productivity, including improving fertiliser use efficiency by 3 per cent and enhancing irrigation water use efficiency by 6 per cent by 2015. The MOA also initiated plans to peak the use of agricultural pesticides and fertiliser by 2020. In the 13^{th} FYP (2016-2020), the Chinese State Council also set specific GHG mitigation targets for the agricultural sector: peaking agricultural N_2O emission and reducing 18 per cent carbon emission per unit of GDP by 2020. These targets are expected to be achieved primarily through direct financial incentives and command and control (CAC) policies.

The Chinese government has also experimented with market based GHG mitigation incentives, justified by the commonly held belief that such instruments are more flexible and potentially more cost-effective than conventional CAC policies (Yang *et al*. 2017; Wu and Ma 2018). However, both the emission trading pilot (ETP) introduced in 2012, and the national emission trading scheme (ETS) excludes the agricultural sector.

Despite the Chinese government's interests in encouraging carbon farming and promoting the reduction of agricultural GHG emission, there is little empirical literature on whether carbon farming provides a cost-effective option for GHG mitigation in the Chinese context, and how famers would respond to agricultural GHG mitigation incentives.

In this paper, we employ a whole farm bioeconomic model to analyse the changes in land use, farm practices and on-farm GHG emission under varying levels of agricultural GHG mitigation incentives in China. We focus on the Loess Plateau, the second largest arable land area in China (Liu et al. 2003). The plateau is a typical semi-arid crop-livestock farming region with fragile ecosystems. We also derive the marginal abatement costs of agricultural GHG emission by investigating how crop-livestock farmers respond to agricultural GHG mitigation incentives and calculating associated reductions in GHG emission. In doing so, we hope to shed new light on the design and implications of cost-effective agricultural GHG mitigation policies.

The rest of this paper is structured as follows. We review the relevant literature in Section 2. Section 3 presents the study region and introduces the whole farm bioeconomic model. The results are presented and discussed in Sections 4 and 5, respectively. The last section provides concluding remarks.

2. Literature review

In the context of policy interest in encouraging carbon farming, there has been an emerging literature analysing how land use and farm practices would change in response to agricultural GHG mitigation incentives. Studies of carbon farming have focused particularly on the effectiveness and costs of carbon sequestration practices. They have found that many carbon farming practices such as conservation tillage (Pendell *et al*. 2007; Khataza et al. 2017), rotational cropping (González-Estrada *et al*. 2008; Havlík *et al*. 2012), uninterrupted cropping (Antle *et al*. 2001), crop stubble management (Thamo et al. 2013; Antle et al. 2018), and reforestation on agricultural land (Stavins 1999; Hunt 2008; Hoang *et al*. 2013) could sequester considerable amount of carbon, but the costs of those practices vary depending on the region of analysis, the farming system, and the mitigation strategy studied (Hunt 2008; Tang *et al*. 2016b). For instance, conservation tillage may be the cost-effective option for the highly industrialised regions, while reforestation is more likely to be cost-effective for industrialising regions (Tang *et al*. 2016b, 2018).

Prior studies of Chinese farming systems focused on the analysis of carbon sequestration from cropping (Zhang *et al*. 2013; Yuan *et al*. 2016; Ji *et al*. 2017). The estimated sequestration potential varies depending on the carbon farming practices adopted. Little information about the associated abatement costs is provided in those studies. More importantly, livestock production emits a large amount of non-CO_2 GHG, contributing 44 per cent of anthropogenic CH_4 emission and 53 per cent of anthropogenic N_2O emission (IPCC, 2006); however, GHG emission associated with livestock are excluded from these studies. In China, livestock production emits approximately half of national agricultural GHG emission (Dong *et al*. 2008). To obtain a comprehensive picture of the impacts of carbon farming on GHG emission in crop-livestock mixed farming systems, it is essential to consider crop-related GHG emission but also those generated by livestock through enteric fermentation and manure. Incentives for agricultural GHG emission mitigation are likely to induce changes in crop enterprises, livestock enterprises, and crop-livestock mixes in farming systems.

In the background of China's recent experiments with market-based carbon reduction (i.e. the emission trading pilot introduced in 2012 and the national emission trading scheme launched in 2017) (Jiang *et al*. 2018), it is also of policy interest to know whether carbon farming provides a cost-effective solution to GHG emission reduction. To ease the implementation of the emission trading pilots, the regulatory authorities were reluctant to set stringent emission caps. For instance, the target in the Tianjin pilot was set to be an annual reduction of 0.2 per cent in emission intensity. As a relative mitigation target, reductions in emission intensity do not necessarily translate to real reductions in carbon emission. With such moderate mitigation targets in pilot markets, observed carbon prices range between 50 and 150 Chinese Yuan (¥) (approximately 10-30 AU$) per metric ton. The relevant question to ask is – with incentives for agricultural GHG emission mitigation set at comparable levels, how much GHG emission can be reduced through carbon farming. The answer to this question depends largely on farmers' responses to mitigation incentives and ultimately their marginal abatement cost (MAC) profiles. To the best of our knowledge, there has been no study investigating how Chinese crop-livestock farmers would respond to agricultural GHG mitigation incentives and whether carbon farming in such mixed farming systems would provide a cost-effective option to the overall reduction of GHG emission. This paper attempts to fill these gaps.

3. Materials and methods

3.1 Study region

3.1.1 Overview

We consider the typical mixed dry land farming in the Loess Plateau located in the north of China. The Loess Plateau covers an area of 630,000 km^2 in the upper-middle reaches of the Yellow River (Figure 1). The plateau consists of tablelands, slopes and highly erodible hills and is mostly 1,000-1,600 metres in altitude with an average elevation about 1,200 m above sea level. The plateau has a *hukou* registered population of about 120 million and a resident population of about 110 million, and the population density (167 people per km^2) is 23 per cent higher than the national average (NDRC 2015). The plateau is the second largest arable land area only next to the Huang-Huai-Hai area but has the largest mixed farming system in China. It supplies more than 20 per cent of the live sheep in China with over 75 per cent of the plateau used for agricultural production (Liu *et al*. 2003; SBNHAR, 2015). Although mixed farming also exists in Qinghai-Tibet Plateau, the agricultural production scale on the Qinghai-Tibet Plateau is less than that on the Loess Plateau due to climatic and environmental conditions.

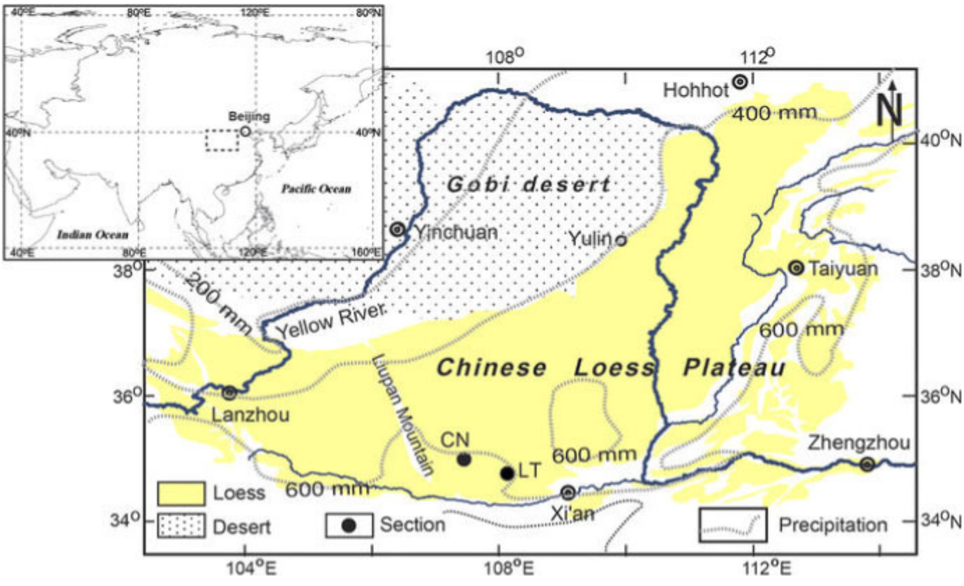

Figure 1 The Loess Plateau in China. [Colour figure can be viewed at wileyonlinelibrary.com] Source: Gong *et al*. (2016).

3.1.2 Climate and Soil

The local climate in the Loess Plateau is a typical semi-arid continental monsoon climate with cold dry winters and hot wet summers. Annual average rainfall decreases rapidly in a north-westerly direction from the plateau's southeast part. The southeast part such as the Guanzhong Plain in the Shaanxi Province receives 600 mm rainfall annually, while the western and northern part of the plateau such as north-western Ningxia and western Ordos Plateau only receive around 200 mm. The annual rainfall in the plateau averages around 450 mm. Approximately 60-80 per cent of the precipitation occurs from July to September (Nolan *et al.* 2008).

In general, soils in the Loess Plateau have low fertility because of the severe soil erosion and surface run-off (Wang *et al.* 2009). Farmers in the plateau use nitrogenous, phosphate, and potassium fertilisers to increase crop yield. Other characteristics of the soils include weak cohesion, high infiltrability and low water retention (Wang *et al.* 2009). Loessial and sandy soils are major agricultural soils in the plateau. Following Messing *et al.* (2003) and Wang et al. (2009), we categorise soils in the Loess Plateau into four main soil types for the purpose of bioeconomic modelling (Table 1).

3.1.3 Farming system

The plateau is a typical mixed dry land farming region with the majority of local farms engaged in integrated crop-livestock management practices (Wang *et al.* 2009). Similar farming systems are also common in the south-eastern part of Central Asia, western Iranian Plateau, and some inland areas of the southern Africa. Since almost no surface water is available and the underground water table is typically 50-80 m below the soil surface and thus difficult to extract, rainfall is usually the sole water source for agriculture in most areas of the plateau (Wang *et al.* 2009). Due to water scarcity, the plateau has a relatively low crop yield. For example, the wheat yield in the plateau is 2.5-3.2 t/ha, which is only about half of the national average of 5.7 t/ha (Tsunekawa *et al.* 2014).

Table 1 Main types of soils in the Loess Plateau†

Soil class	Description
S1: Sandy soils	Sands > 150 cm deep; coarse texture; content of SiO_2 > 60%; organic material < 0.15%
S2: Loess sands	Sands > 100 cm deep; coarse texture; content of $CaCO_3$: 7-12%; organic material < 0.3%
S3: Loessial soils	Pale and loosely packed; silt loam texture; content of $CaCO_3$ 10-20%; organic material: 0.5-2%
S4: Bedrock	Scattered patched of topsoil with bedrock underneath, usually within 20-40 cm; alternate siltstones and massive sandstone outcrops of 5 to 10 metres thick; pH > 8

†Sources: Messing et al. (2003); Wang et al. (2009).

Farm size in the Loess Plateau varies from 0.5 to 3 ha (average 1.8 ha) comprising various soil types (SBNHAR, 2006-2015; YCSB, 2006-2015). Typically more than half of the farm area is allocated to cropping, with the remainder for pasture to graze livestock (Nolan et al. 2008). However, the farmland allocation differs due to diverse farmers' preference and local environmental conditions (e.g. growing season rainfall, temperature, and soil types). The main agricultural products include cereals such as wheat and oats, and livestock such as live sheep.

Crops grown in the Loess Plateau are diverse because of the long history of local farming activities. Local cultivars usually have a high tolerance to drought and other abiotic stresses such as cold, heat, and low fertility (Tsunekawa et al. 2014). Wheat (*Triticum aestivum*) is the major crop on the plateau, accounting for 30 per cent of total crop production, and 20 per cent of the total land use (Nolan et al. 2008). Most of the wheat production is used for household use. Traditionally, wheat is rotated periodically with crop legumes (e.g. dry pea (*Pisum sativum*)), oats (*Avena sativa*), or maize (*Zea mays*). Since the late 1970s, cash crops have been introduced in the region such as rapeseed (*Brassica napus*).

Pastures are also sown in rotation with crops in the plateau. Common legume pastures including lucerne (*Medicago sativa*), a deep-rooted perennial legume, have been planted in the local crop-pasture rotation system for more than 2,000 years. In recent decades, lucerne has been widely planted in the plateau to increase livestock production and to prevent soil erosion (Yuan et al. 2016). Leguminous pastures also help fix nitrogen biophysically in the soil, thus benefiting subsequent crops. Other pastures include crownvetch (*Coronilla varia*), common sainfoin (*Onobrychis vicifolia*), crested wheatgrass (*Agropyron cristatum*), and orchardgrass (*Dactylis glomerata*). Weather condition, soil types, stocking rate, and fertiliser use affect the available amount of pasture biomass. Pasture growth usually starts with spring rain. The amount of pasture biomass typically reaches a peak in later summer or early autumn. Pastures dry off in later autumn but remain a useful source of feed for livestock in winter.

Most farms in the plateau run sheep enterprises. Many local sheep flocks are maintained to be self-replacing. Sheep are run on pastures for producing meat and wool or cashmere. The products are generally for sale. Besides pastures, other feed sources for sheep include crop residues and hay. Sometimes farmers also provide grain as a supplement to maintain the welfare of the flock. In recent years, dry pea, and rapeseed have become important feed sources, especially during the drought seasons.

3.2 Whole farm bioeconomic model

The analysis is based on the whole farm bioeconomic model presented in Tang et al. (2018). The original model (Hailu *et al*. 2011) is a detailed dynamic mathematical programming model developed to facilitate the optimization of gross margins. The gross margin is calculated as farm income deducting all variable and overhead costs. The model optimises land use sequence choice by considering the land use history effects at land management unit level, which means it chooses land uses to maximise the use of the sequencing effects, among other effects that enhance farm profitability. The model considers the biological, technical, managerial, and financial aspects of semi-arid dry land crop-livestock agriculture. The several hundred farm activities in the model include crop-pasture rotations on each of the land management units (LMUs), feed supply and feed use by different livestock classes, and livestock reproduction etc. The solution of the model is the farm activities set of the optimal enterprise that uses available resources to produce maximum gross margin subject to constraints including resource constraints, logical constraints, and technical constraints.

To explore the effect of carbon incentives on land uses, gross margin and GHG emission, we extended the original model by adding a component for the calculation of on-farm GHG emission in the latest version of the model. We used the Intergovernmental Panel on Climate Change (IPCC) inventory method to calculate on-farm GHG emission (IPCC, 2006), but adjusted emission factors to reflect the characteristics of the semi-arid farming region[1] (Tang *et al.* 2016a, 2018). All GHG emission have been converted to carbon dioxide equivalents (CO_2-e). We consider the on-farm emission from crop residues, fertiliser application, livestock, and nitrogen fixing plants. Reductions in GHG emission were calculated from simulated changes in farming practices in response to proposed agricultural GHG mitigation incentives.

The proposed agricultural GHG mitigation incentive in the present analysis is a carbon tax which requires farmers to pay for every tonne of GHG emission. No tax-free emission permits are provided for farmers. The carbon tax rate used is a flat rate and does not change as the taxable amount of GHG emission increases or decreases. We investigate the tax rates varying from 0 to 500 Chinese Yuan (￥)/t CO_2e in increments of ￥50/t CO_2e (AU $10/t CO_2e). The choice of a flat rate carbon tax as the agricultural GHG mitigation incentive is to facilitate a relatively straightforward analysis; however, the whole farm bioeconomic model is adaptable for similar simulation analyses with alternative carbon incentives such as auction-based permit systems.

The model employed simulates a representative farm in the Loess Plateau. The farm has a size of 1.8 ha and been divided into 12 LMUs. To reflect typical soil conditions of local farms in the plateau (Messing *et al.* 2003;

[1] The emission factors (EFs) used in the IPCC (2006) are based on international analyses. The Loess Plateau's semi-arid agroclimatic environment is not well described by the EFs in IPCC (2006). Therefore, we replaced the recommended EFs by the experiment results from those studies conducted in similar agroclimatic conditions. Details about those modifications can be found in Appendix S2 and Tang et al. (2016a).

Wang *et al*. 2009), we have allocated the largest area of the typical farm to *Loess sands* and *Loessial soils*. The soil types and areas of various land management units that comprise the typical farm are shown in Table A1 in Appendix S1.[2] The farm operates a mixture of cropping and livestock enterprises. In this model, the crops grown include wheat, oats, rapeseed, and dry pea. These are planted in rotation with pasture. The livestock on farm are represented by sheep. The sheep enterprise parameters are based on Tang et al. (2018). The annual rainfall is set as 445 mm, representing the typical precipitation in this region which has a semi-arid continental monsoon climate (Nolan et al. 2008).

Prices of crops and livestock commodities used in this study are shown in Table A2 in the Appendix. All prices are farm-gate prices, expressed in 2015 Chinese Yuan (¥). We assume that crop-livestock farmers make their production decisions based on the expected market prices for crops and livestock, production costs, and local environmental conditions (e.g. soil types, growing season rainfall, and crop rotation effects).

4. Results

In this section, the simulation results without agricultural carbon tax are presented first. They are followed by the results simulated with varying agricultural tax rates. Our simulation covers a 10-year horizon. The results presented are averaged over a 10-year period.

4.1 Simulation without agricultural carbon tax

Without agricultural carbon tax, the maximum gross margin is ¥3540.6/ha (AU$708.1/ha) when farmers use the optimal cropping-livestock enterprise (Figure 2). About half of the land is devoted to growing crops, while the remainder is used for producing pastures for grazing. The optimal cropping-livestock enterprise requires 49.4 per cent (0.88 ha), 18.5 per cent (0.33 ha), 21.1 per cent (0.38 ha), 10.75 per cent (0.19 ha), and 0.3 per cent (0.005 ha) of the farmland are devoted to pastures, wheat, oats, rapeseed, and dry pea, respectively. The rotations chosen frequently in this optimal enterprise are continuous pastures, pastures-oats rotations, pastures-wheat-oats rotations and pastures-rapeseed-wheat rotations (Table 2). It should be noted that the typical farm includes twelve LMUs and the included rotations are chosen for different soil types to provide the maximum gross margin farming system overall. The yields of all crops are around 3 t/ha. These simulation results are

[2] These allocations were further consulted with agricultural scientists and agricultural economics at Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Huazhong Agricultural University, and Northwest Agriculture and Forestry University.

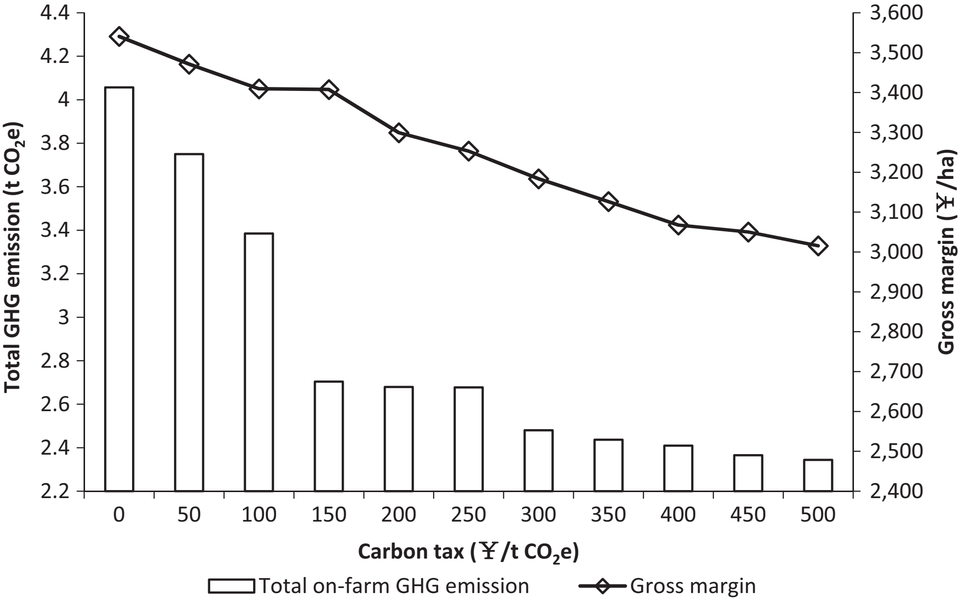

Figure 2 Maximised gross margin and total on-farm GHG emission.

broadly in line with existing empirical studies for the semi-arid farming systems in the Loess Plateau (Tsunekawa et al. 2014).

In the optimal scenario without agricultural carbon incentives, the total on-farm GHG emission are 4.06 tCO_2e per year or 1.95 tCO_2e per hectare annually. Livestock are the major source of emission. On average, livestock production contributes approximately 85 per cent to the total on-farm GHG emission (3.47 tCO_2e annually). Nitrogen-fixing plants are the second largest emitter, producing approximately 12 per cent of the total emission. The emission caused by fertiliser use and crops residues are modest. These numbers are consistent with previous studies conducted for similar semi-arid mixed agricultural systems (Thamo et al. 2013; Tang et al. 2016a).

4.2 Simulation with agricultural carbon tax

Table 2 presents the crop-pasture rotations that maximise gross margin with varying agricultural carbon taxes. Figure 2 shows the corresponding total on-farm GHG emission and maximised gross margin. Figure 3 illustrates the land allocations for the optimised enterprise at varying levels of carbon tax. In Figure 4, we compare the effects of carbon tax on total GHG emission and livestock emission.

With the agricultural carbon tax set at￥50 (AU$10), ￥100(AU$20), and ￥150(AU$30) for each tonne of GHG emitted, the maximum gross margin decreases to ￥3471.2/ha (AU$694.2/ha), ￥3409.3/ha (AU$681.9/ha) and ￥3407.4/ha (AU$681.5/ha), respectively (Figure 2). Farmers expand the

Table 2 Gross margin maximising rotations by soils with varying agricultural carbon taxes

Carbon tax (¥/t CO_2e)	Optimal crop–pastures rotations†			
	S1: Sandy soils	S2: Loess sands	S3: Loessial soils	S4: Bedrock
0	POO, PRO, PPOD	POO, POP, POW, PRO, PWO, PRW, WPRW	PPP, POP, PPO, PWP, PPW, PRW	PRW, PRWP
50	POW, PWW, PRW, WPWO	PPP, POO, POP, PRW, WPRW	POP, POW, PWO, PWW, PWPW, PDW, PWD, PRW, DOP, OODR	POO, POOD
100	PPP, PRW, PDR	PWW, PPW, PRW, PDW, WPRW	PWW, WPW, WPP, PRW, PDW, PPD, WPD	PPP, WDP
150	PPO, WPWO, PPO	PRW, PDW, PWD, DRW	PWW, PDW, PWD, PDWD	PWW, PRW, PRWD
200	PWW, PDW, DPDW	PWW, PRW, PDW, WPDW	PWW, PRW, PDW, PWD, PDWD, DRW, DPDW	PPO, PDW
250	PRW, PDR, DRW	PWW, PRW, PDW, PWD	PWW, PRW, WPRW, PDW, PWD, PDWD	PWW, PDW, PDWD
300	PWW, PWD, PDW	PWW, PDW, PDWD	PWW, PDW, PWD, PDR, WPDO	PWW, DRW
350	PWW, PDW, DPDW, WPR	PWW, PDW, PWD, DPDW	PWW, PDW, PWD, DPDW, DRW	DRW, DRWD
400	PDW, PWD, DRW, DCWR	PDW, PDWD, DRW	PWW, PDW, PWD, PDWD, DPDW	PDR, DRW
450	PDW, PWD, PDR, DRW	PWW, PDW, PWD, PDWD, DRW	PWW, PDW, PWD, PDWD, DPDW, RDR	PDW, PDWD
500	PDW, PDWD, WDR	PWW, PDW, PWD, PDWD, DPDW, WDR	PWW, PDW, PWD, PDWD, DPDW, DRD	PWW, PDW, PDWD

†P = pastures; W = wheat (*Triticum aestivum*); O = oats (*Avena sativa*); R = rapeseed (*Brassica napus*); D = dry pea (*Pisum sativum*).

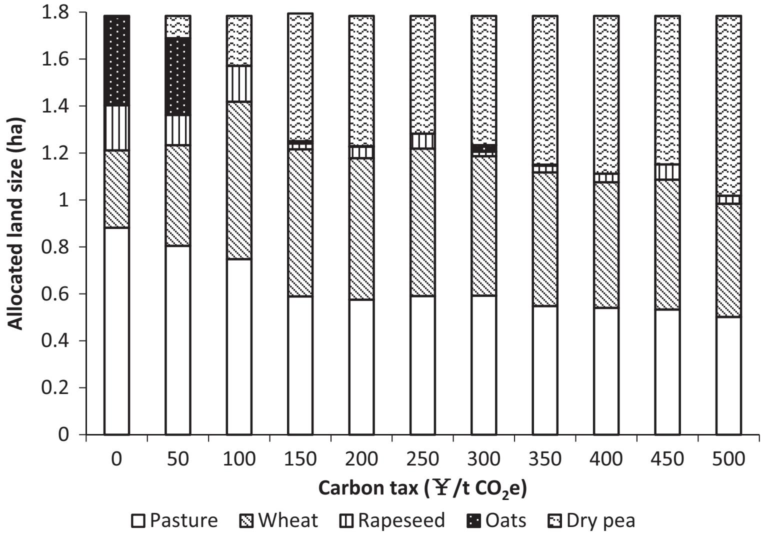

Figure 3 Gross margin maximised land allocations.

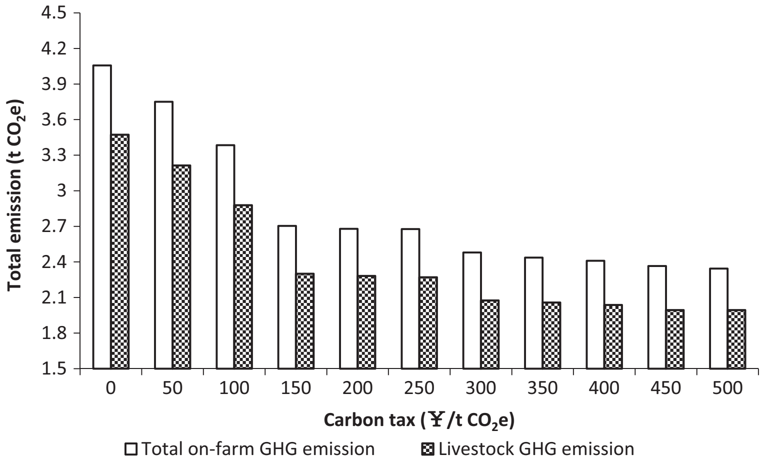

Figure 4 Total on-farm emission and livestock emission for gross margin maximising enterprise mixes.

production of wheat and dry pea, while they allocate less land for pastures, oats, and rapeseed (Figure 3). More rotations that include dry pea are chosen by farmers in the optimal enterprise (Table 2). When the tax rate is higher than ¥100/t CO_2e, the predominant rotations are pastures-wheat rotations and pastures-dry pea-wheat rotations, while oats-based rotations have been excluded in the predominant rotations in the optimal enterprise (Table 2). The total annual on-farm GHG emission with a ¥50/t CO_2e, ¥100/t CO_2e and ¥150/t CO_2e agricultural carbon tax are 7.6, 16.6, and 33.3 per cent lower than the no-tax scenario, and the abated emission come from livestock and cropping proportionally (Figure 4). When wheat is planted as a subsequent crop after dry pea in pastures–dry pea–wheat rotations, the yield of wheat is 3.6 t/ha, which is 11 per cent higher than the yield of wheat in other rotations.

With higher agricultural carbon taxes (￥150 to ￥500/t CO_2e), the optimal gross margin keeps decreasing; however, the reductions in pastures grown area and total emission become limited. Note that wheat and dry pea are chosen as the main crops at all tax levels. In addition, pastures-wheat rotations and pastures-dry pea-wheat rotations are the dominating choices in all soils. If the agricultural carbon tax is as high as ￥500/t CO_2e (AU$100/t CO_2e), In this case, 42.9 per cent of the farmland is used for dry pea production, and the remainder is approximately equally allocated for wheat and pastures. The total GHG emission will be abated to 2.34 tCO_2e (42.2 per cent lower than the no-tax scenario). The maximum gross margin is ￥3,015.4/ha (AU$603.1/ha).

5. Discussion

Our simulation results show that as the carbon tax increases, mixed crop-livestock farming systems in the Loess Plateau would become increasingly crop dominated. Studies have found that livestock production is the dominant source of agricultural GHG emission and more emission intensive than cropping in crop-livestock farming systems (Fiala 2008; Thamo et al. 2013; Herrero *et al.* 2016; Tang et al. 2018). In our analysis, livestock contributes approximately 85 per cent to the total emission in the no-tax scenario. On average, the annual GHG emission from livestock production are approximately 3.85 t/CO_2e/ha, while that for cropping is < 0.65 tCO_2e/ha. If agricultural GHG emission are regulated with a carbon tax, the extra cost of cropping in terms of carbon tax payment is significantly less than that of livestock production. The rational response of farmers would be to limit the emission intensive livestock production including sheep grazing and pastures planting and expand cropping production.

As China's diet is shifting more towards livestock products (Hawkins et al. 2018), a major agricultural production shift away from livestock under GHG mitigation regulations (e.g. carbon tax) could potentially cause a considerable supply–demand gap. An essential action to resolve this dilemma is to further increase livestock productivity and health. Enhancing the genetic potential of livestock, their reproduction, health, and liveweight gain rates are useful methods for abating GHG emission per unit of product (Herrero et al. 2016). Technical and management interventions, including using feed additives, improving feed digestibility, and managing manure could also contribute to the resolution of the trade-offs between increasing livestock product supply and reducing agricultural GHG emission. The supply–demand gap could also create opportunities for major international suppliers including Australia, New Zealand, United States, and Brazil.

Our estimates also show that as the agricultural carbon tax increases, farmers employ less oats-based and rapeseed-based rotations and more dry pea-based rotations in the optimal enterprise mix. This is because the total emission of a crop are determined by the amount of nitrogen fertiliser used and the nitrogen concentration in some crop components such as roots and straw (Gan *et al*. 2009). Researchers have found that dry pea-based rotations emit much less GHG emission than oats-based and rapeseed-based rotations because the former need less nitrogen fertiliser when growing in semi-arid farming systems (Rajaniemi *et al*. 2011). Dry pea fulfils its nitrogen need through biological N-fixation and therefore reduces the need for nitrogen fertiliser and the associated GHG emission. In addition, dry pea can potentially improve the production of subsequent crops via multiple ways. The cereal yield may increase when cereal is planted as a subsequent crop after dry pea in pastures-dry pea-cereal rotations. We found that the yield of wheat in pastures-dry pea-wheat rotations is 11 per cent higher than the yield of wheat in other rotations. This contribution can be further enhanced by increasing the frequency of dry pea in cropping rotations, decreasing the negative impact of high residual soil nitrogen on N-fixation, and improving the synchrony between nitrogen mineralisation from dry pea residues and the peak nitrogen demand of the subsequent crop (Tang et al. 2018). Therefore, with agricultural GHG mitigation incentives, farmers in the Loess Plateau are likely to reduce oats-based and rapeseed-based rotations but increase dry pea-based rotations in the optimised enterprise mix.

We also found that relatively small increases in carbon tax can induce substantial reduction in total on-farm GHG emission whereas the associated costs of GHG mitigation are relatively small. An agricultural tax of ￥50/t CO_2e, ￥100/t CO_2e and ￥150/t CO_2e will reduce total on-farm GHG emission by 7.6, 16.6, and 33 per cent, respectively. The corresponding reductions in gross margin are only 2, 3.7, and 3.8 per cent.

These results suggest that the marginal abatement costs (MAC) of 8.6, 16.6, and 33 per cent of total on-farm GHG emission are <￥50/t CO_2e, ￥100/t CO_2e, and ￥150/t CO_2e, respectively. Wang *et al*. (2014) developed a bottom-up MAC curve for China's agricultural sector, which shows that the MAC of approximatively 40 per cent of total GHG emission is <￥123/t CO_2e. This is consistent with the present analysis.

In the context of China's recent experiments with market-based carbon reduction, our results have significant implications for the design of a national emission trading scheme. With only moderate mitigation targets in the pilot trading markets, observed carbon prices have already reached a level of ￥50 to ￥150 per metric ton. Our results show that with incentives for agricultural GHG emission mitigation set at comparable levels, substantial GHG emission can be reduced. Carbon farming in China's semi-arid crop-livestock agriculture is potentially a very cost-effective mitigation option.

Caution needs to be taken in interpreting our results. First of all, the estimated agricultural GHG emission depend on the assumptions regarding regionally specific prices of agricultural products, soil types, and climates. The results presented are on the basis of a typical farm in the Loess Plateau in China, a semi-arid crop-livestock mixed farming region. The results may be used for understanding agricultural abatement in similar farming systems in the south-eastern part of Central Asia, western Iranian Plateau and some inland areas of southern Africa. However, different farming systems, soil types, climates in other farming areas in China and other countries and variations in product prices could all have impacts on farmer responses in land use changes, gross margin, and the estimated agricultural GHG emission.

Further, the current analysis excludes co-benefits such as soil fertility improvement and biodiversity protection brought by carbon farming practices (Tang et al. 2016b). The Loess Plateau is an area with severe soil erosion and surface run-off, and soils in the plateau usually have low fertility (Wang *et al*. 2009). By adopting carbon farming practices such as rotational cropping and conservation tillage, farmers can reduce soil erosion and improve soil fertility. Such private co-benefits could further reduce the MAC of GHG emission. In addition, carbon farming can also produce public good such as biodiversity conservation. A comprehensive analysis incorporating such private and public co-benefits could potentially justify even higher agricultural carbon incentives.

On the other hand, readers should bear in mind that adopting carbon farming practices will generate extra costs not directly associated with farming activities (Tang et al. 2016b). Such extra costs, including transaction and learning costs, are currently excluded in our analysis and may bring extra barriers for China's crop-livestock farmers to applying carbon farming practices.

6. Conclusions

In this study, we apply a whole farm bioeconomic analysis to explore the changes in land use, farm practices and on-farm GHG emission under varying levels of agricultural GHG abatement incentives in the form of a carbon tax for a semi-arid crop-livestock farming system in China's Loess Plateau.

The results show that the optimised agricultural enterprises move further towards crop-dominated farming for the purpose of producing less on-farm emission since livestock are far more emission intensive than crops. Farmers employ less oats-based and rapeseed-based rotations but more dry pea-based rotations in the optimal enterprise mix. In addition, the results show that small increases in a carbon tax may achieve substantial reduction in on-farm GHG emission and the reduction costs are relatively small. Our estimates indicate that crop-livestock farmers in the Loess Plateau may reduce their on-farm GHG emission by 16.6 and 33 per cent with marginal abatement costs not higher than ￥100/t CO_2e (AU$20/t CO_2e) and ￥150/t CO_2e (AU$30/t CO_2e) in 2015 Chinese Yuan, respectively.

In the context of observed carbon prices in China's pilot carbon trading market, our analysis implies that reducing GHG emission in China's semi-arid crop-livestock agriculture is potentially a low-cost option. By using carbon taxes to provide incentives to farmers to abate GHG emission in China's semi-arid crop-livestock agriculture sector can reduce on-farm GHG emission substantially through changing farms' land use and farm management practices, but also achieve GHG mitigation in a cost-effective way.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Land management units and price of agricultural commodities.

Appendix S2. Additional explanatory notes on modelling parameters.