Research Article

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Planting and mowing cover crops as livestock feed to synergistically optimize soil properties, economic profit, and environmental burden on pear orchards in the Yangtze River Basin

Haoran Fu,[a] Hong Chen,[b] Qingxu Ma,[a*] Bo Chen,[c] Feiyang Wang[a] and Lianghuan Wu[a*]

Abstract

BACKGROUND: Pears, as an important cash crop, are currently facing great issues due to unsustainable management practices. Cover cropping is a sustainable management strategy that can improve soil fertility and increase fruit yield, while it may also stimulate greenhouse gas emissions. Therefore, synergizing multiple indicators to achieve sustainable development is critical. This study introduces a new management system, namely the planting and mowing of ryegrass as a livestock feed system (PRSS), and analyzes its impact on soil quality, economic benefits, and environmental burdens.

RESULTS: Our results indicated that PRSS could increase soil pH from 5.08 to 5.48 and decrease the content of soil alkali-hydrolyzable nitrogen, total phosphate, and available phosphate (26.96–59.89%) while also enhancing yield (+38.51%) compared with the traditional natural grass management system (TMS). The average soil methane fluxes in PRSS were 72.67 μg m^{-2} day^{-1}, higher than those of TMS (61.28 μg m^{-2} day^{-1}). However, the gross primary production was lower than TMS (−37.24%), and no significant difference was observed in soil nitrous oxide fluxes. In different scenarios, the total profit of PRSS mode 1 (mowing ryegrass and selling to a livestock company) and PRSS mode 2 (mowing ryegrass and feeding own sheep) were 10 706.21 \$ ha^{-1} and 26 592.87 \$ ha^{-1} respectively. These values are respectively2.36 times and 5.85 times higher than that of TMS. The total global warming potential of TMS (18.19 t CO_2-eq ha^{-1}) was 1.29 t CO_2-eq ha^{-1} higher and 2.89 t CO_2-eq ha^{-1} lower than that of PRSS mode 1 and mode 2 respectively.

CONCLUSION: Compared with traditional natural grass, planting and mowing ryegrass in pear orchards can optimize soil properties, increase fruit yield, and reduce global warming potential. Different modes can greatly increase revenue but have varying impacts on environmental burdens. These findings can help rebuild the links between farmland and specialized livestock production, contributing to sustainable development in the pear industries.

Supporting information may be found in the online version of this article.

Keywords: mowing ryegrass; pear yield; economic benefit; environmental impact; soil properties

INTRODUCTION

With a planting area of 0.96 × 10^6 ha, pear (*Pyrus* spp.) is the third largest cash crop and an important source of income for smallholders in China.[1,2] To ensure high yields and benefits, unsustainable management practices, such as excessive chemical fertilizer application, have caused extensive problems in terms of environmental impacts, income equality, and soil quality in pear orchards.[3,4] Wang *et al.*[4] highlighted that the average nitrogen (N) fertilizer application rate for pear production on the North China Plain was 693.2 kg ha^{-1}, causing greenhouse gas emissions three to six times greater than those in northern Italy and other countries.[5-7] Additionally, the average pear yield in China is

* *Correspondence to: Q Ma or L Wu, Zhejiang Provincial Key Laboratory of Agricultural Resources and Environment, College of Environmental and Resource Sciences, Zhejiang University, Hangzhou 310058, China, E-mail: qxma@zju.edu.cn (Ma); finm@zju.edu.cn (Wu)*

a *Zhejiang Provincial Key Laboratory of Agricultural Resources and Environment, College of Environmental and Resource Sciences, Zhejiang University, Hangzhou, China*

b *School of Public Affairs, Zhejiang University, Hangzhou, PR China*

c *Hangzhou Yuhang Sanshui Fruits Co., Ltd, Hangzhou, China*

17.9 t ha^{-1} $year^{-1}$, which is one-third of the average yield of the top ten countries worldwide, and the average soil organic matter is 28.9 g kg^{-1}, lower than that in most pear orchards in Japan (>30 g kg^{-1}).[2] Therefore, there is an urgent need to explore sustainable management practices to reduce environmental risks, improve economic benefits, and optimize soil quality.

Cover cropping is a sustainable management strategy in fruit orchards. When the cover crop is harvested, it is primarily used as green manure to cover the ground surface, and the positive effects of long-term green manure application on soil fertility, fruit yield, and fruit quality have been reported.[8-11] However, the low economic benefits have restricted the widespread adoption of this practice.[12,13] Symbiotic farming technologies, such as crop–livestock integration, could substantially improve the economic benefits. The integration of cover crops with livestock grazing has been reported in orchard systems.[14,15] Peterson *et al*.[15] indicated that the yield of integrated crop–livestock systems was higher than that of unintegrated systems on loamy soils. Paolotti *et al*.[14] suggested that combining free-range poultry and olive orchards can improve agricultural sustainability. However, such integrative systems are in sharp decline because of soil quality deterioration and labor shortages.[16,17] In addition, adding cover crops as green manure could stimulate greenhouse gas emissions. This mechanism was mainly related to microbial activity improvement and soil respiration stimulation, with most studies focusing on reducing greenhouse gas emissions during green manure application.[18]

To increase economic benefit, reduce greenhouse gas emissions, and maintain soil quality, we introduced a new management mode: planting and mowing cover crops as livestock feed. Cover crops, usually planted in orchards, can be used as livestock feed, such as forage crop ryegrass (*Lolium perenne* L.).[4,19] Annual ryegrass is grown as a winter cover crop in orchards in southern China and can be used as fodder grass for livestock owing to its high biomass and protein content. Importantly, mowing ryegrass can be used as a forage crop to increase the economic benefit, and low-returning biomass of green manure could help reduce greenhouse gas emissions. In addition, mowing ryegrass can also effectively adjust the excessive soil nutrient content to optimize soil properties. However, it is unknown whether planting and mowing ryegrass as forage positively impacts soil properties, growth status, pear yield, and greenhouse gas emission, and the potential of different modes on economic benefits and environmental impacts are unclear.

The Yangtze River Basin, one of the major pear districts, produces more than 80% of early ripening pears and 20% of the total pear yield in China.[20] Moreover, the climate in this area is warm and has a long frost-free period, making it suitable for grass growth.[21] Zhang *et al*.[22] indicated that China's Yangtze River Basin region is rich in germplasm, with over 3000 natural herbage resources.

In this study, we hypothesized that planting and mowing cover crops as livestock feed on pear orchards would positively affect soil properties, increase yield, and reduce global warming potential (GWP) by decreasing microorganisms' decomposition. We compared two management practices: the first one is a traditional natural grass management system (TMS), and the second one is planting and mowing cover crops as a livestock feed system (PRSS). Moreover, we set two scenarios in the PRSS – mode 1: sell ryegrass directly to livestock companies; mode 2: ryegrass to feed their sheep – aiming to clarify the potentials of different modes. The objectives were (1) to assess the difference between the PRSS and TMS on soil quality, growth status, pear yield, and environmental burdens (methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O) flux) in pear orchards, and (2) to quantify the potential for economic and environmental synergy among different modes.

MATERIALS AND METHODS

Description of the study site

The study site was located in Luniao County, Zhejiang Province, China (119°44′E, 30°27′N), which has a subtropical monsoon climate. The planting area of pear in this county was relatively large, spanning more than 600 ha, and the primary pear cultivar was 'Cuiguan', a representative variety in the Yangtze River Basin. The average annual rainfall is 1350 mm, and the average annual temperature is 16.0 °C, with a frost-free period of 270 days. The spacing in the rows and spacing between rows of trees in the research site is 4 m and 3 m respectively. The soil of the research site was yellow–brown with 18.41 g organic matter per kilogram, 94.09 mg available nitrogen (AN) per kilogram, 10.57 g available phosphate (AP) per kilogram, 149.10 g available potassium (AK) per kilogram, and a soil pH of 5.35.

The field experiment set two treatments (Fig. 1), namely the TMS and PRSS, and was designed with a completely randomized block design, with each treatment set having three replicates. The size of each replicate was 24 m × 3 m, with six pear trees. The PRSS involves planting ryegrass in November and mowing it three times, in March, April, and May, the following year. The natural grass treatment (TMS) allowed all weeds to grow, such as horsetail grass, lice grass, and tiger tail grass. The soil was covered with grass, and only tall grass (above 40 cm) was removed. The cutting time of the TMS was the same as the PRSS, and mowed weeds were directly covered on the surface as green manure. For the TMS, organic fertilizer was purchased at the local store. Alternatively, the mowed ryegrass in the PRSS could be sold to livestock companies or used to feed their sheep, and the manure came from a local livestock company. The organic fertilizer input rate was calculated based on the same total N (TN). The total fertilizer N, phosphorus pentoxide, and potassium oxide application rates were consistent with local farmer fertilization practices (424.2 kg ha^{-1}, 386.4 kg ha^{-1}, and 323.4 kg ha^{-1} respectively), and the fertilizer was applied in October for organic fertilizer and in March and May for chemical fertilizer. The detailed input information for the other management is shown in Supporting Information Table S1.

Indicators of pear growth, soil samples, and pear yield

Pear tree growth indicators were monitored when the new shoots stopped growing (30 June 2021). Three healthy pear trees were selected as sampling points for each replicate in different treatments. The length and thickness of eight new shoots per tree were measured using a tape measure, and the soil plant analysis development (SPAD) value of the mature middle leaves was measured using a chlorophyll meter. The fruit and soil samples were processed on the same day in July 2021. A soil sample at 0–40 cm soil depth was collected from each tree, which was a mix of the three soil replicates within the same plots, similar to Fu *et al*.[20] The soil was air-dried to determine the soil properties according to the method used by Bao.[23]

The soil pH was measured using a Delta 320 pH meter (Mettler–Toledo Instruments Co., Shanghai, China) with a soil:water ratio of 1:5. The soil organic carbon (SOC) was measured using the

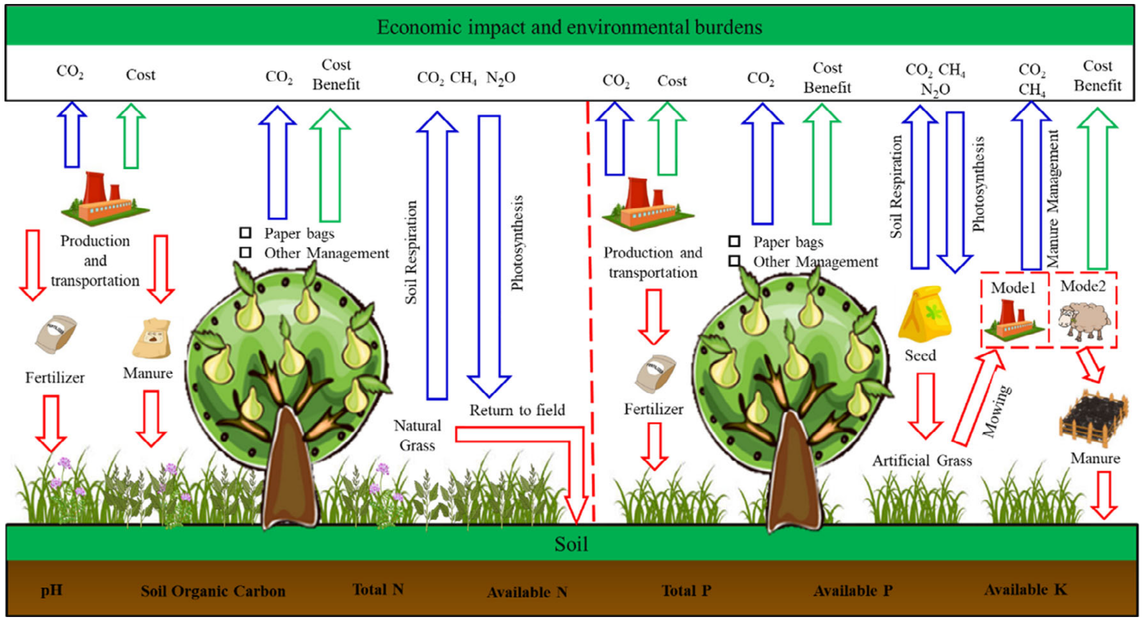

Figure 1. Comparison of management information between traditional natural grass management system and planting and mowing ryegrass as livestock feed system. Available N, alkali-hydrolyzable N; available P, available phosphate; available K, available potassium; mode 1, mowing ryegrass and selling to livestock company; mode 2, mowing ryegrass and feeding own sheep; total N, total nitrogen; total P, total phosphate; CO_2, carbon dioxide; CH_4, methane; N_2O, nitrous oxide. The red arrow represents the inputs and outputs in the production process; Green arrows represent the cost and benefit at different stage; The purple arrows represent greenhouse gas emission information for each section.

potassium dichromate oxidation–reduction titration method. The Kjeldahl digestion method, alkaline diffusion method, and perchloric acid–sulfuric acid digestion method were used to measure soil TN, alkali-hydrolyzable N (AN), and soil total phosphate (TP) respectively. The soil AP was extracted using a hydrochloric acid–ammonium fluoride solution and determined using a spectrophotometer (UV-1780; Shimadzu Corporation, Kyoto, Japan). The AK was measured using ammonium acetate and a flame photometer (INESA 6400A; INESA, Shanghai, China).

The total number of fruits was counted for each tree, and eight peripheral fruits were collected from different positions in the east, south, west, and north. The mean weight of each fruit was then measured. The pear yield per tree was obtained by multiplying the total number of fruits by the average weight of the fruit.

Economic benefit

The total input, output, and profit of the different systems were calculated using the following equations:

$$T_{\text{cost}} = T_{\text{orchard}} + T_{\text{livestock}}$$

where T_{cost} is the total cost for the overall system, T_{orchard} (the cost of pear orchard management) is

$$\begin{aligned} T_{\text{orchard}} = {} & T_{\text{land preparation}} + T_{\text{tree pruning}} + T_{\text{paper bags}} + T_{\text{pesticide}} \\ & + T_{\text{chemical fertilizer}} + T_{\text{organic fertilizer}} + T_{\text{chemical fertilizer}} \\ & + T_{\text{fuel for pear orchard}} + T_{\text{electricity for pear orchard}} \end{aligned}$$

and

$$\begin{aligned} T_{\text{livestock}} = {} & T_{\text{grass seed}} + T_{\text{labor of mowing}} + T_{\text{feeds}} + T_{\text{labor of sheep}} \\ & + T_{\text{fuel for sheep management}} + T_{\text{electricity for sheep management}} \end{aligned}$$

where

$$T_{\text{feeds}} = \left(S_{\text{total feeds}} - S_{\text{ryegrass}}\right) \times \text{Price}$$

$T_{\text{land preparation}}$, $T_{\text{tree pruning}}$, $T_{\text{paper bags}}$, $T_{\text{pesticide}}$, $T_{\text{chemical fertilizer}}$, $T_{\text{organic fertilizer}}$, $T_{\text{fuel for pear orchard}}$ and $T_{\text{electricity for pear orchard}}$ are respectively the inputs of land preparation, tree pruning, paper bags, chemical fertilizer, organic fertilizer, fuel consumption, and electricity consumption in pear production, including the cost of labor, fuel, and electricity. The costs of these processes were obtained through surveys. The amount of organic fertilizer is shown in Supporting Information Table S1, and the price is \$124.0 t^{-1}. $S_{\text{total feeds}}$ is based on each sheep eating 4.0 kg of forage per day, and the feeding cycle is 1 year. The total number of sheep is 75, S_{ryegrass} is the amount of forage provided by the ryegrass in pear orchards (75.0 t ha^{-1}), and Price (P) is calculated using \$29.8 t^{-1} according to the surveys. $T_{\text{labor of mowing}}$ and $T_{\text{labor of sheep}}$ are also obtained using surveys.

$$T_{\text{output}} = T_{\text{pear}} + T_{\text{sheep}}$$

$$T_{\text{profit}} = T_{\text{output}} - T_{\text{cost}}$$

where T_{output} is the total output of the different modes and T_{pear} is pear yield multiplied by pear price (\$1.8 kg^{-1}), where pear yield is the results measured from Section 2.2. T_{sheep} is the number of sheep (75) multiplied by the sheep price per head (\$298.5).

Environmental burdens

CH_4, CO_2, and N_2O flux from cover crop management

Once the cover crop was planted, the *in situ* CH_4, CO_2, and N_2O fluxes were measured using a static chamber. The gas sampling chambers comprised permanent stainless-steel bases

($55 \times 55 \times 12$ cm^3) with a 5 cm groove for water sealing and the upper frame ($55 \times 55 \times 60$ cm^3). A small fan was installed in the upper cover to ensure the even mixing of gases, and a vacuum pump measuring 10 cm × 10 cm × 3 cm was placed in the center of the upper cover for gas sampling. Gas samples were collected every 1–2 weeks, stored in aluminium foil gas bags (250 mL; Delindl, Dalian, China), and analyzed using a gas chromatograph (Shimadzu 14B; Shimadzu Corporation) to determine the gas concentration. Sampling was conducted from November 2021 to June 2022 within 1–2 weeks after planting the ryegrass. On each sampling date, daytime samples were collected from 9:00–11:00 a.m. to 3:00–5:00 p.m., whereas nighttime samples were collected from 7:00 to 9:00 p.m., following a similar method to that of Zheng *et al.*[12]

The gas fluxes were calculated using the following formula:

$$F = \frac{PV}{RA(T+273.15)}\frac{dC}{dt}$$

where F is the gas emission flux (μg m^{-2} h^{-1} forCH_4 and NO_2, mg m^{-2} h^{-1} for CO_2), P is the atmospheric pressure (101.2×10^3 Pa), V is the chamber effective volume (0.125 m^3), and R is the gas constant (8.314 J mol^{-1} K^{-1}). A is the area of the chamber cover (0.25 m^2), T (°C) is the average temperature inside the chamber at the time of testing, and dc/dt is the rate of change in the concentration of CO_2, CH_4, and N_2O.

To calculate the gas fluxes, the daytime and nighttime gas fluxes from the sampling dates were calculated using the following formulas:

$$F_{\text{daytime}} = S_{\text{daytime}} M_1 \frac{F_1+F_2}{2}$$

$$F_{\text{night}} = S_{\text{night}} M_2 F_3$$

$$F_{\text{day}} = F_{\text{daytime}} + F_{\text{night}}$$

where F_1, F_2, and F_3 are the values at 9:00–11:00 a.m., 3:00–5:00 p.m., and 7:00–9:00 p.m. respectively. S_{day} and S_{night} (h day^{-1}) are the day and night lengths respectively on the sampling date. M (g mol^{-1}) is the relative molecular mass of CO_2, CH_4, or N_2O. The net ecosystem exchange (NEE) is the CO_2 value of F_{daytime}, ecosystem respiration (Reco) is the CO_2 value of F_{night}, and gross primary production (GPP) is the sum of the NEE and Reco.

The formula for calculating the cumulative emissions of greenhouse gases (CH_4, CO_2, and N_2O) is

$$W = \sum_{i}^{n} (R_i \times D_i)$$

where W (kg·ha^{-1}) is the total amount of gas emission, R_i (mg m^{-2} day^{-1}) is the daily emission flux at sampling time i, and D_i is the number of days between the two sampling dates (i and $i+1$ time). The GWP (kg CO_2-eq ha^{-1}) is calculated as

$$\text{GWP} = W_{CO_2} + 28W_{CH_4} + 265W_{N_2O}$$

where W_{CO_2}, W_{CH_4}, and W_{N_2O} are the respective total CO_2, CH_4, and N_2O emissions from the soil.

GWP of different systems

The management information and conversion coefficient are shown in Supporting Information Tables S1 and S2 respectively. The formula for estimating the GWP of different systems is as follows:

$$\text{Total GWP}\left(\text{kg } CO_2\text{–eq ha}^{-1}\right) = \begin{array}{l}\text{GWP}_{\text{orchard}} + \text{GWP}_{\text{cover crop}} \\ + \text{GWP}_{\text{sheep management}}\end{array}$$

$$\begin{aligned}\text{GWP}_{\text{orchard}} = {} & \text{GWP}_{\text{chemical fertilizer production}} \\ & + \text{GWP}_{\text{organic fertilizer production}} + \text{GWP}_{\text{pesticide}} \\ & + \text{GWP}_{\text{paper bags}} + \text{GWP}_{\text{fuel}} + \text{GWP}_{\text{electricity}} \\ & + \text{GWP}_{\text{labor of management}} + \text{GWP}_{\text{organic fertilizer application}}\end{aligned}$$

where $\text{GWP}_{\text{orchard}}$ is the gas emission from pear production, which includes producing and transporting chemical fertilizer, organic fertilizer, pesticide and paper bags, labor, electricity, and fuel consumed by field management. The calculation of $\text{GWP}_{\text{organic fertilizer application}}$ is derived from Wang *et al.*[4] and Zhang *et al.*[24] $\text{GWP}_{\text{organic fertilizer production}}$ in TMS is estimated according to Supporting Information Table S1, whereas the $\text{GWP}_{\text{organic fertilizer production}}$ in PRSS is calculated using the following formula, according to Eggleston *et al.*:[25]

$$\begin{aligned}& \text{GWP}_{\text{organic fertilizer production}} \\ & = 28 \times CH_{4\,\text{emission}} + 265 \times \left(N_2O_{\text{direct}} + N_2O_{\text{indirect}}\right)\end{aligned}$$

where

$$N_2O_{\text{direct}} = \{[\sum(N \times \text{Nex} \times \text{MS})] \times \text{EF}_3\} \times \frac{44}{28}$$

and

$$\begin{aligned}N_2O_{\text{indirect}} = & \left\{[\sum(N \times \text{Nex} \times \text{MS})] \times \text{Frac}_1 \times \text{EF}_4\right. \\ & \left. + [\sum(N \times \text{Nex} \times \text{MS})] \times \text{Frac}_2 \times \text{EF}_5\right\} \times \frac{44}{28}\end{aligned}$$

Table 1. Soil properties under traditional management system (TMS) and planting and mowing cover crops as livestock feed (PRSS) treatment from the 0–40 cm soil layer

Indicator	TMS	PRSS	Suitable standard
pH	5.08 ± 0.33b	5.48 ± 0.12a	5.0–6.0
SOC (g kg^{-1})	15.81 ± 5.59a	12.62 ± 4.93a	5.8–14.5
TN (g kg^{-1})	0.99 ± 0.32a	0.88 ± 0.26a	0.5–1.3
AN (mg kg^{-1})	130.85 ± 47.66a	95.57 ± 37.83b	60.0–130.0
TP (g kg^{-1})	1.15 ± 0.24a	0.74 ± 0.16b	—
AP (mg kg^{-1})	80.47 ± 32.39a	32.39 ± 23.93b	10.0–40.0
AK (mg kg^{-1})	195.80 ± 52.09a	168.20 ± 56.01a	65.0–200.0
SOC:TN	16.17 ± 4.97a	14.14 ± 2.44a	—
SOC:TP	13.54 ± 3.26b	16.83 ± 4.56a	—
TN:TP	0.87 ± 0.21b	1.20 ± 0.31a	—

Note: Values are presented with mean plus/minus standard deviation ($n = 3$) and the following different letters in the same column indicate significant differences ($P < 0.05$). The standard required was referenced by Li *et al.*,[32] which indicates the mineral nutrition value suitable for early ripening of sand pears in China.

Abbreviations: AN, alkali-hydrolyzable nitrogen (N); AP, available phosphate; AK, available potassium; C:N, soil SOC:TN ratio; C:P, soil SOC:TP ratio; N:P, soil TN:TP ratio; SOC, soil organic carbon; TN, total nitrogen; TP, total phosphate.

where the conversion coefficient of CH_4 to CO_2 is 28, the CH_4 emission is 0.15 kg year^{-1} per head, the conversion coefficient for N_2O to CO_2 is 265, the number of sheep N is 75, and Nex is the average N excretion per head of sheep (17.1 kg N year^{-1}). MS is the proportion of total annual N excretion of sheep manure managed by the manure management system. EF_3 is 0.005, the emission factor for direct N_2O emission in the management system, attributed to the manure derived from sheep farming. $Frace_1$ is 12%, representing the proportion of N in manure management through ammonia and nitrogen oxides volatilization. EF4 is 0.025, the emission factor for the N_2O emission attributed to atmospheric N deposition on the soil and water surface. $Frace_2$ is 3%, representing the percentage of N loss from manure due to runoff and leaching during storage in manure management. EF5 is 0.0075, the emission factor for N_2O emissions from N leaching and runoff. The conversion coefficient factor 44/28 converts N_2O-N emissions into N_2O emissions.

$$GWP_{\text{cover crop}} = GWP_{\text{cover crop management}} + GWP_{\text{seed}} + GWP_{\text{labor of cover crop}}$$

$GWP_{\text{cover crop}}$ includes greenhouse gases from seeds, cover crop growth and fertilization, and the labor of mowing management.

$$GWP_{\text{sheep management}} = GWP_{\text{labor}} + GWP_{\text{fuel}} + GWP_{\text{electricity}}$$

where GWP_{labor} represents the labor involved in sheep management, and GWP_{fuel} and $GWP_{\text{electricity}}$ represent fuel and electricity consumption respectively.

Statistical analyses

Data processing and visualization were performed using R software (version 4.0.3), Microsoft Office Excel 2016 (Microsoft Corporation, Redmond, WA, USA), and SPSS 20.0 (IBM Corp., Armonk, NY, USA). Data normality was analyzed using the Kolmogorov–Smirnov test (Supporting Information Table S3), and differences in the soil properties, pear growth indicators, pear yield performance, and greenhouse gas emission were analyzed using one-way analysis of variance in SPSS 20.0. Significant differences were detected using a least significant difference multiple range test with $P < 0.05$ and $P < 0.01$. The relative importance of variables to the yield change was analyzed using the randomForest package in R4.0.3. A partial least-squares path model analysis was used to explain the relationship between the influence factors and pear yield using the plspm package in R4.0.3. It was hypothesized that pear yield was

Table 2. Pear tree growth indicators and pear yield performance between traditional management system (TMS) and planting and mowing cover crops as livestock feed (PRSS)

System	Pear tree growth			Pear yield performance		
	New shoots length (cm)	New shoots thickness (cm)	Leaf SPAD	Fruit per plant	Mean fruit weight (g)	Yield (t ha^{-1})
TMS	51.42 ± 13.41b	0.65 ± 0.12a	46.54 ± 4.20b	33.20 ± 8.85b	267.46 ± 47.31a	7.40 ± 1.31b
PRSS	66.55 ± 13.42a	0.72 ± 0.12a	50.21 ± 3.32a	46.80 ± 15.98a	262.75 ± 27.04a	10.25 ± 1.06a

Note: Values are presented with mean plus/minus standard deviation (n = 3), and different letters indicate significant differences (P < 0.05). Abbreviation: SPAD, soil plant analysis development.

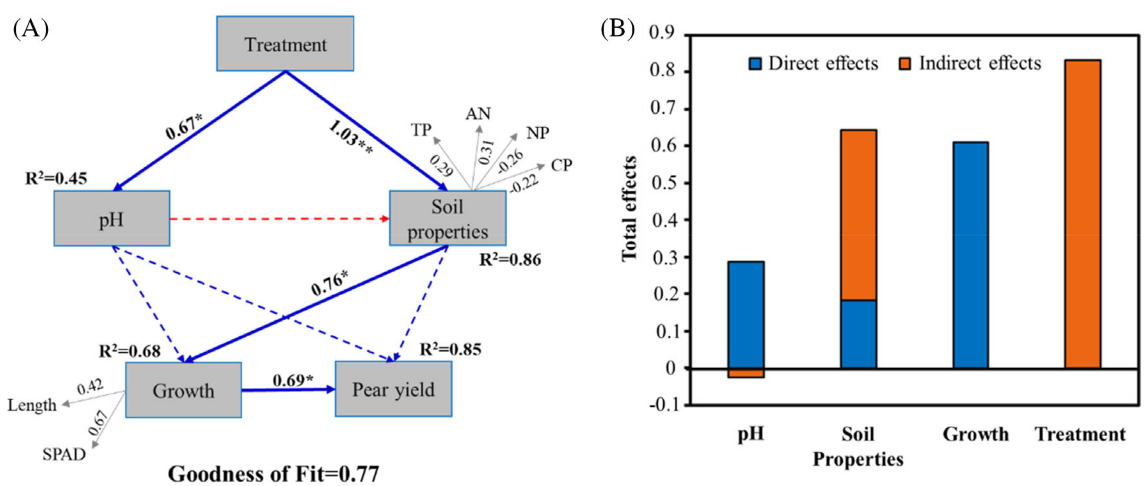

Figure 2. (A) Partial least-squares path model (PLS-PM). Positive and negative effects are shown by blue and red arrows respectively. Significant path coefficients are indicated by * (P < 0.05) and ** (P < 0.01) with solid lines, whereas insignificant values are shown as dashed lines. The goodness of fit was used to assess the model. AN, alkali-hydrolyzable N; CP, soil SOC:TP ratio; Length, length of the new shoots; NP, soil TN:TP ratio; SPAD, soil plant analysis development; SOC, soil organic carbon; TN, total nitrogen; TP, total phosphate. (B) Direct and indirect effects of different variables on the yield based on the PLS-PM analysis.

significantly correlated with treatment, soil properties, and growth indicators.

RESULTS

Effects of different treatment on pear orchards

Soil properties

The effects of different treatments on the soil properties are shown in Table 1. The values of soil pH, SOC:TP, and TN:TP were significantly higher ($P < 0.05$) in PRSS than those in TMS. However, the average values of AN and AP in PRSS were significantly lower (26.96–59.89%) but more suitable for pear growth than TMS. There were no significant differences in SOC, TN, and AK within the standard ranges between TMS and PRSS (Table 1).

Pear tree growth and yield

Compared with TMS, the length of new shoots and leaf SPAD in PRSS significantly increased from 51.42 cm to 66.55 cm and from 46.54 to 50.21 respectively, whereas there was no difference in the thickness of the new shoots (Table 2). Regarding pear production, the number of fruits per plant and the yield under PRSS increased by 40.96% and 38.51% respectively compared with TMS.

Random forest models were used to assess the importance of different variables to yield change (Supporting Information Fig. S1). The results indicated that the important factors affecting yield were AP, TP, SPAD, AN, and length. In addition, the partial least-squares path model showed that treatment had significantly positive effects on pH (path coefficient, 0.67) and soil properties (1.03). Growth (0.69) had a significant positive effect on yield. However, no significant direct effect of pH and soil properties was observed on yield (Fig. 2(A)). Regarding the effects of different indicators on yield, the total effect of treatment was the highest, reaching 0.81. Soil properties had direct and indirect effects on yield, with respective values of 0.18 and 0.46.

Greenhouse gas emissions

The average soil CH_4 flux under PRSS was 72.67 μg m^{-2} day^{-1}, higher than that of TMS (61.28 μg m^{-2} day^{-1}; Fig. 3(A)). Compared with TMS, the amount of CH_4 flux in PRSS was significantly higher in winter, whereas that of TMS gradually increased in spring. No significant difference in the N_2O emissions was found between TMS and PRSS (Fig. 3(B)).

The changes in Reco were similar, and the NEE of the two treatments initially exhibited CO_2 uptake, indicated by a negative value, followed by CO_2 release between TMS and PRSS (Fig. 4(A)

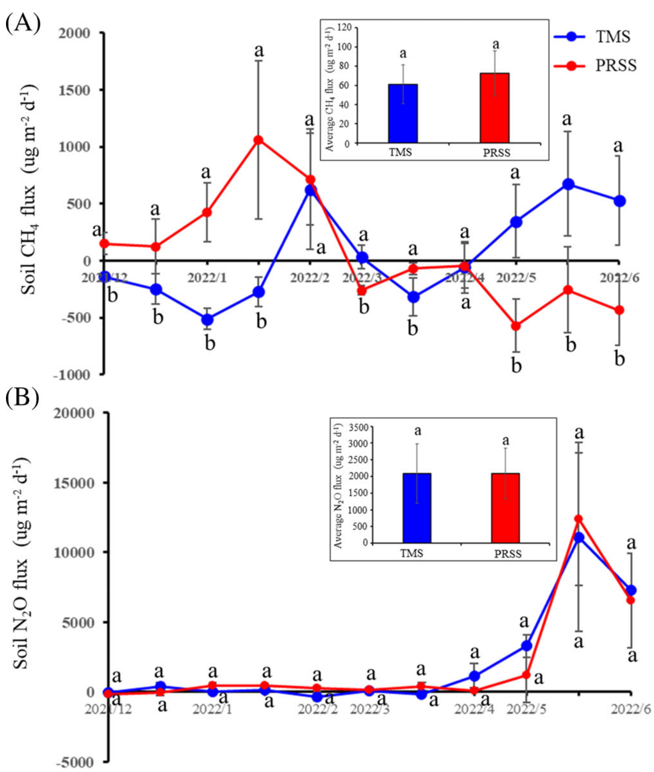

Figure 3. Variation (mean plus/minus standard error, $n = 3$) in the soil methane (CH_4) (A) and nitrous oxide (N_2O) (B) fluxes between traditional natural grass management system (TMS) and planting and mowing ryegrass as livestock feed system (PRSS). Different small letters at the same time point indicate significant difference at the 0.05 level.

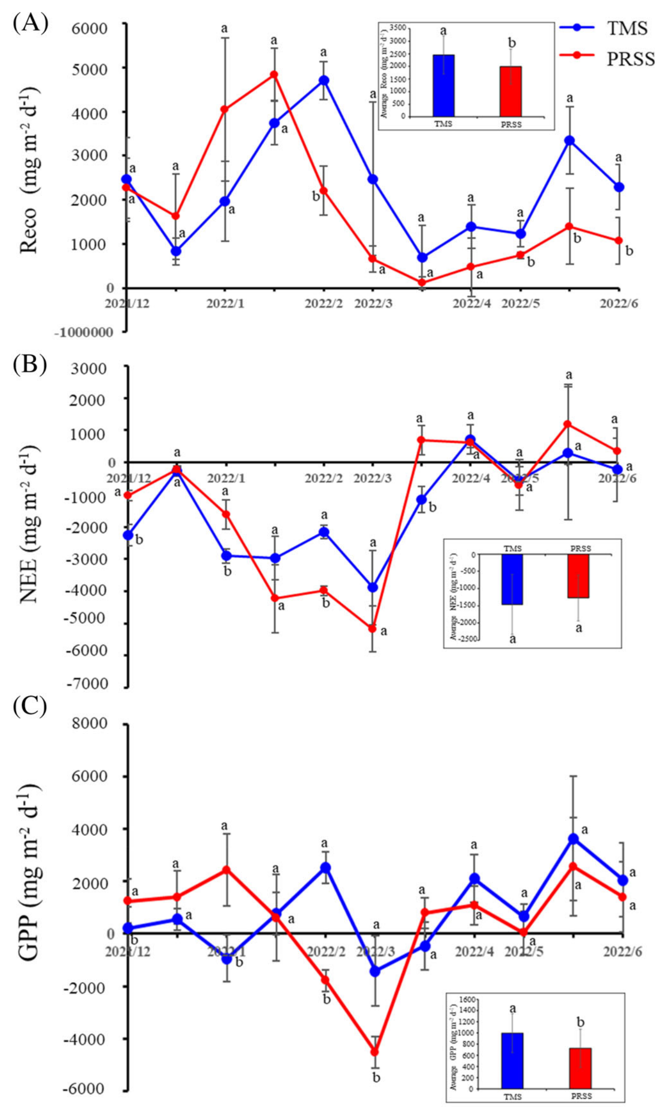

Figure 4. Variation (mean plus/minus standard error, $n = 3$) in the ecosystem respiration (Reco) (A), net ecosystem exchange (NEE) (B), and gross primary production (GPP) (C) between traditional natural grass management system (TMS) and planting and mowing ryegrass as livestock feed system (PRSS).

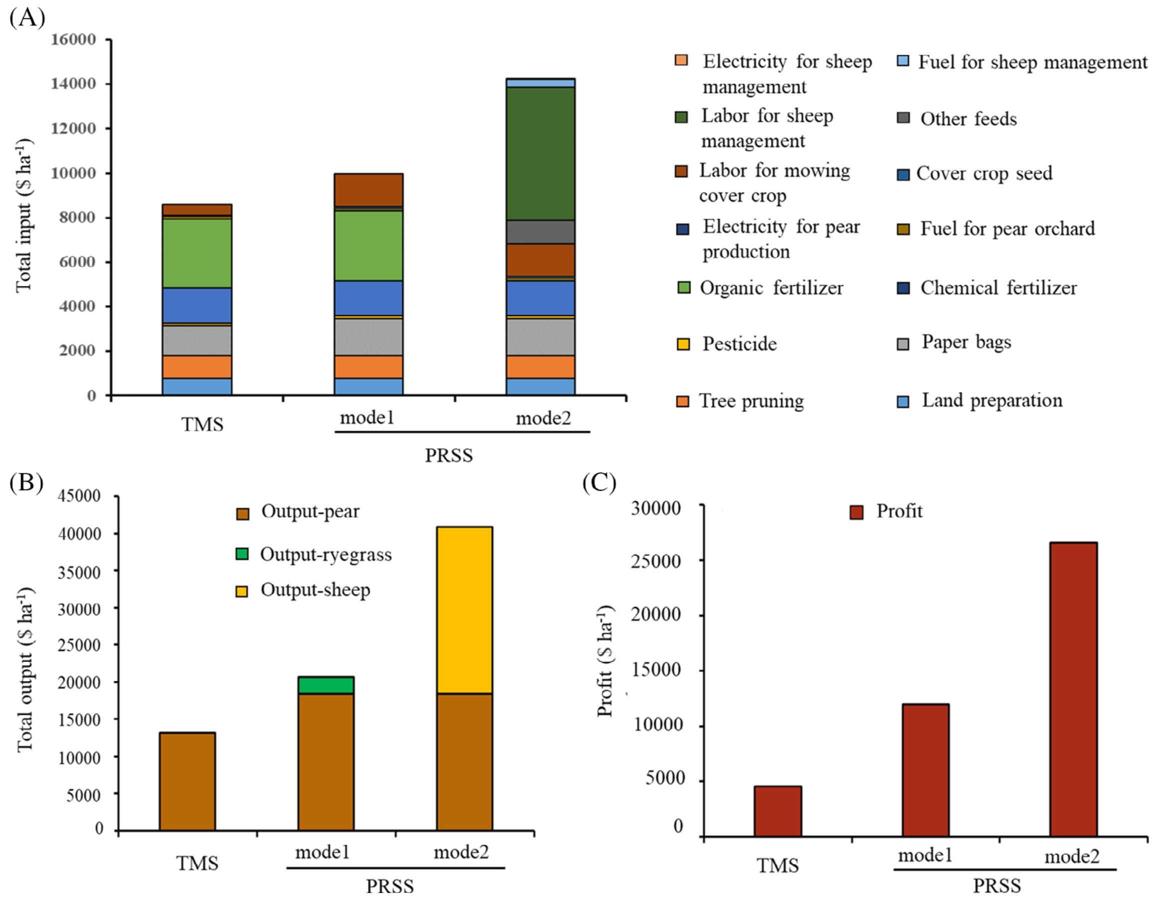

Figure 5. Total input (A), total output (B), and profit (C) of traditional natural grass management system (TMS) and planting and mowing ryegrass as livestock feed system (PRSS). Mode 1, mowing ryegrass and selling to livestock company; mode 2, mowing ryegrass and feeding own sheep.

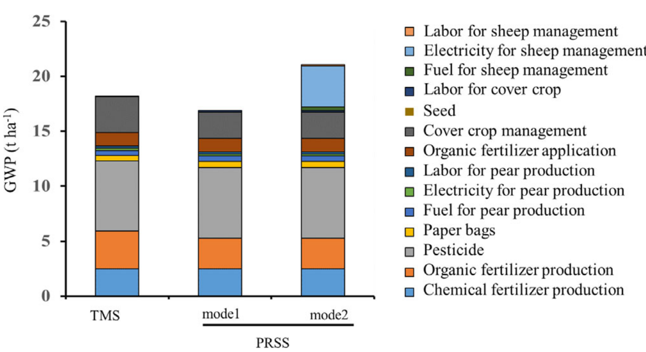

Figure 6. The global warming potential (GWP) for different treatments: traditional natural grass management system (TMS) and planting and mowing ryegrass as livestock feed system (PRSS). Mode 1, mowing ryegrass and selling to livestock company; mode 2, mowing ryegrass and feeding own sheep.

and (B)). The average GPP for the entire growth period of the different treatments was CO_2 release, with 996.07 mg m^{-2} day^{-1} under TMS and 725.78 mg m^{-2} day^{-1} under PRSS (Fig. 4(C)).

Economic benefit and environmental impact of different systems

Cost and benefit

Compared with TMS, the total input of PRSS mode 1 and mode 2 increased by 16.15% and 65.76% respectively. These increases were mainly related to the labor cost from sheep management ($5992.54 ha^{-1}), and the paper bags cost increased from $1343.28 ha^{-1} in TMS to $1679.10 ha^{-1} in PRSS (Fig. 5(A)). The output value for PRSS mode 1 ($20 686.57 ha^{-1}) and PRSS mode 2 ($40 853.82 ha^{-1}) increased by 57.50% and 210.94% respectively compared with TMS (Fig. 5(B)). The output from the sheep in PRSS mode 2 was $22 388.06 ha^{-1} and the output of pears increased by 40.45% compared with TMS. PRSS mode 1 and PRSS mode 2 profits were $10 706.21 ha^{-1} and $26 592.87 ha^{-1} respectively, whereas that of TMS was $4542.03 ha^{-1} (Fig. 5(C)).

GWPs of different systems

The GWP of PRSS modes 1 (16.90 t CO_2-eq ha^{-1}) and PRSS mode 2 (21.08 t CO_2-eq ha^{-1}) were significantly different from that of TMS (18.19 t CO_2-eq ha^{-1}; Fig. 6). The GWP produced by cover crop management under PRSS was significantly lower than that of TMS, with a decrease of 0.91 t CO_2-eq ha^{-1}. In addition, the GWP from organic fertilizer production and transport of TMS, reaching 3.40 t CO_2-eq ha^{-1}, increased by 22.74% compared with the PRSS mode.

DISCUSSION

Effect of planting and mowing cover crop on soil properties

Several researchers have reported that cover cropping can improve soil physical structure[26] and enhance nutrient bioavailability.[27,28] Xie *et al.*[29] indicated that the soil N content could significantly increase after winter cover grass is returned to the field. Chicken grazing on cover crops can also increase the soil C and N contents.[12] However, most of the soil nutrient contents of PRSS showed a downward trend in our study (Table 2). This trend may be related to soil nutrients absorbing in ryegrass growth. Our results also found that planting ryegrass can significantly increase pH in acidic soil, which aligns with the findings of Zhao *et al.*[30] The increase in pH can reduce phosphorus fixation and increase phosphorus availability in soil for absorption by ryegrass. This process might explain our study's decrease in TP and AP (Table 1).

Pear yield and economic benefits

Cover cropping has been recognized as an effective method to enhance fruit yield in the subtropics zone.[31] However, the effect of planting and mowing cover crops on yield has remained unclear. Our study found that planting and mowing cover crops can significantly improve pear yield compared with natural grass. In China, excessive fertilizer application is common, often leading to low pear yield.[2,4] Theoretically, appropriate soil nutrient contents are beneficial for high crop yields. In our study, soil AP content emerged as an important factor influencing yield. The content under natural grass was more than 50 mg kg^{-1} (Table 1), higher than the suitable value in southern China (10–40 mg kg^{-1}).[32] In contrast, planting and mowing cover crops reduce the AP content to appropriate ranges, enhancing fruit tree growth and resulting in higher yield.

An effective farming system can create more economic value.[33,34] A study by Zhang *et al.*[35] stated that combining cover crops with chicken grazing can increase rice yield and increase economic output. Compared with TMS, the total profit in PRSS increased by more than \$6100 ha^{-1} (Fig. 5(C)). Apart from the benefits arising from yield increases, mowing ryegrass can also provide additional income, ~\$2200 ha^{-1} in PRSS mode 1. PRSS mode 2 also provided an extra economic output from sheep. Furthermore, PRSS mode 2 achieved self-sufficiency in organic fertilizer supply, reducing input costs. In summary, planting and mowing cover crops as livestock feed holds great potential for increasing economic benefits.

Environmental impact

Compared with natural grass, ryegrass grown in winter produced a significantly higher amount of CH_4 (Fig. 3(A)). This might be related to its large biomass, developed root system, and strong microbial respiration during winter. In the later stages, CH_4 emissions of TMS gradually increased because the crop cover inputs provide abundant C sources for CH_4 production, in line with the findings of Huang *et al.*[34] García-Palacios and Chen[36] suggested that soil microbial communities largely drive soil C responses to climate change. The correlation between microbial community changes and greenhouse gas emissions under different treatments can be further explored. Additionally, we found no significant difference in N_2O emission between different treatments in our study (Fig. 3(B)). The N_2O emission is closely related to the N fertilizer application,[37,38] and similar N fertilizer input in the two treatments may be an important reason for this insignificant difference. Moreover, the average GPP of PRSS and TMS was CO_2 release in the entire period, possibly due to high respiratory production in winter and low photosynthesis caused by low biomass in spring.

Integrated systems can considerably reduce greenhouse gas emissions, a finding consistent with our results. Planting and mowing ryegrass reduced CO_2 emissions in pear production, and the organic fertilizer transfer process also reduced emissions, with resources directly obtained from local livestock industries. However, the amount of N_2O emissions generated by the entire system cannot be ignored. In our study, the input rate of fertilizer N, more than 400 kg ha^{-1}, is higher than the recommended fertilization rate in China,[39] suggesting that greenhouse gas emissions have considerable reduction potential. If the N use efficiency increased to 50%, N_2O emissions could be reduced by 39%.[40] Therefore, exploring optimized nutrient practices is important to achieve sustainable agriculture.

Uncertainties and future work

In this study, uncertainties in our analysis primarily stemmed from the data and coefficients used in the scenarios. In the crop–livestock integration scenarios, the emission coefficients of sheep management and pear production, such as those for fertilizer production and transport, were obtained according to Eggleston *et al.*[25] These could potentially cause inaccuracies compared with the actual situation. According to our results, planting and mowing ryegrass showed great potential for increasing pear yield and reducing the environmental burden. Furthermore, this mode's maximum potential and optimal management practices could be further explored.

CONCLUSIONS

In this study, we found that planting and mowing ryegrass in pear orchards can reduce excess nutrient content in the soil, increase yield, and reduce overall GWPs. For mode potentials, PRSS mode 1 can increase pear yield and reduce the cost of organic fertilizer, and an additional income comes from sheep in mode 2. Regarding environmental benefits, mode 1 can reduce the environmental impact by 7.1%, whereas mode 2 increases the environmental impact by 15.9% owing to the enhanced sheep management process compared with TMS. We concluded that planting and mowing ryegrass in pear orchards benefits farmers and mitigates the negative environmental impact. Future research can explore the optimal management strategies and potentials for planting and mowing ryegrass in pear orchards.

AUTHOR CONTRIBUTIONS

Haoran Fu: formal analysis and writing – original draft. Hong Chen, Feiyang Wang, and Bo Chen: formal analysis. Qingxu Ma: writing – review and editing. Lianghuan Wu: conceptualization.

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CONFLICT OF INTEREST STATEMENT

The authors have no relevant financial or nonfinancial interests to disclose.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

SUPPORTING INFORMATION

Supporting information may be found in the online version of this article.

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