

Effectiveness of integrated low-carbon technologies

Evidence from a pilot agricultural experiment in Shanghai

Chunzeng Fan

Antai College of Economics and Management, Shanghai Jiao Tong University, Shanghai 200030,
China, and

Taoyuan Wei

Center for International Climate and Environmental Research—Oslo (CICERO), PO Box 1129,
Blindern, NO-0318 Oslo, Norway

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Abstract

Purpose – Constructing a low-carbon agriculture park is considered an effective means to reduce greenhouse gas emissions in developing countries. This study explores the effectiveness of integrated low-carbon agricultural technologies based on evidence from a pilot low carbon agriculture experiment in Shanghai of China from 2008 to 2011.

Design/methodology/approach – Integrated low-carbon technologies in an agricultural park were adopted to reduce greenhouse gas emissions. Reduced emissions and net economic benefits were calculated by comparing emissions before and after the implementation of the experiment.

Findings – Results show that the low-carbon agricultural park experiment markedly reduced greenhouse gas (GHG) emissions. This outcome can be attributed to the integrated technologies adopted in the experiment including the reuse and recycle of resources, control of environmental pollution and GHG emissions, and improvement of economic efficiency and social benefit. All the technologies adopted are already available and mature, thus indicating the great potential of low-carbon agriculture (LCA) to reduce GHG emissions despite the lack of advanced technologies. However, supporting policies may be necessary to motivate private interests in LCA because of the considerable starting investments.

Originality/value – Previous macro-level and policy studies on low-carbon agriculture (LCA) are based on knowledge from experimental studies, which typically specify environmental conditions to explore solely the effects of one low-carbon technology. Practically, integrating several low-carbon technologies in one experiment may be more effective, particularly for extensive agriculture, in developing countries. The effectiveness of integrated technologies is insufficiently discussed in the literature. Therefore, this study explores how effective integrated feasible LCA technologies can be in terms of both emission reduction and economic benefits based on the data obtained from an experiment in Shanghai of China.

Keywords Low-carbon agriculture, Integrated engineering technologies, Emission reduction, China

Paper type Case study

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1. Introduction

Agriculture is one of the largest anthropogenic sources of greenhouse gas (GHG) emissions. Approximately 13.5% of global anthropogenic GHG emissions are from agriculture (excluding those associated with the production of fertilizers and other agro-chemicals) similar to that from transportation (IPCC 2007). Nevertheless, a few authorities have considered this information in their proposals and programs for low-carbon development (Norse 2012). In China, GHG emissions from agriculture accounted for 17% of national emissions (NCCCCO 2004). To reduce CO₂ emissions, one effective means is to develop and promote modern low-carbon agriculture (LCA). Reducing agricultural CO₂ emissions by shifting to LCA can also improve food security (Fan and Ramirez 2012) and acquire other benefits (Konyar 2001). The present study explores the effectiveness of integrated low-carbon technologies to reduce emissions and improve economic benefits based on a pilot agricultural experiment in Shanghai.

The existing studies on LCA mainly aim to decrease GHG emissions from agriculture. The literature can be divided into three types. The first type pertains to the estimation of reduction potentials or reduction quota of agriculture using factors from experiments or those from the Intergovernmental Panel on Climate Change (IPCC). A number of studies have estimated the global technical GHG mitigation potential from agriculture (e.g., Cole et al. 1997, Brink et al. 2005, and Beach et al. 2008). Particularly, the global technical GHG mitigation potential from agriculture by 2030 is estimated to be 5.5–6.0 GtCO₂e/year (Benbi 2013). Lal (2004, 2011) concluded that only the correction of the misuse and mismanagement could result in soil sequestration of over 1.2–1.3 billion tons C/year globally as well as the improvement of soil quality and crop yields. Several studies have focused on the potential of soil sequestration at the regional level (e.g., McCarl and Schneider 2000, Moran et al. 2011, and Aertsens et al. 2013). These estimates focus on a large scale, make rough calculations, and obtain results from the status quo and basic tendency by considering key aspects, such as soil, crop, energy, crop residual, fertilizer, and pesticides.

The second type examines the policy issues implied by agricultural carbon reduction estimation and experimental evidence. For example, Norse (2012) analyzed the pathway of LCA. Smith et al. (2001) explored the constraints and barriers to mitigate agricultural GHGs, climate and non-climate policy in different regions of the world, and the potential for agricultural GHG mitigation in the future. Schneider et al. (2007) simulated the CO₂ reduction policies under changing tillage systems, reduced fertilization, improved manure management, and partial afforestation. They concluded that energy crop plantations could serve as an important GHG abatement policy if carbon price is sufficiently high. Auld et al. (2014) reported an original systematic review of 165 empirical, ex-post studies examining the policies that promote the development and use of low-carbon technologies. Usually, these studies are comprehensive at the macro level and depend on the information obtained from studies of the first and third types.

The present study is classified under the third type, which reports and analyzes

experiments on GHG emission reduction (e.g., Cerri et al. 2004, Wan et al. 2013, and Powlson et al. 2016). Summarized from other aspects of the entire agriculture lifecycle, these studies are generally more accurate than those classified as first and second types in only one aspect or combined several ones. The results from these studies can serve as the foundation of the first two types. The third type of studies typically specify an experimental environment, including time, place, soil, climate, temperature, and tillage conditions to explore solely the effects of one low-carbon technology. Practically, integrating several low-carbon technologies in one agricultural experiment may be more effective, particularly for extensive agriculture, in developing countries such as China. The effectiveness of integrated low-carbon technologies is not sufficiently discussed in the literature. Therefore, the present study intends to explore how integrated feasible technologies can be used to develop LCA and how effective these integrated technologies can be in terms of both emission reduction and economic benefits based on the data obtained from the pilot experiment of the Dongtan low-carbon agriculture park (DLCAP) in Shanghai.

Specifically, this study analyzes the data obtained from a complicated experiment conducted in a 200 ha farmland in a suburb county of Shanghai Metropolis. In the experiment, agricultural residuals such as straw and cow dung were collected to produce biogas, heat, electricity, and organic fertilizer. The production was supported by several low-carbon technologies for the prevention of straw burning, soil and vegetation sequestration, bio-energy from straw, substitution of chemical fertilizer by organic fertilizer, paddy and manure management, reduction of chemical pesticide and chemical fertilizer, tillage change, introduction of cover crops to crop rotation, and low-carbon construction. The experiment progressed for three years to cover the entire agriculture lifecycle. This innovative means aims to develop LCA by integrating many technologies in one experiment.

2 DLCAP experiment

The DLCAP in Chongming Island (Figure 1) is a modern agricultural experiment of ecological, low-carbon, and recycling economy implemented by the Shanghai Industrial Investment (Group) Co., Ltd (SIIC) and supervised by the Shanghai Science and Technology Committee (SSTC) from 2008 to 2011. This low-carbon agriculture park (LCAP) experiment aims to demonstrate how to develop modern LCA in Shanghai to mitigate CO₂ and other GHG emissions, save resources, and increase desirable outputs. The LCAP experiment intends to provide evidence for the local government to make decisions on the LCA development. Evidence from the experiment can also be a useful example of LCA development for other domestic regions and developing countries.

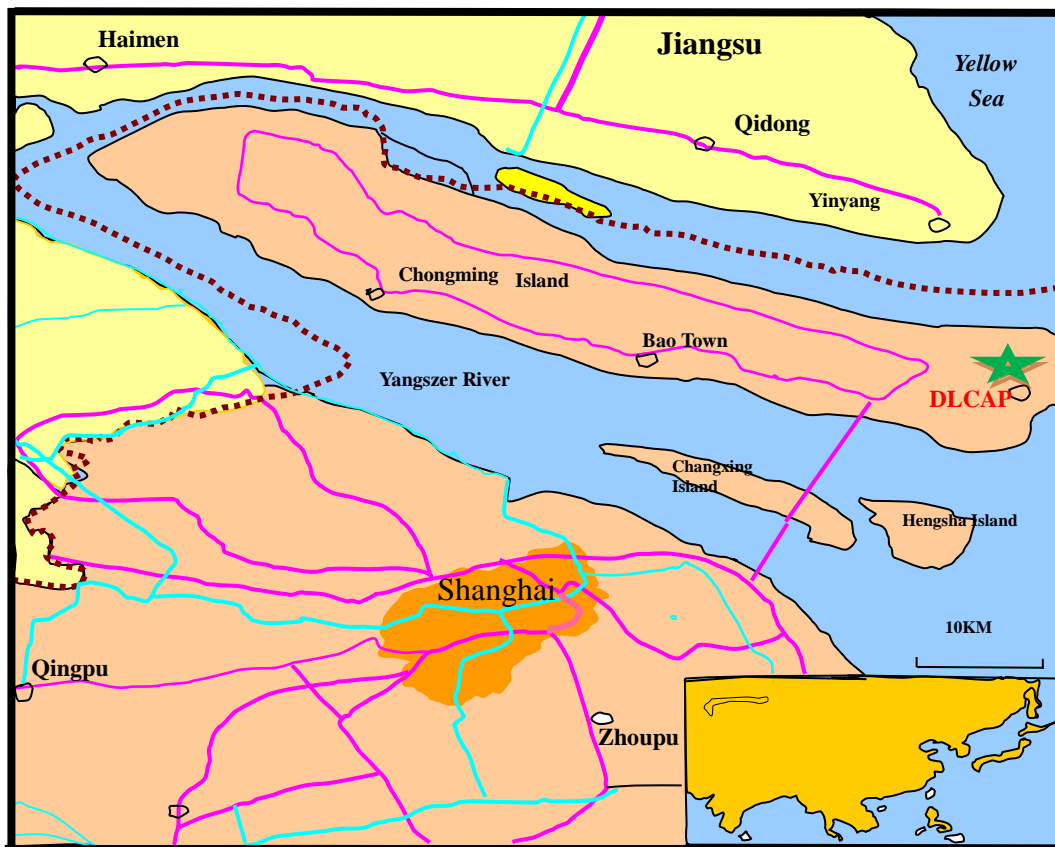


Figure 1. Location of DLCAP

2.1 Implementation of the experiment

The experiment in 200 ha of arable land aims to provide a comprehensive assessment on CO₂ reduction caused by integrated low-carbon technologies. It emphasized the key factors in an agriculture lifecycle to reduce CO₂ emissions, such as constructing biogas engineering and organic fertilizer to substitute for fossil energy and chemical fertilizer, respectively, adjusting crop structure, improving soil fertility and carbon sequestration, reducing soil pollution, changing tillage, and enforcing paddy management. As an example for farmers, the experiment used particularly low-carbon measures that could increase crop yields and economic revenue.

To identify the effect of the integrated low-carbon technologies adopted in the experiment, the 2008 situation before the experiment was used as a reference case. Thus, the data of all the inputs and outputs in 2008 were collected to denote the business-as-usual situation of traditional extensive agriculture in the region. In 2008, this 200 ha farmland mainly planted field crops, including 106.67 ha of rice, 86.67 ha of wheat, 26.67 ha of maize, and 13.33 ha of horticulture. Rice and wheat were mainly planted in summer and winter, respectively. The other part of the land was occupied by water, road, sunning ground, and buildings. The agricultural production required yearly inputs of 65 t of nitrogen fertilizer, 15 t of potash, 15 t of phosphate fertilizer, and 3.75 t of pesticide. The other yearly inputs included 82,933 kWh of

thermal electricity, 3,000 kg of diesel, 1,200 kg of gasoline, and certain building materials (e.g., cement, steel, tile, and brick). Fifty-eight employees worked in the farmland, including eight managers. The net benefit of the farmland was only 2.856 million Chinese yuan (CNY) in 2008.

In 2008, the isolated region in Shanghai remained sizable because of the ongoing construction of the Chongqi Bridge that connects Chongming to Qidong in Jiangsu Province. The inconvenient transportation inside Chongming could not effectively connect with the built Changjiang Tunnel-Bridge linking Chongming to Shanghai. This barrier for modern agricultural development was improved by the end of 2011.

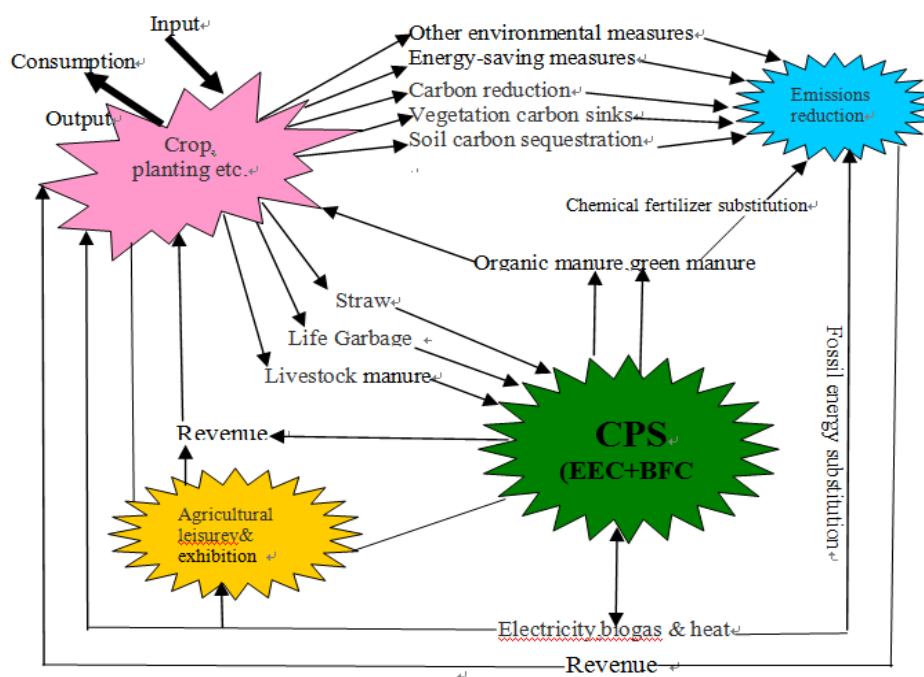


Figure 2. Environmental protection flows adopted in the DLCAP experiment

The DLCAP land was divided into the central processing system (CPS) area, planting area of ecological agriculture, and agricultural exhibition and leisure area (Figure 2). In the CPS area, a biomass energy–fertilizer system was established, and it composed of the energy engineering center (EEC) and bioorganic fertilizer center (BFC). The CPS produced gas, heat, electricity, and organic fertilizer from raw materials (e.g., waste straw, cow dung, and garbage). The EEC was equipped with an advanced anaerobic fermentation production line catalyzed by the anaerobic fermentation agents. Waste straw and cow dung was decomposed to biogas and other outputs including biogas residues and slurry. The biogas was further used to generate electricity and heat. The BFC adopted aerobic fermentation and overturning technology to produce organic fertilizer from straw, cow dung, and biogas residues.

In the planting area of ecological agriculture, main crops including rice, wheat, watermelon, horticulture, and maize were planted ecologically by adopting measures to reduce the use of chemical fertilizer and pesticide and by changing the traditional

land use and tillage.

The agricultural exhibition and leisure area was designed for attracting tourists with the park's landscape and ecological agricultural products. This area served as a channel to raise income and decrease the financial risk of the experiment. In this area, tourists could enjoy various agricultural activities, such as nature discovery, farm camping, herb planting, flower planting, fruit planting, and animal breeding. These activities were organized in featured areas, such as the orchard, flower garden, herb garden, greenhouse and leisure square, laboratory, and exhibition rooms.

At the end of the experiment in 2011, DLCAP had a yearly designed capacity of handling 9,500 t of organic waste and produced 0.37 million cubic meters (m³) of methane, 584,000 kWh of green electricity, and over 5,000 t of solid organic fertilizer. The implementation of the experiment changed the structure of energy use by using clean energy in the agricultural production, recycling the agricultural waste, and increasing agricultural carbon sequestration.

2.2 Key technologies to reduce emissions

Technology is the application of sciences to useful arts (Bigelow 1831). It initially emerged to its modern sense in 1829 (Klein 2007). "Technology" is a broad term, and everyone has his/her own understanding of it. Technology can be products, processes, or organizations. It is adopted to extend the abilities of humans in solving a problem. In this paper, low-carbon technology is defined broadly to include diverse knowledge, experience, knowhow, tools, and methods that directly or indirectly reduce or eliminate CO₂ emissions in agricultural activities.

The DLCAP experiment implemented numerous technologies to reduce GHG emissions and other pollutants, and to improve economic and social benefits. The advanced technologies under development were not adopted because the experiment aimed to provide evidence of the integrated effect of the existing mature technologies. Thus, various mature technologies were implemented simultaneously to reduce emissions and to improve the local environment. Specifically, these technologies can be classified into six groups.

2.2.1 Straw anaerobic and aerobic fermentation technology. The CPS was designed to utilize the straw from this park and cow dung from a nearby dairy farm to produce biogas and associated residue and slurry. The CPS could also utilize the garbage generated from kitchen and livestock. The biogas was mainly used to produce electricity and heat. The biogas residue was used to produce organic fertilizer. The biogas slurry was directly sent back to the farmland. The technology prevented open straw incineration, the piling of cow dung in open air, and consequently the associated emissions.

As inputs to the CPS, biomass was abundant in the DLCAP and nearby areas. In 2011, the total biomass was equivalent to 18,000 t of coal equivalent (tce) including 31,800 t of crop residues, 32,000 t of reed and *Spartina anglica*, and 8,000 t of cow dung. The

crop residues in the DLCAP were over 1,838 t in dry matter. Considerable electricity could be generated if the electricity was connected to the grid and in a full load operation. In this experiment, electricity was generated at a low efficiency of 0.75 kWh per cubic meters of biogas, whereas the electricity generated in the design was 1.6 kWh per cubic meters of biogas.

2.2.2 Non-point source pollution control technology. Agriculture can lead to non-point source pollution by overusing or misusing chemical fertilizer and pesticide. The DLCAP experiment reduced the use of chemical fertilizers in the production of maize, wheat, rice, and green manure crop plantation. The technology reduced water pollution and indirectly CO₂ emissions as well as increased crop yields. In practice, organic fertilizer, urea, and compound fertilizer were mixed at a ratio of 225:24:15 in wheat plantation. Nitrogen fertilizers were provided by mixing organic and chemical fertilizer at a ratio of 3:7 in the maize plantation. Chemical fertilizers were used depending on the crop growth seasons. For example, urea was used in the rice plantation by 112.5 kg/ha at the 6- and 11-leaf periods. At the 12-leaf period, compound fertilizer (N+P₂O₅+K₂O equally weighted) was used by 134.5 kg/ha, and the total nutrient was above 45%. In the post-flowering period, green microbial organic fertilizer was used by 15,000 ml/ha.

The experiment also reduced the pesticide utilization of PS-15 II frequency–vibrancy moth-killing lamp driven by the electricity generated from biogas or solar energy. Such activities reduced the use of chemical pesticides and CO₂ emissions related to fossil energy. The experiment also used bioremediation technology to purify the farmland from pollution and maintain the ecological balance of soil and water.

2.2.3 Clean energy substitution technology. Electricity and heat generated from the CPS were used for various activities. Certain biogases were directly used to heat the greenhouse in winter. The biogas use avoided considerable CO₂ emissions by substituting the use of fossil energy, particularly electricity generated from coal, gasoline, and diesel.

The experiment also developed wind and solar energy to supply lighting services. Although seemingly far from the LCA, wind and solar energy have a great potential to develop by utilizing agricultural spatial resources. For example, the average annual solar radiation in Shanghai is 4461 MJ/m² in recent years. An efficient solar water heater on top of a building can produce 60 kg of 40 °C–60 °C hot water. Compared with coal-driven water heaters, a square meter of solar water heaters can reduce coal use by 150–180 kg, resulting in an emission reduction of 300 kg of CO₂, 2 kg of SO₂, 2 kg of NO₂, and 3 kg of particles.

2.2.4 Low-carbon building technology. In the DLCAP experiment, new buildings were necessary for the laboratories, agricultural products and exhibition, leisure square, and organic fertilizer plant. Solar energy and effective energy saving technology were used in these buildings to reduce CO₂ emissions. These buildings were constructed using self-insulating bricks made from river mud and straw from the experiment to lower construction cost and promote resource recycling. Energy-saving

lights were powered by wind and solar energy. Thus, the comprehensive energy saving rate of these buildings reached 39%. The saving rate of a building refers to the share of reduced CO₂ emissions in total emissions if the building was constructed through ordinary methods.

2.2.5 Tillage and planting technology. Farming techniques were improved to increase economic benefits and the capacity of soil carbon storage. The experiment adopted reduced tillage in the maize–rice rotation and no tillage in the wheat–maize, rice–watermelon, and rice–green manure rotations. Thus, the ploughing times and depth were reduced to avoid soil disturbance and CO₂ emissions from soil.

Organic fertilizer was increasingly used to improve fertilizer efficiency and to reduce the use of chemical fertilizer and related GHG emissions. Fertilizer use technology could reduce fertilizer input by 41.1% and integrated water pollution by 45.4%.

Irrigation technology was also adopted to reduce CH₄ and N₂O emissions from paddy fields by maintaining feasible soil moisture conditions, that is, submergence (one month) in the first period, drainage (7–10 days) in the midterm, and alternate submergence and drainage (one month before harvest) in the last period.

The planting structure was optimized to reduce emissions and improve yields and economic benefits. For example, fruits and flowers were planted besides crops. The experiment implemented maize–vegetable (38.67 ha), rice–wheat (40 ha), rice–green manure (33.33 ha), and rice–watermelon (33.33 ha) rotations. A 1.33 ha modern greenhouse was also in operation.

2.2.6 Soil-fertility-increasing technology. To increase soil fertility, the experiment constructed the BFC to improve organic fertilizer production and utilization, which directly reduced chemical fertilizer use, increased soil fertility, and indirectly reduced fossil energy consumption associated with fertilizer production.

The experiment adopted green manure fertile technology. Green manure crops with high carbon sequestration capacity were selected to reduce CO₂ emissions and increase soil fertility. For example, the potential nitrogen fixation of milk vetch, rape, ryegrass, *Medicago falcata*, and *Vicia faba* is over 322, 439, 407, 339, and 134 kg per hectare, respectively. According to the field experiments of planting green manure crops, which is covered underground with tillage in flowering seasons, the total soil phosphorus and available soil potassium can increase by more than thrice and more than 57%, respectively. The potential organic carbon content of ryegrass can be fixed up to 6,790 kg/ha, which is equivalent to a reduction of more than 25% of fertilizer input. If the rotation is rice–green manure–watermelon, the soil sequestration increases to 13.12 t/ha.

3. Data and methodology

3.1 Data

The agricultural data came from field experiments in the park from 2008 to 2011 supplied by the Dongtan Agriculture Company of SIIC. Specific fertilizer and

pesticide data came from the online database “Dynamic Detection and Management System of Shanghai Agriculture”¹ supported by the Shanghai Agriculture Committee. Carbon conversion factors of GHGs were obtained from IPCC (2007).

3.2 Reduced emissions

In DLCAP, GHG emissions were mitigated from the entire agriculture lifecycle, including source emissions (e.g., chemical fertilizer-related emissions), processing emissions (e.g., CH₄ emissions in the course of organic production), and subsequent emissions (e.g., increased GHG emissions of soil after fertilizer use).

3.2.1 Avoided emissions from agricultural residues

Straw was directly burned in the field, and fresh cow dung was piled in open air before the experiment. The avoided CO₂, CH₄, and N₂O emissions (ΔC_1) in terms of CO₂ equivalent (CO₂e) can be expressed by

$$\Delta C_1 = \alpha_1 \times (R_1 + R_2) + \alpha_2 \times R_3 \times \tau + \alpha_3 \times R_3 \times \varphi, \quad (1)$$

where R_1 is the straw used to produce biogas instead of burning; R_2 is the straw used to produce organic fertilizer instead of burning; R_3 is the fresh cow dung used in the organic fertilizer plant; α_1 is the CO₂ emissions per unit of straw burning; α_2 and α_3 are the CH₄ and N₂O emissions per unit of fresh cow dung in open air, respectively; τ is the CO₂e corresponding to one unit of CH₄, and φ is the CO₂e corresponding to one unit of N₂O.

In 2011, the data from the experiment show that $R_1=600$ t, $R_2=747.47$ t, $R_3=7800$ t, $\tau=25$ tCO₂e/t CH₄, $\varphi=296$ tCO₂e/t N₂O, $\alpha_1=1.84$ tCO₂e/t, $\alpha_2=24d_1 \times d_y$, and $\alpha_3=24d_2 \times d_y$, where d_1 and d_2 are the emission density of CH₄ and N₂O from cow dung, respectively, and d_y is the open-piled time of cow dung. According to the DLCAP experiment, $d_y=60$ days, $d_1=9.0 \times 10^{-4}$ kg/kg.h, and $d_2=1.521 \times 10^{-5}$ kg/kg.h.

3.2.2 Reduced emissions from chemical fertilizer and pesticide

Compared with that in 2008, the experiment in 2011 reduced the use of chemical fertilizer and pesticide and utilized more self-produced organic fertilizer. These reduced emissions (ΔC_2) can be calculated by

$$\Delta C_2 = \beta_1 \times F + \beta_2 \times P, \quad (2)$$

where F and P are the reduced use of chemical fertilizer and pesticide,

respectively, β_1 is the emissions per unit of chemical fertilizer production, and β_2 is the emissions per unit of pesticide production (Table 2). In this study, $\beta_1=16.85$

¹ The Web address of the database (only Chinese version available) is <http://116.239.6.146:8080/>.

tCO₂e/t of nitrogen fertilizer and $\beta_2=15.50$. The reduced use of chemical fertilizer resulted from the joint use of organic and chemical fertilizer and from the chemical fertilizer replaced directly with organic fertilizer. In 2011, the used organic fertilizer was 1463.3 t, which is equivalent to 14.243 t of nitrogen fertilizer or 21.91% of the nitrogen fertilizer used in 2008. The reduced pesticides amounted to 1.23 t, 7.5 kg/ha, or 33.34% of the pesticides used in 2008.

3.2.3 Reduced emissions from electricity used in buildings

The buildings adopted low-carbon construction technologies and demanded significantly less electricity than ordinary buildings in Shanghai. As most of the electricity in China is generated from coal-fueled plants, these reduced emissions (ΔC_3) are expressed by

$$\Delta C_3 = \delta \times E \times \omega_1 \times \omega_2 \times \omega_3, \quad (3)$$

where $E=100$ kWh/m² is the electricity consumption per unit area of ordinary buildings, $\omega_1=39\%$ is the electricity saving rate of the buildings compared with that of ordinary buildings, $\omega_2=0.404$ kgce/kWh is the coal consumption to generate one unit electricity, $\omega_3=2.50$ tCO₂e/tce is the emissions per unit coal used for electricity generation, and $\delta=1290$ m² is the building area in the experiment. A special research group supported by the experiment designed and supervised the electricity consumption of these buildings and calculated the parameter values.

3.2.4 Soil and vegetation sequestration

The capacity of soil and vegetation sequestration were improved by adopting various low-carbon technologies, such as using organic fertilizer, planting green manure, increasing orchards, and decreasing vineyards. The increased sequestration of CO₂e emissions (ΔC_4) is calculated by

$$\Delta C_4 = \gamma_1 \times S_1 + \gamma_2 \times S_2 + \gamma_3 \times S_3 + \gamma_4 \times S_4 + \gamma_5 \times S_5, \quad (4)$$

where S_1 and S_2 are the total farmland of 166.67 ha and forest land of 13.33 ha, respectively, $\gamma_1=0.72$ tCO₂e/ha is the additional CO₂e sequestered per hectare of farmland, $\gamma_2=1.50$ tCO₂e/ha is the additional CO₂e sequestered per hectare of fruit-bearing forest and landscaping forest vegetation, S_3 is the total green manure crop area of 33.33 ha, S_4 is the paddy area of 73.33 ha, $\gamma_3=0.34$ t/ha is the additional soil CO₂e sequestered per hectare of farmland by utilizing organic fertilizer and reduced tillage, $\gamma_4=11.511$ t/ha is the additional soil CO₂e sequestered per hectare by green manure in the underground, and $\gamma_5=0.73$ t/ha is the additional CO₂e sequestered per hectare by paddy management. The reduced CO₂ emissions from the paddy imply that paddy management has a certain effect despite the minimal reductions.

3.2.5 Avoided emissions through renewable energy use

The experiment consumed self-produced renewable energy rather than fossil energy. The avoided emissions through energy substitution (ΔC_5) are calculated by

$$\Delta C_5 = \mu_i \times \sum_{i=1}^n y_i, \quad (5)$$

where y_i is the fossil energy directly and indirectly substituted by renewable energy, and μ_i is the emissions per unit of fossil energy. Renewable energy included biogas and electricity generated from biogas, solar, and wind. However, solar and wind energy was trivial and only used for lightning. Approximately 48,174 m³ of biogas was used to heat the greenhouse and the anaerobic fermentation tank of the project. These items were not calculated in the avoided emissions. The avoided emissions in the calculation included only those from the coal used for generating the same electricity produced from biogas. In 2011, the electricity produced from the biogas was 0.109277 million kWh.

3.3 Costs and benefits of low-carbon engineering technologies

The experiment adopted integrated engineering technologies to reduce emissions. The costs and benefits associated with these engineering technologies were calculated to assess their economic efficiency. Total costs include input values of electricity, raw material, labor, maintenance, and depreciation of fixed assets (such as the anaerobic fermentation tank, loader, straw pulverizer, cracker, blender, solid liquid separator, biogas generator, desulfurization facilities, and certain buildings). The labor cost includes part of the artificial bundling fee, the load and unload fee in the straw collection, and the payment of six workers who worked for the project. The material cost includes all the expenses on cow dung, ferment, deodorizer, desulfurizer, and so on.

Total benefits include the values of self-produced biogas, electricity, organic fertilizer, biogas slurry, and subsidies from the government. Net benefit is calculated as the difference between total benefit and cost. The net benefit rate to total cost is also calculated. The total cost is divided by the total emission reduction to obtain the average cost per unit emission, and the total benefit is divided by the total emission reduction to obtain the average benefit per unit emission.

3.4 Costs and benefits of the DLCAP experiment

Apart from the implementation of low-carbon engineering methods, the experiment included crop farming and horticultural activities. Although this complex had a tourism design and expected tourism revenue, the tourism aspect was not in operation in 2011. Therefore, this item was not included in the cost and benefit calculation. The total costs of the experiment (C_T) can be expressed by

$$C_T = \sum_{i=1}^n a_i C_i + d_h C_h + C_{lp}, \quad (6)$$

where C_i is the costs per hectare of crop i , C_h is the costs per hectare of horticultural land, a_i is the sown area of crop i , and d_h is the horticultural land area.

The total benefits of the experiment (B_T) are

$$B_T = \sum_{i=1}^n a_i B_i + d_h B_h + \sum_{j=1}^m S_j + B_p, \quad (7)$$

where B_i is the income from per hectare crop i , B_h is the income from per hectare of horticultural land area, and S_j is one type of subsidy j . The net benefits (NB_T) are the total benefits minus the total costs of the experiment.

4. Results and discussion

4.1 Reduction in GHG emissions

Table 1 presents the reduction in GHG emissions resulting from the implementation of the experiment. The net reduction in emissions is considerable, reaching 4 426.46 t CO₂e. This amount implies that the yearly reduced emissions are around 26.55 t CO₂e per hectare. The negative emissions obtained reach over 900 t CO₂e compared with the positive 3556.03 t CO₂e in 2008 (Table 2) although the experiment adopted only mature low-carbon technologies. Considering the large emissions from agriculture in the world, a considerable emission mitigation potential can be expected through technology changes in agricultural activities, particularly in developing countries such as China.

Emissions are reduced from various sources as shown in Table 1. Among these sources, the largest emission reduction comes from reduced straw burning, accounting for over 50% of the total reduction. The other 37% of the total reduction is related to organic fertilizer production and consumption from sources 2–5 and 10 in Table 1. These results are reasonable because the experimental design and adopted technologies focus on straw utilization to avoid open burning. By contrast, the substitution of fossil energy and low-carbon construction of buildings contributes to only a small share of the total emission reduction. The production of biogas and electricity from straw is far below its designed capacity, thus signifying a considerable potential to reduce emission by substituting fossil energy with biomass.

These results suggest at least two effective low-carbon policies. One policy is to encourage the use of straw for non-incineration activities, such as biogas and organic fertilizer production. The other policy is to promote organic fertilizer production and consumption using straw, cow dung, and other residues from agricultural activities. The effect of these two policies may result in zero or even negative emissions from the agriculture sector even if only mature low-carbon technologies are adopted as demonstrated by the DLCAP experiment. Currently, these technologies have not been adopted widely in Shanghai and other provinces in China. One of the key barriers may be the potential economic losses for farmers to adopt these technologies in their agricultural activities. Therefore, the net benefit of these low-carbon engineering technologies and that of the entire DLCAP experiment are estimated in the following subsections.

Table 1. Reduced emissions after the implementation of the DLCAP experiment

Emission reduction source	Reduced emissions	Share in total	Explanation
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	(t CO ₂ e)	reducti on (%)	
1. Straw utilization	2 479.35	56.01	Rather than incinerated, straw was used for the production of biogas and organic fertilizer.
2. Increased use of organic fertilizer rather than chemical fertilizer	585.33	13.22	Utilizing organic fertilizer can substitute for and reduce chemical fertilizer and reduce fossil energy consumption and indirectly reduce GHG emissions.
3. Joint use of organic and chemical fertilizers	240.00	5.42	The joint use of organic and chemical fertilizers reduces 41% of fertilizer inputs and indirectly reduces emissions from chemical fertilizer production.
4. Avoided N ₂ O emissions from organic fertilizer plant	50.60	1.14	Organic fertilizer plant can reduce emissions of N ₂ O using overturning technology in organic fertilizer production.
5. Cow dung utilization	253.25	5.72	Fresh cow dung of 7,800 t from Yu An Farm is used to produce organic fertilizer. Cow dung piled in open air could emit considerable CH ₄ . The organic fertilizer plant uses continuously overturning technology and hardly produces CH ₄ .
6. Green energy rather than fossil energy	110.37		Using the electricity generated by biogas and substituting the electricity generated by burning fossil energy reduce CO ₂ emission.
7. Low-carbon construction	50.6	1.14	CO ₂ emission is reduced by saving energy consumed by the construction.
8. Fermentation and biological pest control	19.33	0.43	About 7.5 kg/ha pesticide can be saved, and CO ₂ emission of 116 kg/ha can be indirectly reduced.
9. Vegetation sequestration	144.00	3.25	Carbon absorption of crops and other vegetation
10. Soil carbon sequestration	493.96	11.16	Using organic fertilizer increases the capacity of soil sequestration. Green manure crops can also increase soil sequestration. Paddy management can reduce GHG emission from soil.
Total reduction	4 426.46	100.00	
Sources leading to increased emission	46.38		Indirect CO ₂ emissions from increasing cement, steel, diesel, gasoline, tile, plastic film (for the emission factor, see Table 2).
Net reduction	4 380.08		

Sources: Data are calculated with the experiments of the DLCAP research group. Several emission factors are taken from IPCC (2007).

Table 2. Benchmark of emissions (Emissions in 2008 when the experiment was not yet implemented)

Emission Items	Quantity	Emission factor (t CO ₂ e per unit)	CO ₂ emissions (t)	Percentage (%)
Straw burning (t)	800.00	1.84	1 472.00	34.88
Electricity (MWh)	82.93	0.86	71.32	1.69
Diesel (t)	3.00	3.95	11.85	0.28
Gasoline (t)	1.20	4.00	4.80	0.11
Nitrogen fertilizer (pure discount) (t)	65.00	16.85	1 095.25	25.95

Phosphate fertilizer (t)	15.00	8.21	123.15	2.92
Potash (t)	15.00	4.18	62.70	1.49
Pesticide (t)	3.75	15.50	58.13	1.38
Cement (t)	72.50	1.50	108.75	2.58
Bricks and tiles (t)	25.79	0.52	13.41	0.32
Steel (kg)	20.00	2.70	54.00	1.28
Plastics (kg)	60.00	0.85	51.00	1.21
Methane emission from rice fields (hm ² ·a)	135.00	2.74	369.50	8.76
N ₂ O emissions from farmland (hm ² ·a)	167.00	4.34	724.18	17.16
Total emission (t)			4 220.03	100
Soil carbon sequestration (hm ² ·a)	190.00	0.80	152.00	
Forest carbon sequestration (hm ² ·a)	40.00	12.80	512.00	
Total absorption (t)			664.00	
Net emissions (t)			3 556.03	

Source: Data of CH₄ and N₂O emissions are from the Dongtan Agriculture Company of SIIC. CO₂ emission factors are from IPCC (2007).

4.2 Costs and benefits of low-carbon engineering technologies

Integrated engineering technologies were adopted to reduce CO₂ emissions. The costs and benefits to implement these technologies are reported in Table 3. The local government (SSTC) provided financial support to the experiment in the form of direct investment and subsidies. To assess if the experiment is profitable for a private investor, the costs and benefits were reported for the case in which the governmental investment was burdened by the investor (SIIC). Subsidies were also excluded as shown in the last column of Table 3.

The results indicate a positive net benefit for these technologies with heavy financial support from the government. Even without carbon premium to compensate for the reduced emissions, the investor (SIIC) can obtain a net benefit of 44.4 CNY per ton CO₂e reduction, accounting for 16% of the total cost. This estimated amount motivates the investor to implement the experiment. However, the investor may suffer considerable loss of 155 CNY per ton CO₂e reduction, accounting for 36% of the total cost, if the support from the government does not exist. The losses are four times the average CO₂ price (38 CNY per ton) in the Shanghai Environment Energy Exchange in the year since its first trading on December 20, 2013.

These results indicate at least two barriers for these technologies to emerge as an industrial business in Shanghai and other regions in China. One barrier is the large

starting investment. In the experiment, the initial investment is over 6 million CNY, more than triple the annualized total cost. This amount is equivalent to an initial investment of over 1,000 CNY per ton CO₂ reduction. The other barrier is the considerable losses if private investors implement these technologies without support from the government. To make the business profitable, the CO₂ price has to be as high as 155 CNY per ton, which is roughly the same as the 25 USD upper bound on the quota price proposed by the United States (UNFCCC 2010). In recent years, the CO₂ price has dropped to a low level. According to the World Bank (2012), the global CO₂ price was only 17.12 USD per ton in 2011 and dropped to only 5.27 USD in 2013 (World Bank 2014).

In China, CO₂ trading began in June 2013 in seven regional markets. In the Shanghai Environment Energy Exchange, the CO₂ price has fluctuated from 26 to 48 CNY per ton. In the entire Chinese carbon market, the highest CO₂ price is less than 120 CNY, and the average CO₂ price is 30 CNY per ton (from June 18, 2013 to March 22, 2015) in all the seven regional markets². These technologies are not economically effective because private investors will suffer considerable losses although they are compensated by the carbon premium evaluated at current market prices in China.

Table 3. Costs and benefits of low-carbon engineering technologies in 2011 (CNY 2005)

	Government's investments and subsidies included	Government's investments to be taken by SIIC and subsidies excluded
1. Fixed assets invested by SSTC	3 947 600	0
2. Fixed assets invested by SIIC	967 700	4 915 300
3. Fixed asset depreciation (10% of asset value)	96 770	491 530
4. Interests	63 868	324 410
5. Electricity cost	311 800	311 800
6. Material cost	461 600	461 600
7. Labor cost	200 000	200 000
8. Reparation cost	100 000	100 000
Total cost (C_{lp}, sum of items 3–8)	1 234 038	1 889 340
9. Value of self-produced electricity	112 500	112 500
10. Value of self-produced organic fertilizer	780 000	780 000
11. Value of chemical fertilizer saving	320 000	320 000
12. Subsidies	216 000	0
Total benefit (B_{lp}, sum of items 9–12)	1 428 500	1 212 500

² <http://www.tanjiaoyi.org.cn/>

Net benefit without carbon premium (NV_{LP1})	194 462	-676 840
Net benefit with premium of 30 CNY/ton CO ₂ (NV_{LP2})	325 864	-545438
Costs and benefits per ton CO₂ reduction		
Total cost without carbon premium (AC_{ip})	281.74	431.35
Total benefit without carbon premium (AB_{ip})	326.14	276.82
Net benefit without carbon premium	44.40	-154.53
Net benefit with premium of 30 CNY/ton CO ₂	74.40	-124.53

Sources: Data are from the Dongtan Agriculture Company of SIIC. The CO₂ price is approximately the average price of the entire Chinese carbon market and the fourth season of 2014 in the Shanghai Environment Energy Exchange. Emission factors are from IPCC (2007).

4.3 Costs and benefits of the entire DLCAP experiment

In China, large farms can also implement these technologies independently. Farmers should consider if the implementation is profitable by including the additional benefits of these technologies for agricultural production. For example, using organic fertilizer can increase crop yield and improve the quality of agricultural products. In the market, these products can be sold at a significantly higher price than other products although constant prices are adopted in the following calculation. These benefits would not be considered by a private investor other than farmers. Thus, the authors were motivated to calculate the costs and benefits of the entire DLCAP experiment.

Additional costs and benefits for agricultural production are estimated by comparing the situations before and after the implementation of the experiment. In 2008, the DLCAP farmland planted rice, wheat, maize, and horticultural crops of 106.67, 86.67, 26.67, and 13.33 ha, respectively. The park also owns a forest of 33.33 ha without any economic benefits. By adopting the constant prices of 2005, the net income of rice, wheat, maize, horticultural crops was 7,275, 4,500, 10,500, and 15,000 CNY/ha, respectively. The net benefits (including income from crops and governmental subsidy) amounted to 2.856 million CNY from the agricultural production in 2008.

In 2011, after the implementation of the experiment, the cropland for planting rice, wheat, watermelon, maize, horticultural crop, and green manure changed to 73.33, 53.33, 33.33, 26.67, 13.33, and 33.33 ha, respectively. The net income of rice, wheat, maize, horticulture, and watermelon was 8,025, 5,250, 11,550, 16,800, and 78,090 CNY/ha, respectively. Green manure was used for improving own land quality without any revenue. The net benefits (including income from crops and governmental subsidy) amounted to 5.23 million CNY. Together with the net benefits from the low-carbon engineering technologies, the total net benefits of the DLCAP experiment reached 5.424 million CNY in 2011 at constant prices of 2005. If the net

benefits from the engineering technologies were calculated in the case without financial support from the government, the total net benefits of the entire experiment would remain positive and as high as 4.5532 million CNY in 2011. Even in this case, the net benefits of the entire experiment were 1.59 times of that in 2008. The carbon premium to compensate for the emission reduction is not included, and the additional net benefits are calculated annually. Hence, large farms can benefit considerably from implementing these low-carbon engineering technologies even without financial support from the government.

However, these technologies are seldom adopted by large farms in China. After the DLCAP experiment, even the investor (SIIC) of the experiment abandoned most of these low-carbon technologies although the biogas and electricity production continues running in a low efficiency and the watermelon planting continues. Particularly, the chemical fertilizer and pesticide input increased to the original high level in 2008. As stated by the investor, the net benefits mainly come from the watermelon planting in 2011 apart from the subsidies from the government. The benefit from watermelon planting is not mainly recognized as a result of low-carbon technologies because watermelon is a strong cash crop. Nevertheless, using low-carbon technologies can increase the net income by 18.2% by comparing the watermelon inside DLCAP with that outside DLCAP. The watermelon market in Shanghai, a metropolis with a population of over 24 million, is huge and profitable for the investor because the transportation cost was lowered markedly after the Changjiang Tunnel-Bridge was opened in 2011. However, this aspect may not be copied and popularized effectively in other places without such good market conditions.

The increased net income of crops (maize, rice, wheat, and horticulture) is between 750 CNY/ha and 1,800 CNY/ha after the implementation of these integrated low-carbon technologies. If the sowing farmland across crops is assumed to be the same as in 2008 and 1800 CNY/ha is assumed as the increased net income of crops from these low-carbon technologies, then the total increased benefit will only be 0.4200 million CNY in 2011. The amount cannot offset the cost of these technologies amounting to -0.6768 million CNY if government support is excluded.

Therefore, the increased net benefits become negative if watermelon planting is replaced with planting of other crops (rice, maize, wheat, and horticulture) after the application of low-carbon technologies. The investor understood that the integrated low-carbon technologies could increase land productivity and product quality. However, the increased crop yields generated from these technologies are implicit and insufficient to cover the costs of these technologies although the increased product quality can be compensated by higher prices in the market. Furthermore, the government stopped subsidizing these technologies after the experiment. Thus, the investor would suffer losses from maintaining the operation of the integrated low-carbon technologies. These technologies cannot be adopted even by large farms without additional financial support.

However, the calculation does not include long-term effects of these technologies.

Firstly, the continuously organic fertilizer use is estimated to improve soil fertility by 5-10% according to the plantation structure in 2011. The improved soil fertility can increase crop yields, quality, and related benefits. This can also mitigate the potential food security problem. Secondly, potential long-term benefits can come from tourism associated with the landscape and ecological agricultural products in the experiment. The tourism income can be considerable since the demand for this kind of tourism services keeps increasing in Shanghai. Thirdly, the calculation does not include the benefits associated with the reduced environmental pollutants other than GHG emissions. If these long-term benefits are considered, the negative net benefits may be reversed even without external financial support.

5. Conclusion

This study reports the effectiveness of integrated low-carbon engineering technologies in a pilot agricultural experiment in Shanghai. These technologies effectively reduce emissions as they result in negative emissions in our case. These technologies can effectively utilize straw and cow dung to produce biogas, electricity, and organic fertilizer and to increase crop and soil sequestration, thus implying a significant potential of CO₂ emission reduction in agriculture. Among these technologies, straw fermentation and organic fertilizer technology are the most important for emission reduction. Therefore, in terms of emission reduction and environmental benefits, promoting the transition from the traditional extensive agriculture to the modern intensive and LCA is attractive in developing countries.

In economic terms, straw was comprehensively utilized. The net income from crops increased together with CO₂ reduction and environment improvement. However, the high cost of the core technology of straw–biogas–organic fertilizer production diluted the profits of the experiment and lowered the total return rate. This consequence decreases the attraction of integrated low-carbon technologies. Without financial support from the government, a private investor may suffer considerable losses from implementing these technologies although the carbon premium evaluated at current market prices was used for compensation. This possibility explains why these technologies have not emerged as independent businesses outside agricultural production. An investor (e.g., a large farm) can suffer losses in the short term from adopting these technologies. However, an investor may receive net benefits if considering the long-term effects on agricultural production, food security and the environment. Therefore, at the current stage of Shanghai, the LCAPs integrating low-carbon technologies can be feasible only with the provision of additional financial support in the form of subsidies, carbon premium, and compensation for external effects on agricultural production. A small complex with carefully selected economically effective technologies can be attractive to private investors.

The government should make policies to motivate private investments on these low-carbon technologies by allocating the social benefits associated with these technologies to private investors. In China, environmental problems such as air and land pollution and food security have emerged as the prioritized agenda for the

government in recent years. Given the considerable environmental benefits associated with these low-carbon technologies, the government should support the adoption of and research on these technologies to promote the development of modern agriculture. Implementing policies, laws, and institutions is urgently required to support the LCA development in China.

The experimental results also reveal that synergies can be obtained in an integrated complex of LCAP. For example, straw was used for producing biogas and organic fertilizer. Biogas was further used for electricity generation, and organic fertilizer was used to improve land quality, thus replacing chemical fertilizer. If only one technology such as biogas production was applied independently, then its economic benefits through electricity generation and effect on emission mitigation would be reduced considerably.

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About the authors

Dr. Chunzeng Fan is a full-time faculty specialized on environmental economics and management at Antai College of Economics and Management, Shanghai Jiaotong University. He worked as PostDoctoral at Fudan University from 2004 to 2006 and as Visiting Scholar at the University of West Ontario from 2013 to 2014 and at the University of Connecticut in 2015. He has been involved in several projects financed by the National Natural Science Foundation of China, the National Social Science Foundation of China and the Shanghai Municipal Government.

Dr. Taoyuan Wei is a senior researcher at Center for International Climate and Environmental Research - Oslo (CICERO). He moved to CICERO after receiving his PhD in Economics from the University of Oslo in 2009. He has been responsible for macroeconomic modeling in research projects related to energy, environment and climate change issues. His PhD dissertation was on accounting for the income arising from nonrenewable resources. He has worked on input-output survey, accounting and analysis at National Bureau of Statistics of China. Taoyuan Wei is the corresponding author and can be contacted at: taoyuan.wei@cicero.uio.no.