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RESEARCH ARTICLE

Selecting low-carbon technologies and measures for high agricultural carbon productivity in Taihu Lake Basin, China

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Abstract

In this paper, Delphi method was used to evaluate the low-carbon technologies and measures for high agricultural carbon productivity in Taihu Lake Basin. We established the selecting process and standards and obtained the final list of low-carbon technologies and management measures of high agricultural carbon productivity in Taihu Lake Basin: (1) the initial list of low-carbon technologies and measures of planting industry included 19 items, of which 10 items were included in the final list. The 10 technologies and measures included in the final list were reducing fertilizers, mixed use of organic fertilizer and chemical fertilizer, soil testing and formulated fertilization, application of controlled release fertilizer, deep application of fertilizers, cultivation of new variety, extension of conservation tillage, extension of midseason/alternate drainage, paddy-upland rotation (rice-rape/rice-wheat), and reducing pesticides. (2) The initial list of low-carbon technologies and measures of animal husbandry included 11 items, of which 4 items were included in the final list. The 4 technologies and measures included in the final list were reasonable ratio of concentrate to roughage in ration, treatment straw feed by silage/ammoniation/shredding, application of nutritive cube/dietary additives, and promotion of high productivity livestock breeds. (3) Low-carbon agricultural technologies and management measures need to be adapted to local conditions according to different geographical, climatic, and socio-economic development characteristics, and it is necessary to form a regionally differentiated system of low-carbon agricultural technologies and management measures. The final list of low-carbon technologies and management measures of high agricultural carbon productivity can provide decision-making reference for the formulation of agricultural carbon emission reduction technology system and low-carbon agricultural development planning of provinces and cities in Taihu Lake Basin. At the same time, the final list can be considered a priority for the promotion of agricultural low-carbon technologies and measures in China and even in the world.

Keywords Low-carbon technologies and measures · High agricultural carbon productivity · Selecting process · Final list · Taihu Lake Basin

Introduction

Global climate change, characterized by global warming caused by greenhouse gas emissions, has brought significant adverse effects on human society and economic development (IPCC 2014; NOAA 2015). The coupling relationship between agricultural production and climate change is obvious. On the one hand, climate change will lead to the contradiction between productive potential and effective supply of agricultural resources, which will bring great uncertainty to agricultural production (FAO 2016; Arunrat et al. 2017); on the other hand, under the development mode of “mechanization + chemistry = agricultural modernization,” agriculture has become the second major source of greenhouse gases (Tubiello et al. 2015; Carlson et al. 2017; Springmann et al. 2018; Xiong et al. 2020). According to a new study published in science, even if greenhouse gas emissions from energy, transportation, and manufacturing industries were immediately halted, current trends in global food systems would prevent the

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achievement of the 1.5 °C target and, by the end of the century, threaten the achievement of the 2 °C target (Clark et al. 2020). This makes agricultural carbon emission reduction more urgent.

Carbon emissions from the agricultural ecosystem accounted for 17% of China's total greenhouse gas emissions, which was approximately 4% higher than the proportion of the world (Xiong et al. 2016a; Charkovska et al. 2019; USEPA 2019). Agricultural GHG emissions of CH_4 and N_2O accounted for 50% and 92% of China's total CH_4 and N_2O emissions, respectively (Xiong et al. 2016b). Modern petroleum agriculture relied on a large number of chemical fertilizers, pesticides, and other external inputs. The serious negative externalities such as cross pollution of soil, water, and air and food insecurity are becoming increasingly prominent. Under this background, the innovation of low-carbon agricultural system and the promotion of agricultural low-carbon technologies and measures to achieve the synergy of agricultural carbon emissions reduction and adaptation to climate change has become an important research topic.

Studies on agricultural low-carbon technologies and measures mainly included three aspects: the first was the low-carbon technologies and measures for agricultural carbon emission sources (that is, the low-carbon technologies and measures in agricultural production activities), the second was the low-carbon technologies and measures for rural life, and the third was the utilization of biomass energy (Mi 2013). The low-carbon technologies and measures of agricultural carbon emission source were mainly to reduce agricultural carbon emissions by using fertilizer saving technology, water saving technology, livestock and poultry health breeding technology, no tillage technology, and other technologies (Lal 2004; Gilbert and Metealf 2008; Zhao and Qian 2009; Burney et al. 2010; Zou et al. 2011; Kragt et al. 2012; Xiong et al. 2016b). Cai et al. (2003) accumulated a lot of basic data for nitrous oxide and soil methane emissions from farmland (including dry land and paddy field) in China. Dong et al. (2008) summarized 4 major and 12 sub-item low-carbon technologies and measures for reducing methane emission from livestock intestinal fermentation, reducing methane emission from paddy field, reducing methane emission from livestock manure, and reducing nitrous oxide emission from farmland. Pimentel et al. (2005) used the farming system trial to study the differences of energy input, soil organic matter, water quality, biological resources, output level, and labor input of three different tillage methods, namely, traditional intensive agriculture (chemical fertilizer), organic farming combined with planting and breeding (manure), and legume rotation organic agriculture (plant nitrogen fixation). The low-carbon technologies and measures for rural life mainly included biogas project, solar energy utilization, and saving firewood and coal stove (Zhang et al. 2010; Zou et al. 2011). In terms of biomass energy utilization, low-carbon technologies and measures included straw energy utilization, biogas engineering, and energy crops (Steenbli and Moise 2010; Zou et al. 2011). These studies mainly focus on single technology and measure or a kind of technologies and measures, without evaluating the technologies and measures, and not forming a complete set of agricultural low-carbon technologies and management measures system.

Taihu Lake Basin is a famous water town in the south of the Yangtze River, with flat terrain, fertile land, crisscross river branches, scattered lakes, warm and humid climate, and four distinct seasons, which has been known as "land of fish and rice" (Su et al. 2010). However, with the extensive use of chemical fertilizers, pesticides, herbicides, agricultural film, and the rapid development of breading industry, the emissions of agricultural greenhouse gases in Taihu Lake Basin increased rapidly, and the agricultural greenhouse gas emissions per unit agricultural output value were low, so it became a "high emission, high efficiency" agriculture. The agriculture carbon productivity was not high, and the low-carbon competitiveness of agriculture was not prominent (Tian and Zhang 2013; Tian et al. 2014; Wu et al. 2014). How to develop agriculture can not only ensure production but also reduce agricultural carbon emissions in the Taihu Lake Basin? Improving agricultural carbon productivity is the key. Therefore, this study uses Delphi method to establish selecting process and standards to screen low-carbon agricultural technologies and measures in Taihu Lake Basin, and forms the final list of low-carbon technologies and management measures of high agricultural carbon productivity, which provides decision-making reference for the formulation of agricultural low-carbon technology system and low-carbon agricultural development planning of provinces and cities in Taihu Lake Basin. At the same time, the final list can be considered a priority for the promotion of agricultural low-carbon technologies and measures in China and even in the world.

There are two innovations in this paper: first, Delphi method–based reasonable selection process and quantifiable selection criteria of low-carbon technologies and measures for high agricultural carbon productivity were established, which were simple and practical for localizing selection; second, the final list of low-carbon technologies and management measures of high agricultural carbon productivity was obtained.

Materials and methodology

Connotation of low-carbon technologies and measures for high agricultural carbon productivity

Food security is the eternal theme of China's agriculture. Therefore, what agriculture needs are technologies and measures of "increasing production and reducing carbon emissions, or at least stabilizing production and reducing carbon emissions." Agricultural business entities (including household operation, collective operation, cooperative operation and enterprise operation, etc.) are the direct implementers of carbon emission reduction technologies and management measures. The impact of low-carbon technologies and measures on agricultural output and the difficulty in spreading them to agricultural business entities are the core contents in this paper. In addition, the certainty, technical feasibility, and carbon emissions reduction potential are also the connotation of low-carbon technologies and measures in this paper

Delphi method

The Delphi method is a structured communication technique or method based on the results of multiple rounds of questionnaires sent to a panel of experts. The experts can only have relations with the investigators, but do not have horizontal contact with each other, and are not allowed to discuss with each other. Repeated questionnaires are used to gather the consensus of the respondents and collect the opinions of all experts (Linstone and Turoff 2002). This paper simplifies the Delphi method and achieves the research objectives through two rounds of questionnaires (see the screening process section for details).

Selecting process of low-carbon technologies and measures for high agricultural carbon productivity

The selecting process of low-carbon technologies and measures for high agricultural carbon productivity is divided into three phases, that is, the preparatory phase, the implementary phase, and the summarizing phase (Fig. 1).

The preparatory phase

The first is to determine the goal of the study, which is to select the agricultural low-carbon technologies and measures that are "high certainty, high feasibility, large emission reduction potential, impact on yield increase or stability, and easy to promote" according to the connotation of low-carbon technologies and measures for high agricultural carbon productivity.

In order to achieve the research objectives, the next step is to determine experts and questionnaire design. In terms of experts, this study selected 7 experts, including 2 rural agricultural technicians, 2 Agricultural Technology Extension Station investigators, and 3 low-carbon agricultural research scholars in Taihu Lake Basin.

In terms of questionnaire design, in order to simplify the Delphi method, we omitted the first round of open questionnaire, and obtained the initial list of 30 agricultural low-carbon technologies and measures through the combination of references (Dong et al. 2008; Mariano et al. 2012; Xiong et al. 2019, 2020), expert interviews, field visits, and household surveys, which can save time and cost, and make the research more focused. Through the questionnaire survey, we evaluated the certainty, technical feasibility, carbon emission reduction potential, impact on agricultural output, and promotion difficulty degree of the 30 agricultural low-carbon technologies and measures. The questionnaire consists of five parts: certainty evaluation, feasibility evaluation, emission reduction potential assessment, impact on agricultural output, and promotion difficulty degree evaluation. The Likert 5-point scale is used to evaluate the extent of various low-carbon technologies and management measures. Certainty assessment from 1 to 5 indicates the change of certainty from low to high; feasibility assessment from 1 to 5 represents the change of feasibility from low to high; emission reduction potential assessment from 1 to 5 represents the change of emission reduction potential from small to large; the assessment of impact on agricultural production 1–5 represents large decrease in output, small decrease in output, no impact on output, small increase in output, and substantial increase in output, respectively; the promotion evaluation of difficulty degree from 1 to 5 indicates the change of difficulty of popularization from difficult to easy.

The implementary phase

We conducted a questionnaire survey on two agricultural technicians and two investigators in the form of interview, and three scholars were investigated by letter evaluation. Experts can list the problems of technologies and measures and give suggestions in the questionnaire.

For the selection of low-carbon technologies and measures for high agricultural carbon productivity, this paper sets a specific average standard, which requires certainty ≥ 4, feasibility ≥ 4, impact of agricultural product output ≥ 3, emission reduction potential ≥ 4, and difficulty degree of promotion ≥ 4. According to the evaluation results of experts, the technologies and measures meeting the requirements are listed in the final list. The second round of questionnaire survey was conducted on the technologies and measures meeting the three and four requirements in the five assessments, and experts' opinions were consulted to determine whether to maintain the original judgment or make changes. Finally, it is decided whether the technology and measures are included in the final list according to the feedback of experts and the selection standard.

The summarizing phase

We provided the final list of technologies and measures of high agricultural carbon productivity in the form of research results and explained them. We analyzed the reasons for the lost technologies and measures in the form of discussion.

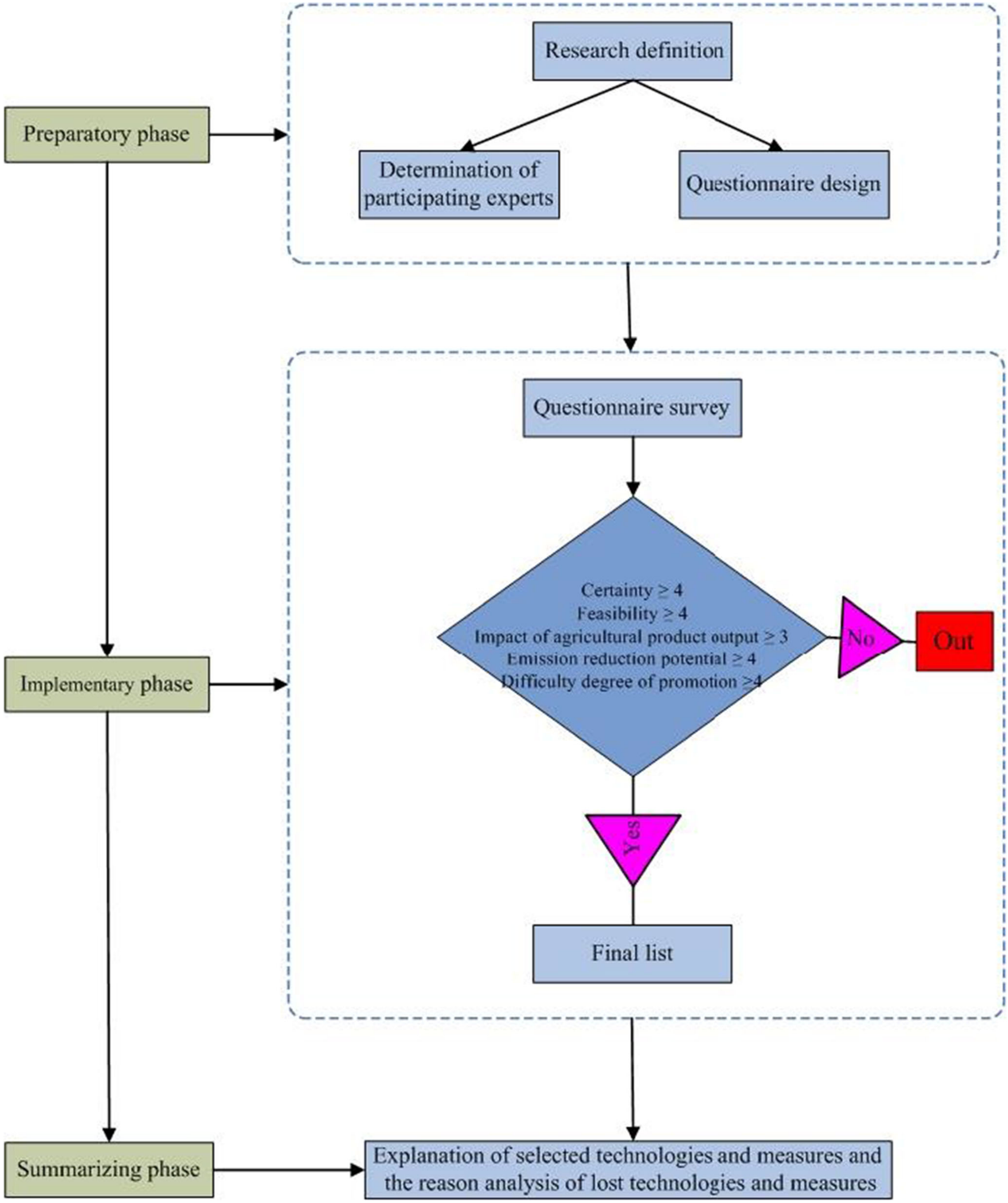

Fig. 1 The selecting process of low-carbon technologies and measures for high agricultural carbon productivity

Empirical results

The initial list of agricultural low-carbon technologies and measures in Taihu Lake basin included 30 items, and 14 high agricultural carbon productivity technologies and measures selected by experts were included in the final list (Table 1).

The initial list of low-carbon technologies and measures of planting industry included 19 items, of which 10 items were included in the final list (Table 1). The 10 technologies and measures included in the final list were reducing fertilizers, mixed use of organic fertilizer and chemical fertilizer, soil testing and formulated fertilization, application of controlled

Table 1 The selecting results of low-carbon technologies and measures for high agricultural carbon productivity

Mitigation technologies and measures	Certainty	Feasibility	Impact of agricultural product output	Emission reduction potential	Difficulty degree of promotion	Is it included in the final list?
Mitigation technologies and measures of planting industry	-	-	-	-	-	-
Reducing fertilizer	4.29	4.43	3.00	4.43	4.00	Yes
Mixed use of organic fertilizer and chemical fertilizer	4.14	4.57	3.57	4.29	4.29	Yes
Mixed application of nitrification inhibitor and chemical fertilizer	3.00	4.00	3.00	3.86	3.71	No
Using animal manure as fertilizer	3.00	4.57	2.71	2.71	4.43	No
Soil testing and formulated fertilization	4.00	4.43	4.00	4.57	4.14	Yes
Application of controlled release fertilizer	4.14	4.14	3.86	4.14	4.00	Yes
Deep application of chemical fertilizer	4.00	4.14	3.43	4.29	4.14	Yes
Application of integrated management of water and fertilizer	2.71	3.57	4.00	4.57	2.71	No
Improving land drainage	3.00	3.86	3.43	3.86	3.43	No
Legumes as green manure	3.29	3.57	3.14	4.00	2.57	No
Cultivation of new variety	4.43	4.14	4.00	4.29	4.00	Yes
Extension of conservation tillage	4.29	4.57	3.00	4.57	4.14	Yes
Retain crop residues, reducing bare fallow	3.57	3.57	3.14	3.00	3.14	No
Extension of midseason/alternate drainage	4.29	4.43	3.71	4.00	4.00	Yes
Application of CH4 inhibitors	4.00	3.86	3.14	4.00	3.57	No
Paddy-upland rotation(rice-rape/rice-wheat)	4.14	4.71	3.86	4.43	4.57	Yes
Mulching rice cultivation technology	2.14	3.00	3.29	2.57	2.14	No
Reducing pesticide	4.29	4.14	3.14	4.29	4.29	Yes
Biological control	2.14	2.43	2.57	2.86	2.29	No
Mitigation technologies and measures of animal husbandry	-	-	-	-	-	-
Reasonable ratio of concentrate to roughage in ration	4.71	4.57	3.71	4.29	4.57	Yes
Treatment straw feed by silage/ammoniation/shredding	4.86	4.57	3.57	4.43	4.57	Yes
Application of nutritive cube/dietary additives	4.29	4.29	4.29	4.43	4.14	Yes
Feed with vegetable fats or higher fatty acids	2.71	4.14	3.29	2.43	3.57	No
Small amount of multiple feeding	2.57	2.43	3.00	2.43	2.43	No
Promotion of high productivity livestock breeds	4.14	4.71	5.00	4.43	4.00	Yes
Modification from wet to dry cleaning manure process	4.57	2.86	3.00	2.71	2.00	No
Construction of standardized farms	4.57	2.43	3.43	2.71	2.57	No
Adding pebbles or covering straw during manure storage	3.43	4.43	3.00	2.29	3.29	No
Construction of liquid manure biogas project with livestock manure as raw material	4.71	4.71	3.00	1.57	1.43	No
Construction of solid manure organic fertilizer plant with livestock manure as raw material	4.43	2.57	3.00	2.57	2.14	No

release fertilizer, deep application of fertilizers, cultivation of new variety, extension of conservation tillage, extension of midseason/alternate drainage, paddy-upland rotation (rice-rape/rice-wheat), and reducing pesticides. Reducing fertilizers means avoiding excessive application of chemical fertilizer, improving the utilization efficiency of chemical fertilizer, so as to reduce the emission of greenhouse gases such as NO_2. Mixed use of organic fertilizer and chemical fertilizer refers to using all kinds of organic fertilizer as much as possible, increasing the content of soil organic matter, and adjusting the amount of chemical fertilizer, so as to reduce the emission of greenhouse gases such as NO_2. Soil testing and formulated fertilization refers to proposing fertilizing quantity, period, and application methods according to the law of crop fertilizer demand, soil fertilizer supply performance, and fertilizer effect, which improves fertilizer utilization efficiency and reduces the emission of greenhouse gases such as NO_2. Application of controlled release fertilizer means reducing the loss of fertilizer volatilization, prolonging the effective period of fertilizer, improving the fertilizer utilization efficiency, so as to reduce the emission of greenhouse gases such as NO_2. Deep application of chemical fertilizer means that compared with surface application, deep application of 10 cm layer can reduce the loss of fertilizer volatilization, leaching, and denitrification losses, which reduces the emission of greenhouse gases such as NO_2. Cultivation of new variety refers to the cultivation of rice varieties with low exudation rate and high N-use efficiency, which reduces the emission of greenhouse gases such as NO_2 and CH_4. Extension of conservation tillage refers to reducing tillage times, diversifying rotation tillage, increasing the amount of straw returned to the field, which can increase soil organic carbon content, improve soil fertility, and reduce the demand for external chemical fertilizer input. Extension of midseason/alternate drainage refers to changing the water condition of paddy field and the methane bacteria anaerobic environment, so as to control the generation and emissions of CH_4. Paddy-upland rotation (rice-rape/rice-wheat) can effectively reduce the methane bacteria number, thus reducing the emission of CH_4. Reducing pesticide means avoiding excessive application of pesticide, improving the utilization efficiency of pesticide, so as to reduce the emission of greenhouse gases.

The initial list of low-carbon technologies and measures of animal husbandry included 11 items, of which 4 items were included in the final list (Table 1). The 5 technologies and measures included in the final list were reasonable ratio of concentrate to roughage in ration, treatment straw feed by silage/ammoniation/shredding, application of nutritive cube/dietary additives, promotion of high productivity livestock breeds, and construction of liquid manure biogas project with livestock manure as raw material. Reasonable ratio of concentrate to roughage in ration means controlling content of crude cellulose in dietary, thereby, decreasing pH in rumen and inhibiting the activity of methanogens, so as to reduce the generation and emissions of CH_4. Treatment straw feed by silage/ammoniation/shredding can effectively improve the palatability and digestibility of straw, and improve feed utilization, so as to reduce the generation and emissions of CH_4. Application of nutritive cube/dietary additives can reduce the number of methanogens so as to reduce the generation and emissions of CH_4. Promotion of high productivity livestock breeds means that high livestock productivity can reduce CH_4 emissions per unit of livestock products.

Discussion

(1) In the second round of questionnaire survey, the technologies and measures included reducing fertilizers, reducing pesticides, extension of conservation tillage, and application of CH_4 inhibitors. The focus of the dispute among experts on reducing fertilizers, reducing pesticides, and extension of conservation tillage was whether the output of agricultural products would be reduced. Finally, the experts concluded that the excessive use of chemical fertilizers and pesticides in Taihu Lake Basin was widespread. Therefore, reducing the use of chemical fertilizers and pesticides would not affect the yield of agricultural products. As for extension of conservation tillage, some experts think that it would increase yield, while others think it would reduce yield, especially no tillage. The final feedback result was impact of agricultural product output ≥ 3. Therefore, reducing chemical fertilizer, reducing pesticide, and extension of conservation tillage were included in the final list (Table 1). For the application of CH_4 inhibitors, the final scores of certainty, feasibility, impact of agricultural product output, emission reduction potential, and difficulty degree of promotion were 4.00, 3.86, 3.14, 4.00, and 3.57 respectively (Table 1). Although it did not meet the selection criteria and enter the final list, it was also a good agricultural low-carbon measure.

(2) The scores of the mixed application of nitrification inhibitor and chemical fertilizer, improving land drainage, retain crop residues were all above three points, and they were good low-carbon technologies and measures. Using animal manure as fertilizer, feed with vegetable fats or higher fatty acids, and adding pebbles or covering straw during manure storage were excluded from the final list mainly because of the low emission reduction potential (Table 1). The main reason for the failure of such technologies and measures as application of integrated management of water and fertilizer, mulching rice cultivation technology, and biological control was the low certainty (Table 1).

(3) Scientific studies showed that green manure crops can promote soil carbon storage, and the conclusion that nitrogen fertilizer input can be reduced by biological nitrogen fixation has been reached a consensus (Izaurralde et al. 2001; West and

Post 2002). Although legume and other green manure crops rotation, and intercropping had been applied in the agricultural production practice of Taihu Lake Basin, it needed to increase the input of raw materials and labor costs, which affected the willingness of farmers to adopt and it was difficult to promote. Similarly, the measure of small amount of multiple feeding had low scores due to the labor costs involved.

(4) Construction of liquid manure biogas project with livestock manure as raw material is a good agricultural carbon emission reduction project, but it is an obsolete carbon emissions reduction technology in Taihu Lake Basin. There are two reasons. One is the lack of raw materials. Except for a small number of chickens and ducks, there are almost no other livestock like pigs, cattle, and sheep in the rural areas of Taihu Lake Basin. The other is that the rural farmers in Taihu Lake Basin have a higher living standard. They mainly use natural gas stoves, electric cookers, induction cooker, and other electronic products for cooking.

(5) Experts agreed that the carbon emission reduction certainty was high, but from the perspective of applicable objects, it was mainly large-scale farms, and it was extremely difficult for individual small-scale farmers to adopt the three measures, namely, modification from wet to dry cleaning manure process, construction of standardized farms, and construction of solid manure organic fertilizer plant with livestock manure as raw material (Table 1).

(6) Experts had paid special attention to the willingness of farmers to adopt emission reduction technologies with high certainty, strong feasibility, and great emission reduction potential. There are two main factors affecting farmers' adoption: first, some low-carbon technologies are labor-intensive; however, the increasing labor cost limits the adoption of farmers, and farmers are more concerned about output than emissions reduction; second, some low-carbon technologies need to be supplemented by strong agricultural technology promotion.

(7) In this paper, the final list of low-carbon technologies and management measures of high agricultural carbon productivity was obtained, which was suitable for the Taihu Lake Basin. It can only be a priority choice for other regions, but may not be applicable. We should know that low-carbon agricultural technologies and management measures need to be adapted to local conditions according to different geographical, climatic, and socio-economic development characteristics. In the future, it is necessary to form a regionally differentiated system of low-carbon agricultural technologies and management measures.

Conclusions

In this paper, Delphi method was used to evaluate the low-carbon technologies and management measures for high agricultural carbon productivity in Taihu Lake Basin. We established the selecting process and standards and obtained the final list of technologies and management measures of high agricultural carbon productivity in Taihu Lake Basin:

(1) The initial list of low-carbon technologies and measures of planting industry included 19 items, of which 10 items were included in the final list. The 10 technologies and measures included in the final list were reducing fertilizers, mixed use of organic fertilizer and chemical fertilizer, soil testing and formulated fertilization, application of controlled release fertilizer, deep application of fertilizers, cultivation of new variety, extension of conservation tillage, extension of midseason/alternate drainage, paddy-upland rotation (rice-rape/rice-wheat), and reducing pesticides.

(2) The initial list of low-carbon technologies and measures of animal husbandry included 11 items, of which 4 items were included in the final list. The 4 technologies and measures included in the final list were reasonable ratio of concentrate to roughage in ration, treatment straw feed by silage/ammoniation/shredding, application of nutritive cube/dietary additives, and promotion of high productivity livestock breeds.

(3) Low-carbon agricultural technologies and management measures need to be adapted to local conditions according to different geographical, climatic, and socio-economic development characteristics, and it is necessary to form a regionally differentiated system of low-carbon agricultural technologies and management measures.

The final list of low-carbon technologies and management measures of high agricultural carbon productivity in Taihu Lake Basin can be considered a priority project for the promotion of agricultural emission reduction technologies and measures in China and even in the world, and it can provide decision-making reference for the formulation of agricultural carbon emission reduction technology system and low-carbon agricultural development planning of provinces and cities in Taihu Basin.

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Declarations

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