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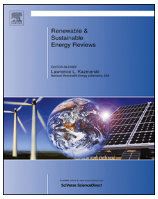

Modelling the policies of optimal straw use for maximum mitigation of climate change in China from a system perspective

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ABSTRACT

Understanding the competitive uses of straw resources as substitutes for fertilizer nutrients, forage and fossil energy is critical to maximize the mitigation of climate change. Focusing on the mitigation of global warming, we developed an uncertainty model for the optimal use of straw in China based on available studies of life-cycle assessment that have determined the advantages of energy savings and reductions of greenhouse gases (GHGs) of 14 conversion technologies. The current pattern of straw use has saved China 0.75 EJ of energy and has reduced GHGs by 270.76 Mt CO_2e on average annually. Among all competitive uses, the use of straw as forage was most environmental friendly, followed by the uses of straw as alternative sources of nutrients and energy. Simulated scenarios for policies of competing straw uses suggested that joint decision-making among administrative departments was vital to maximize the national mitigation of global warming (i.e. 1.84–2.26 EJ of energy saved or reductions of GHGs of 464.89–568.61 Mt CO_2e annually) by considering all straw uses comprehensively instead of overemphasizing a single use.

Contents

Abbreviations: ABC, ammonium bicarbonate; AS, ammonium sulfate; MAP, monoammonium phosphate; DAP, diammonium phosphate; SSP, single superphosphate; TSP, triple superphosphate; MOP, potassium chloride; SOP, potassium sulfate; $N_{machine}$, nutrient use of straw returned to farmland by machinery; F_{silage}, forage use of straw by silage technology; $F_{ammonification}$, forage use of straw by ammonification technology; $F_{untreated}$, forage use of straw by direct feeding without treatment; P_{pure}, pure combustion for power; $P_{cofiring}$, co-firing 15% biomass and 85% hard coal for power; $P_{gasification}$, gasification and combustion for power; $P\&H_{digestion}$, anaerobic digestion for heat and power generation; $H_{stove(TSC)}$, traditional household cook-stove burning for heat; $H_{stove(ISC)}$, improved energy-saving cook-stove burning for heat; H_{boiler}, combustion in biomass boiler for heat; $H_{gasification}$, gasification and combustion for heat; $H_{h\text{-}digestion}$, household anaerobic digestion and combustion for heat; $H_{L\text{-}digestion}$, large-scale anaerobic digestion and combustion for heat; IPCC, Intergovernmental Panel on Climate Change.

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1. Introduction

Straw contributes to the mitigation of climate change in multiple ways [1,2]. By leaving straw in the field in both tilled and untilled farming systems, soil fertility can be maintained by the addition of nutrients and soil organic carbon (SOC) [3–5]. Straw can also be used to feed cattle, especially in mixed crop-livestock systems in developing countries [6]. Crop residue is also a promising alternative to fossil energy due to its carbon neutrality, which can contribute to the mitigation of climate change [7–9]. Different users compete for the limited straw resources. Policy makers are challenged by the dilemma of quantitatively allocating limited resources among different straw users to maximize the environmental benefits of energy savings or reductions in greenhouse gases (GHGs) [10].

Life-cycle assessment (LCA) is an effective methodology for quantifying environmental impacts caused by products or services [11], including global-warming potential specified by flows of energy and GHGs. Numerous LCA studies have recently been published on bioenergy based on the raw material feedstock of straw, with the dual challenges of the energy crisis and GHG reduction [12–15]. LCA, combined with optimization, has been effectively used for the planning of bioenergy production, by both prioritizing the input of biomass for specific energy types and optimizing the size and location of a power plant [16,17]. Available reviews [18–20] have also summarized the environmental benefits of various systems of bioenergy from a LCA perspective, highlighting the two issues of result uncertainty and competition among multiple straw users, on which this study focuses.

Uncertainty is an inherent deficiency of LCA methodology originating from various processes. It cannot be avoided completely but can be analyzed by established methodologies, such as Monte Carlo simulation [21,22], meta-analysis [23] or fuzzy evaluation [24]. Resource competition among various straw users for bioenergy, fertilizer nutrients and livestock forage has been frequently highlighted [8,18,25]. An LCA-based system simulation has rarely been conducted to help policy makers to optimally allocate straw resources among various users for the maximum mitigation of climate change, although the environmental impacts of straw used as energy, forage and fertilizer have been compared [26].

The rapid development of China is leading to energy shortages, farmland degradation and increasing demand for animal-based foods. The central government has vowed to cut GHG emissions by 40–50% per unit of GDP by 2020 relative to the 2005 level (Central Government, PRC) [27]. These challenges are closely linked to straw management. The Ministry of Agriculture (MOA) reported that approximately 800 Mt of straw was produced annually in China, with the majority used in an environmentally friendly way. Unfortunately, a large amount of straw (210 Mt) was directly burnt in the fields (Section A1 in Appendix A), leading to substantial environmental burdens such as air pollution [28,29]. Multiple administrations are responsible for straw uses as nutrients, forage and energy, policy-making for multiple straw uses compete to each other in practice. A study is thus needed to analyze the problem of the optimal allocation of straw resources among multiple competitive users to maximize the mitigation of climate change.

We quantified the net rates and uncertainties of climate-change mitigation of 14 conversion technologies based on a series of reviewed and developed LCAs by comparing corresponding reference systems to provide equivalent products or services. We then developed an optimization model with uncertainties to maximize energy saving or GHG reductions by allocating straw resources as substitutes for fertilizer, commercial forage and fossil energy. We also simulated and compared scenarios for various policies of straw use.

2. Materials and methods

2.1. Optimization system for straw use in China

The system of straw use in China was constructed in accordance with the pattern of straw uses (Fig. 1, Section A2 in Appendix A). The life-cycle inventories of commercial fertilizers and forages (reference systems 1 and 2) were investigated in this study. Commercial fertilizer plays two important roles: as a necessary input to grow corn as raw material for forage production and as a nitrogen source for accelerating microbial activities during straw silaging and ammonification.