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# Environmental potentials of policy instruments to mitigate nutrient emissions in Chinese livestock production<sup>☆</sup>



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## HIGHLIGHTS

- A framework based on an Agent Based Model is built for policy assessment.
- The effects of five policies on nutrient mitigation are simulated and compared.
- Only three policies prove to be the most effective to reduce nutrient emission.
- Medium-scale farms are more relevant for ecological reform of livestock production.
- A number of policy implications and development strategies are concluded.

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## ABSTRACT

To minimize negative environmental impact of livestock production, policy-makers face a challenge to design and implement more effective policy instruments for livestock farmers at different scales. This research builds an assessment framework on the basis of an agent-based model, named ANEM, to explore nutrient mitigation potentials of five policy instruments, using pig production in Zhongjiang county, southwest China, as the empirical filling. The effects of different policy scenarios are simulated and compared using four indicators and differentiating between small, medium and large scale pig farms. Technology standards, biogas subsidies and information provisioning prove to be the most effective policies, while pollution fees and manure markets fail to environmentally improve manure management in pig livestock farming. Medium-scale farms are the more relevant scale category for a more environmentally sound development of Chinese livestock production. A number of policy recommendations are formulated as conclusion, as well as some limitations and prospects of the simulations are discussed.

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## 1. Introduction

The negative effects of modern agricultural production, especially water eutrophication, are a world-wide environmental problem, which has been well documented in research of both developed countries and developing countries such as China (Foy et al., 2003; Ulén et al., 2007; MEP, 2010; Jarvie et al., 2013). Agricultural nutrient emissions, mainly in the form of non-point source pollution (NPSP), can be the result of runoff from either livestock farms, or from farmlands after manure or chemical fertilizer application. The need to mitigate nutrient losses has been the focus and subject of policy-making in certain

countries over some decades. Some of these policies target the national or international level, e.g. the EU Water Framework Directive and the Clean Water Act in the US, whereas others work on regional or lower levels. A surplus of manure from increasing and more intensive animal production is considered a major cause of agricultural nutrient pollution (Maguire et al., 2009). Therefore, environmental management practices in these countries aim at better manure management by such means as manure recycling through anaerobic digestion, restricting animal density on agricultural land, or setting limitations on manure application (Maguire et al., 2009; Zaks et al., 2011).

China has been one of the most important producers of livestock products in the world since its economic reform (FAO, 2006). Due to the government's priority of increasing agricultural productivity and output as well as the steep rise in meat consumption, China significantly increased meat production over the past 30 years at a rate twice as fast as the world average (Li, 2009; Ortega et al., 2009). Thus, it is no surprise to find that livestock production is a major source of nutrient pollution,

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which almost equals that from crop production (MEP, 2010). As a consequence of increasing pollution, Chinese livestock policies have gradually shifted from a one-sided objective of economic development to a more integrative objective that also includes environmental considerations. This process dates back to 2001, when management measures for pollution control and standards of pollutant discharge were issued in livestock sector, although these measures and standards only attempted to govern large-scale industrialized animal producers. However, environmental policies so far have performed poorly in rural China, because of the limited voice of environmental agencies, the insufficient environmental interest of local governments, and no market demand for 'ecological' livestock products, among other issues (Swanson et al., 2001).

When confronted with the problem of how to enhance the effectiveness of environmental policies for Chinese livestock production, policy-makers face two essential questions. The first question concerns the policy instruments to implement. There are few studies that explore the effectiveness of environmental policy instruments in Chinese livestock production. However, such research is deemed crucial because theoretically optimal policy instruments, such as environmental taxes, may have quite different effects depending on the sector and issue (Mickwitz et al., 2008). A second question confronting policy-makers concerns the appropriate definition of the producer group that should be targeted by environmental policies. Actors in one economic sector can be heterogeneous; some are large-scale producers, whereas others are small or micro-producers; and some may act as promoters and supporters of strict environmental management, others may not (Oye and Maxwell, 1994). Since the mid-1980s, Chinese farmers have been permitted to keep more animals than needed for self-consumption, i.e. farmers can undertake animal production as a means of revenue generation. Consequently, livestock production in China has undergone considerable intensification and diversification. This change also implies that depending on production scale, livestock producers may have distinct environmental considerations, show distinct responses to policies and differ in their contributions to nutrient emissions (Zheng et al., 2013a). As a consequence, environmental management of rural livestock production in China has become rather complex. Chinese policy-makers need to find effective policy instruments for the different categories of livestock producers to achieve better nutrient mitigation.

This research takes into consideration the complexity of rural livestock production in China and explores the potential of Chinese livestock policies to mitigate nutrient emissions using an agent-based analysis. An Agent-Based Model (ABM) simulates the behavior of a system based on autonomous agents who individually but interdependently make their

decisions according to a set of rules (Page, 2008; Macal and North, 2010). ABMs can thus cope with the heterogeneity of individuals and capture emergent phenomena generated by heterogeneity and interactions among agents (Grimm and Railsback, 2005; Macal and North, 2007). In this way, ABMs can incorporate the diversity of livestock producers in rural China, their different responses to policies, and the aggregate effects of their decisions, i.e., policy implementation effectiveness.

## 2. Methods

### 2.1. Research framework

The framework to assess the mitigation potentials of policies can be divided into two levels: the individual level of farmers and the system level, as shown in Fig. 1.

National policies from governmental agencies function at the system level, attempting to constrain and guide livestock producers in operating their farms. Two types of national policies exist for Chinese livestock production. Most national policies are implemented for non-environmental purposes, such as food security, livelihood improvement and poverty reduction. For instance, government-financed insurance attempts to expand overall animal production, while subsidies for constructing industrial farms aim to promote intensive livestock production (GOSC, 2011). A second type of policy aims to reduce the environmental effects of livestock production by improving manure management practices. Although there is no comprehensive policy program in China to improve manure management or control pollution from livestock production, the central government integrates environmental concerns into a number of other policies. For instance, the promotion of household biogas digesters also contributes to improving environmental management in livestock production (SCC, 2012; He et al., 2013). Policies addressing environmental concerns will be summarized under "environmental policies" in this research; the aforementioned policies will be summarized as "agricultural policies" (Fig. 1). Apart from national policies, aggregate livestock production and its associated environmental performance are also measured at the system level. At an individual level, farmers make a diversity of decisions in response to policies. An Agent-based Nutrient Emission Model (ANEM) was used to predict farmers' decision-making, as well as the economic and environmental performance of livestock production, whereas policies were considered exogenous forces (Zheng et al., 2013b).

The assessment of the effects of environmental policies is conducted as scenario analysis. The scenarios for different policy instruments are

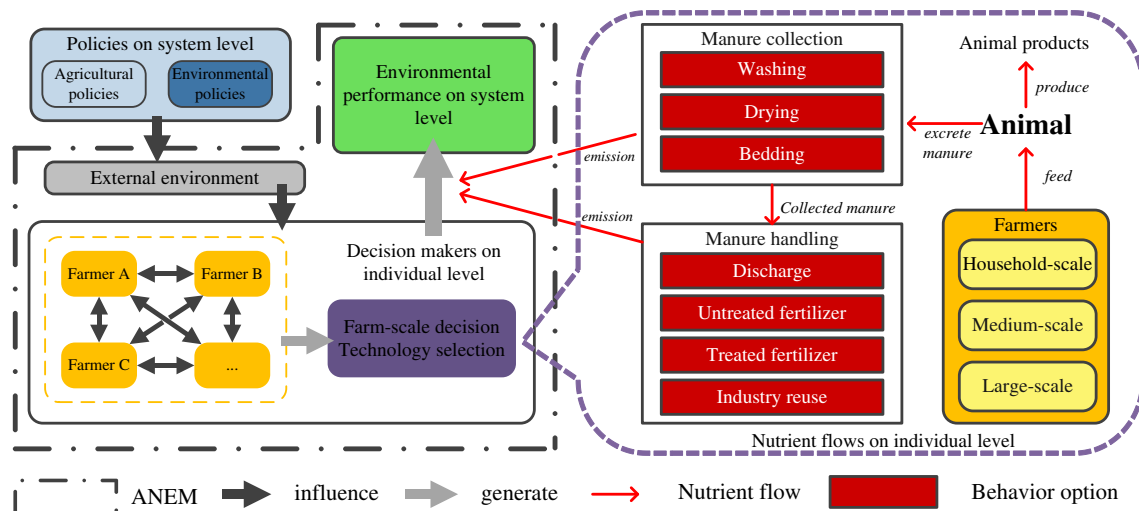


Fig. 1. Conceptual framework and model structure.

based on current Chinese policies and hypotheses concerning policy implementation. One common problem of policy studies is the difficulty decoupling the effects of policy instruments from those of parallel policies and exogenous factors (Guedes Vaz et al., 2001). Because an ABM analyzes a complex system as composed of “behavioral” entities (i.e., individual agents), it is able to identify their responses with a single policy in an integrated policy package (Bonabeau, 2002). It thus identifies the effects of the single policy from other parallel policies. The model results show the potential of nutrient mitigation in livestock production. This potential is defined as the reduction in nutrient emissions due to policy intervention compared with a reference scenario without intervention.

## 2.2. ANEM model

As delineated in Fig. 1 by black dash-dotted lines, the ANEM comprises the external environment, the individual animal producers who make decisions and interact, and the resulting aggregate performance. Through empirical calibration, the ANEM is flexible in simulating livestock production and associated environmental performance in different areas of China.

The simulation unit, i.e., one artificial farmer, autonomously performs “farm-scale decision” and “technology selection” on his farm (see Fig. 1) under the co-influence of the external environment, personal factors, and interactions with other farmers. The number of animals on a farm determines the quantity of manure generated, while manure management practices determine the proportion of nutrient emissions from manure to the environment. Although this research only focuses on environmental policies, the potential for nutrient mitigation possibly derives from both the reduction of the number of animals and the ecologizing of manure management practices. The ANEM distinguishes among household-, medium-, and large-scale farmers. This categorization helps to identify mitigation potentials that are dependent on the farming scale and captures the dynamics within livestock production, as agents can change from one scale to another. Manure management practices in China mainly comprise the adoption of manure collection and handling technologies. Three manure collection and four manure handling technologies are involved in the ANEM, as shown in Fig. 1. A conventional method of manure management in China is to wash animal pens to collect the manure and then to either handle the slurry as fertilizer without treatment, or to directly discharge the slurry to the environment (Chen, 2007). Alternative technologies are more environmentally friendly because these alternatives reduce nutrient emissions to the environment.

Farmers' decision-making is conceptualized as innovation adoption processes. Larger-scale production and new, less environmentally disturbing manure management technologies are considered as innovations. Innovation diffusion theory, which is built on many empirical studies, is employed to formulate decision-making sequences in the ANEM (Rogers, 2003). It is assumed that a farmer passes through various stages, first gaining “knowledge” concerning innovations, then learning from nearby examples, followed by evaluating expected economic and environmental benefits, adopting or rejecting innovations, and finally seeking confirmation of the decision. Accordingly, interactions among farmers are defined as observing neighbors to learn about innovations and then assessing the economic and environmental performance of the innovations (High, 2009). The external environment of farmers consists of non-agent resources and certain influential factors, such as the prices of meat, feed and manure and the information provided by authorities. The external environment is affected by exogenous policies and then provides input and conditions for an individual farmer's decision-making. More details of the ANEM are given in Appendix I.

Four indicators are calculated to represent the aggregate performance of the ANEM. The first one is nutrient emissions measured in tons per year, representing a negative effect on the environment. The

second indicator shows how much improved environmental management affects economic performance and is measured in total animal numbers. The last two indicators are relevant for understanding the extent to which livestock farms have integrated pollution mitigation into their production process. One indicator is the overall improvement in manure management practices and is measured as the penetration rate (%) of different collection and handling technologies. The other indicator is pollutant nutrient emissions per animal.

## 3. Simulation

This section first introduces how the agent-based assessment framework is applied to a case study, which is pig production in Zhongjiang County, Southwest China. Then, the methodology for designing policy scenarios is presented.

### 3.1. Case study

Zhongjiang County is a traditional and important livestock-producing region. Pig production contributes more than 60% to the total monetary output of local livestock production. However, the share of intensive pig production (medium- and large-scale farms) is much lower than China's average. This lower average means that farmers in Zhongjiang are more scattered, smaller and more heterogeneous, which highlights the importance of evaluating livestock production with an agent-based analysis.

A survey was carried out in 2010 among animal producers. The collected data, which consisted of individual farmer's characteristics and behavioral rules, was entered into a database. To collect information on policies and on environmental and economic performance at the system level, interviews with governmental officials were conducted, and statistical data from yearbooks and governmental files were collected. The ANEM was programmed on the MATLAB® platform and simulated the dynamics in the case area from 2005 to 2008. When the simulation results were compared with the aggregate historical dynamics of livestock production, the results approximated the real-world observations in terms of livestock product output, technology change and nutrient emissions (Zheng et al., 2013b). This comparison demonstrated the capability of the ANEM to replicate the real-world characteristics and behavioral rules of Chinese farmers.

In this research, the ANEM simulates pig production at the survey site and its associated nutrient emissions for the next 10 years. The number of farmers in the simulation is 1/7 the actual number of livestock producers in Zhongjiang County. The simulation is initialized in 2010 and takes one year as the time step. The parameters customized in the empirical research of Zhongjiang are used in the scenario simulations. Diverse policy alternatives are introduced into the model as abrupt interventions just after the initial year. Because the ANEM does not consider the time delay of policy implementation, the policy interventions are expected to take effect immediately. Other inputs apart from the policy alternatives are set as constant for all the scenarios, available in Appendix II.

### 3.2. Policy scenarios

To improve manure management practices, policies can utilize various instruments, including regulatory, market-based, and communicative instruments (Norberg-Bohm, 1999). Five policy instruments are assessed in this research. These policies address at different farmer groups, kinds of technologies, and decision-making sequences (details are available in Appendix III). The reference scenario is benchmarked with all five policy instruments mentioned above.

Regulatory instruments are the oldest environmental policy instruments. These tools are often believed to lack incentives for technology change, but still are considered important because they guarantee a baseline for safeguarding public and ecosystem health (OTA, 1995;

Mickwitz et al., 2008). The Chinese technology standard (HJ/T 81-2001) prescribes “dry collection” for intensive (medium- and large-scale) animal farms as the standard manure handling practice, and bans the direct discharge of manure into areas such as rivers or lakes. Additionally, the technology standard encourages the utilization of manure as an energy source. Although the standard is weakly implemented in case area, it is assumed to be strictly implemented in the “technology standard” scenario.

A shift from conventional command-and-control regulations to instruments, that use incentives, forms part of a general change in China's environmental management (He et al., 2012; Liang and Mol, 2013). Market-based mechanisms are commonly believed to be superior for promoting technology change, because they make nutrient mitigation profitable, and, if well-designed, motivate both ecologically and economically rational producers (Requate, 2005). Our scenarios represent different kinds of economic incentives. One incentive involves pollution fees, i.e., pollution fees are not levied if a livestock producer reduces emission costs through abiding by a pollution standard. Another incentive is an increase in income through subsidies or the sale of manure.

Pollution fees have been widely applied in China since the 1980s. According to Mol (2006), pollution fees provide an important source of income for local environmental agencies and significantly elicit the implementation of environmental measures. However, several studies found that the current fees are so low that most polluters prefer paying the fees instead of responding to the incentive, e.g., investing in improved technologies to reduce emissions (Taylor and Xie, 2000; Zheng et al., 2013b). It is found in the field survey that pollution fee is hardly implemented in the agricultural sector of the case area. The “pollution fee” scenario is designed to examine the effect of doubling the pollution fee.

Subsidies are also an especially widespread instrument in current Chinese agricultural policies. Biogas subsidies from the central government started in 2005 and are one of the major instruments to promote household biogas production in rural China (Chen et al., 2010; Bluemling and Hu, 2011; Qu et al., 2013). Biogas digesters are important for manure management because they hold livestock manure and thereby avoid manure emission into the natural environment. Furthermore, the nutrients in manure are mineralized during the digestion process, and the processed manure can be better applied to fields as “treated fertilizer”. Additionally, digester tanks permit the flexible scheduling of manure applications according to crop requirements. However, the goals of the biogas subsidies contrast with the general condition of livestock breeding in China, where tanks for collecting manure hardly exist. The “biogas subsidy” scenario accordingly analyzes the extent to which the subsidy is able to promote the diffusion of biogas infrastructure and the mitigation of total nutrient emissions. According to government interviews of field survey, household biogas production is valuable to improve farmers' livelihood, and hence has been promoted for years in the case area. The current subsidy is around 1000 yuan for building a digester tanks.

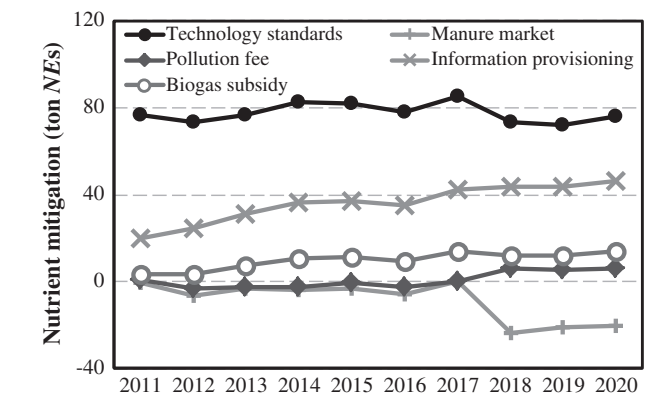
As an additional instrument for providing positive economic incentives to mitigate manure emissions, the effects of a “manure market” are explored. In our empirical research, manure markets proved to be an increasingly important local solution to cope with the imbalance between manure supply and demand. Some food companies purchase livestock products as well as manure, making manure profitable for livestock producers. Unlike pollution fees and subsidies, a manure market provides direct incentives to farmers to handle manure properly without the necessity of government involvement, e.g., government subsidies or the monitoring of emissions. Given these advantages, the effects of a “manure market” are examined in a further scenario using the farmers' expected manure prices obtained in our household survey.

The last policy instrument, whose effects will be assessed in a scenario, is “information provisioning”. According to some studies, the perception of technologies is a crucial barrier to their adoption because the

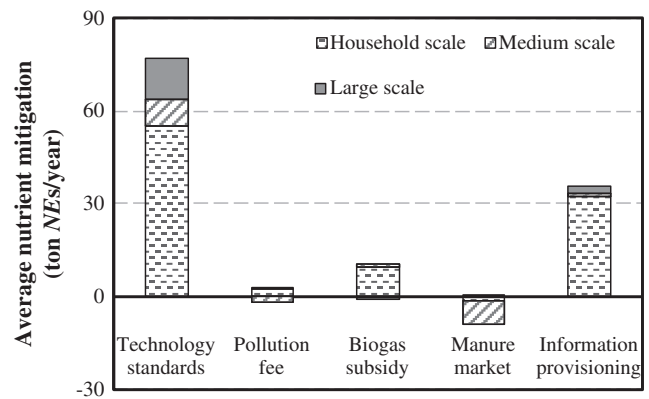
payoff from environmental technologies occurs only in the long term and is associated with high uncertainty (Norberg-Bohm, 1999; Berger, 2001). To provide more information to farmers, the Chinese government decided to establish more local service offices (at township and village levels) and government-financed training programs. Nevertheless, these relatively new policies have not been well implemented in the case area. The “information provisioning” scenario assumes that farmers are able to obtain knowledge on all technologies via governmental consultation.

#### 4. Results

In this section, the effects of the above outlined policy instruments are analyzed using the four indicators of nutrient emissions, animal output, the penetration rate of different technologies, and pollutant nutrient emissions per animal. To understand the marginal effects of the policy instruments, we compare the policy scenarios with the reference scenario. First, nutrient mitigation is assessed through time and by the scale of the groups. Subsequently, we analyze how environmental policy instruments affect total animal output as well as output changes across the farm scales. We finally focus on the extent to which pollution mitigation is incorporated into livestock production after the implementation of the above outlined policy instruments. To cope with the random nature of ABM, multiple simulations of each scenario are carried out until stabilization of mean results occur, and these mean results are used for further analysis (see for details Appendix IV).



(a) dynamics of animal output



(b) average annual animal output per scale-groups

Fig. 2. Nutrient mitigation for five scenarios over 10 years (a) and on annual average (b). (a) Dynamics of nutrient mitigation, and (b) average annual nutrient mitigation per scale group.

#### 4.1. Mitigation of negative environmental effects

Fig. 2 illustrates the performance of all the policy instruments on the mitigation of nutrient emissions. The nutrient equivalents (NEs) shown in this figure are calculated as the weighted sum of nitrogen and phosphorus. The policy instruments “technology standard”, “biogas subsidy” and “information provisioning” successfully reduce total emissions compared to the reference scenario. The introduction of a technology standard mitigates nutrient emissions most strongly and by more than 70 t out of 1391 t of NEs per year. Household-scale farms contribute approximately 72% of the nutrient mitigation in this scenario, whereas medium- and large-scale farms contribute 11% and 17%, respectively (see Fig. 2b). The time curve for the “technology standards” scenario is almost horizontal (see Fig. 2a), which indicates a lack of continuous improvement as a result of the standards. Surprisingly, the scenario “information provisioning” reaches an average mitigation of 35 tons per year compared with the reference scenario. This policy produces most of its positive effects during the first half of the simulation and then remains relatively constant. Similar to the introduction of a technology standard, it is the household-scale farmers who contribute the most to overall mitigation under the “information provisioning” policy instrument, while medium- and large-scale farmers equally contribute a minor share (see Fig. 2b). According to the results, biogas subsidies would also mitigate nutrient emissions from no emission reductions during the first year to a peak of approximately 14 t of NEs (compared to the reference scenario). Nutrient mitigation through biogas subsidies comes only from household- and medium-scale farms. The increased pollution fee apparently has no significant effect on the mitigation of nutrient emissions. Furthermore, the introduction of a manure market leads to an increase in emissions, with medium-scale farms primarily responsible for the mitigation failure.

#### 4.2. Total animal output

Different environmental policies have different effects on the development of animal production. The changes in animal outputs as a result of the implementation of the different policies are shown for the scenarios over 10 years in Fig. 3a. Fig. 3b shows the average annual animal output per scale group for the whole period. Fig. 3a indicates that stricter environmental management obstructs farm expansion, represented as negative relative pig outputs, to a greater or lesser degree. The only exception is the manure market policy, which boosts animal outputs in the last three years, with approximately 4000 pigs per year more than the benchmark of 276,000 pigs from the reference scenario. Accordingly, in Fig. 3b, the average annual relative output is positive for the manure market scenario. Medium-scale farmers benefit the most from the manure market, apparently the increase in the average output only occurring in this farm category. Contrary to the manure market, the introduction of a technology standard causes the largest and most immediate reduction in animal output compared to the reference scenario. Unlike the other scenarios, the technology standard significantly slows the development of animal production from the first year of intervention by nearly 9400 out of 265,000 pigs. Such a negative effect continues and strengthens later. Thus, the average annual output gap compared to the reference scenario is more than 11,000 out of 270,000 pigs. However, medium-scale farms are hardly affected, and surprisingly, the largest output limitation (60%) occurs with household-scale farms. The other policy instruments show less influence on animal output compared with the reference scenario. On average, their output reduction per year is no more than 2000 out of 274,000 pigs. With increased pollution fee, biogas subsidies and information provisioning, medium-scale farmers are slightly motivated to expand, whereas the other two groups are negatively affected and decrease their stock.

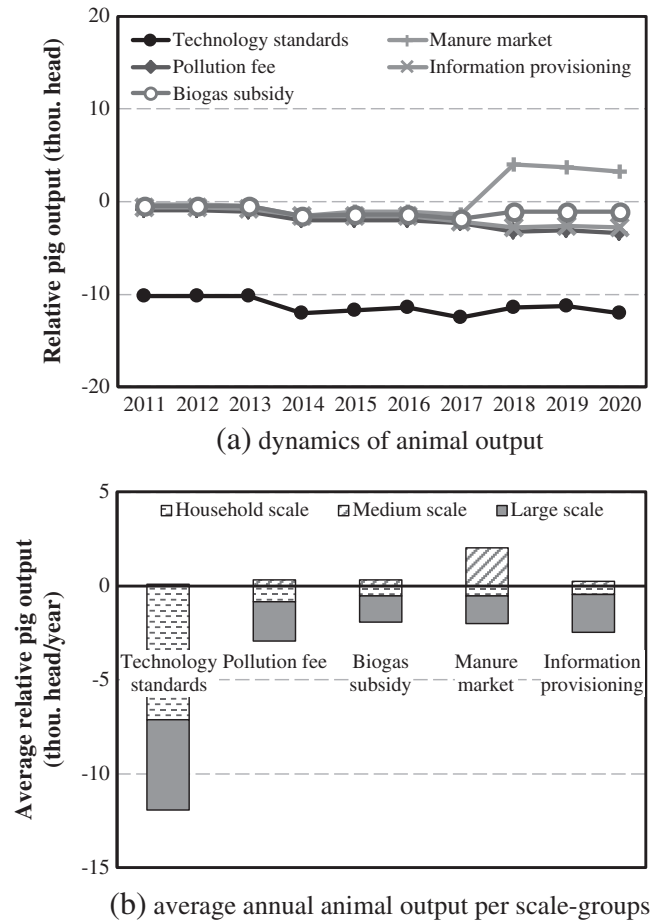


Fig. 3. Total animal output for five scenarios over 10 years (a) and on annual average (b). (a) Dynamics of animal output, and (b) average annual animal output per scale-groups.

#### 4.3. Technology diffusion

The simulations reveal that alternative technologies diffuse rapidly in the first year, and then the diffusion process stabilizes (see Appendix V). For manure collection, “washing manure” shifts mainly to “dry collection” and little to “bedding”. This shift is considered as more environmentally sound because dry collection saves water and prevents nutrients from leaking into the environment. The newest collection technology, which is “bedding”, remains at a low saturation level (<1%) in every scenario. If a typical S-shaped cumulative curve was to be used to describe system-specific technology diffusion, bedding would not have entered the rapid diffusion stage (Rogers, 2003). The application of “treated fertilizer” is the dominant alternative manure handling technology, with the application of “untreated fertilizer” in second place. Selling the manure to “Industry” does not occur at a high level in the different policy scenarios. However, no technology completely disappears by 2020. The diffusion of technologies reaches a ceiling within five years and shows no remarkable further penetration between 2016 and 2020. The detail of diffusion of manure management practices among all farms for selected years, and over the total period of ten years is available in the Supporting Information.

The cross-sectional data of 2020 are used to represent the cumulative effects of the policy instruments on technology diffusion. Fig. 4 depicts the differences in technology penetration rates with and without policy interventions in 2020. The environmental policies generally are more consequential for manure handling than for manure collection. The simulation results show that providing information is the most effective way to improve collection practices. This policy instrument encourages 3.3% more farmers to adopt dry collection (at the cost of

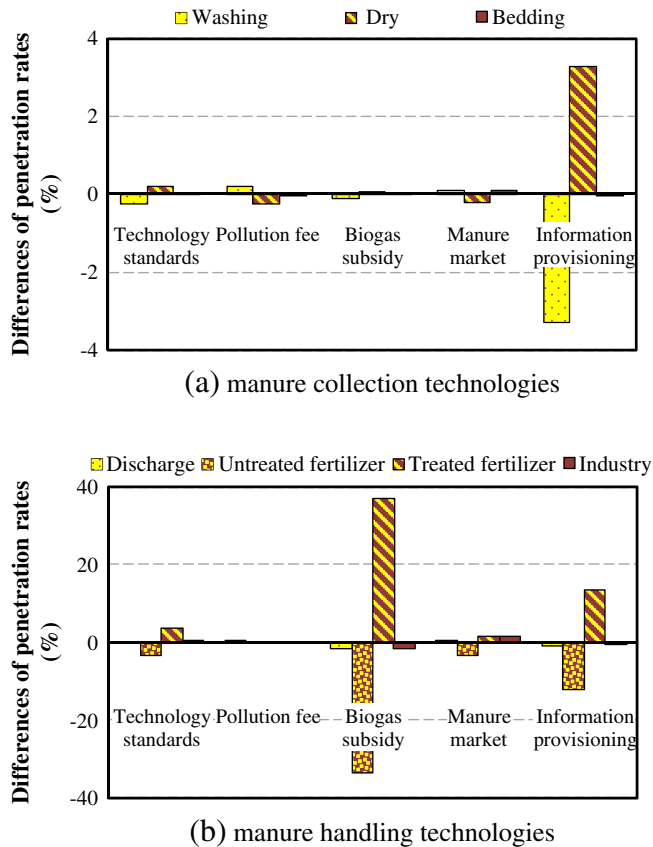


Fig. 4. Different penetrations of manure management practices for five policy scenarios. (a) Manure collection technologies, and (b) manure handling technologies.

washing) than what occurs with the reference scenario, which is ten times more than the effects of the other instruments. Because neither biogas subsidies nor the manure market aims to improve manure collection, their low efficacy is predictable. Information provisioning is the second strongest driving force for diffusing manure handling technologies, after biogas subsidies. There are 14% more farmers (than in the reference scenario) who adopt biogas production as a consequence of information provisioning. Biogas subsidies increase the penetration rate of biogas infrastructure by 37% compared to the reference scenario. The simulated manure market appears to indicate manure profitability and thus to most promote more innovative technologies, i.e., selling manure and bedding. The stricter implementation of a technology standard stimulates some adoption of dry collection and biogas infrastructure. A higher pollution fee proves to play no significant role in improving manure management practices.

#### 4.4. Pollutant emissions per animal

The coefficients of nutrient emissions per animal are assumed to vary by farm scale and respective manure management practices. Therefore, the effects of the different policies will be presented as the change in pollutant nutrient emissions per pig (change here is relative to the reference scenario) for a certain farm scale group (as shown in Fig. 5). The results indicate that only a stricter technology standard reduces the emissions per pig in all three scale groups. The relative reductions that are brought about by the application of the technology standard grow almost linear as the scale increases ( $R^2 = 0.98$ ). This scenario shows the largest relative reduction in Fig. 5. The effect of biogas subsidy and information provisioning is weaker; however, except on large scale farms, the emission reductions are still noticeable and meaningful. Developing a manure market has an opposite effect, represented in Fig. 5 by the negative column for large scale and no effects for the

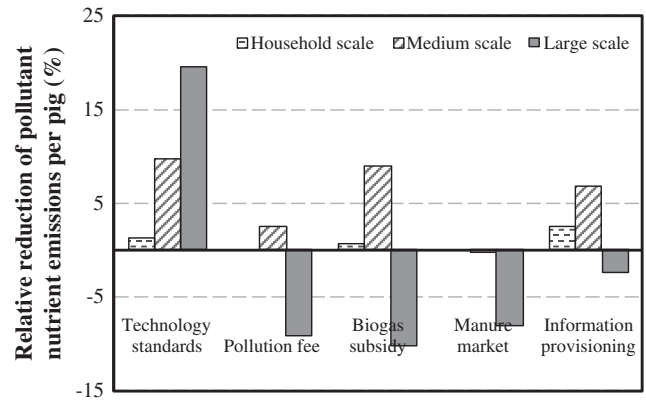


Fig. 5. Pollutant emissions per animal of scale groups for five scenarios.

other two scales. In four scenarios, but not in the one on stricter standards, large-scale farmers perform worse than in the reference scenario (9%, 10%, 8% and 2.3%, respectively) and their performance change is opposite to those of the other two scale groups. When compared with the reference scenario, medium-scale farmers are the forerunners of better manure management in most policies.

## 5. Discussion

Many previous studies compared the effects of policy instruments on technological changes using theoretical models or empirical research. With these approaches, it proved difficult to draw conclusions on the effectiveness of a policy instrument (Requate, 2005). Our research attempted to fill this information gap by outlining the effectiveness of different policy instruments in mitigating the nutrient emissions of different kinds of livestock farms. To this end, our research used an empirically sustained ABM and employed different indicators to assess policy performance. The policies were assumed to be effective if both emissions are reduced (per animal and in total) and the development of production is not negatively affected. Robustness analyses (see Appendix IV) proved that the results of the policy scenarios are robust and meaningful.

There are notable differences among the five analyzed policy interventions, including their policy designs (see Table S3) and consequences (see Figs. 2 to 5). Three policies are effective in reducing nutrient pollution, but no win-win scenario exists in which both environmental and economic benefits occur. A stricter technology standard attempts to stimulate the adoption of mitigation technologies and especially addresses intensive livestock farms. Although obviously mitigating nutrient emissions in the simulations, the constraints of a stricter standard on production development are stronger than for other policy interventions. Our findings show that such regulatory intervention as a standard does not necessarily stimulate radical technology changes, which is consistent with earlier research (Ashford et al., 1985). Given the decrease in production, it can be assumed that such a regulatory mechanism is not likely to be favored by the Chinese government, which is pursuing steady economic growth. Biogas subsidies focus on a single technology, and the scenarios show that these subsidies can effectively achieve emission reduction. However, large-scale farms are excluded from biogas subsidies, resulting in an average emission increase per pig. Our findings thus contradict research that considers market-based instruments to be superior in promoting low-cost environmental improvements (Kemp and Pontoglio, 2011). Instead, a preferred policy intervention for the mitigation of pollution from livestock production is likely to be information provisioning, which slightly affects production development and promotes technology improvement across two major scales (i.e. household and medium scales), thus reducing total emissions.

Responding to our two research questions, this research has shown that differences across scale groups play an important role in determining the effectiveness of policy instruments for mitigating nutrient emissions from livestock production. Until 2020, aggregate pollution from household-scale farmers is the largest source and is responsible for more than 90% of the nutrient discharge by the pig sector. However, this group is also the largest contributor to nutrient mitigation. Since household-scale farms show little change in manure management practices, their contribution to nutrient mitigation mostly comes from decreasing the number of animals. Large-scale farms reduce pollutant emissions per pig under the scenario of technology standards but neither under the three market-based policies nor under information provisioning. For medium-scale farms, many policy instruments are effective, but not the installation of a manure market. These farms are capable of mitigating negative effects through a further increase in animal production. Governing medium-scale farms is likely to be extremely critical for environmental management in rural areas. Because the Chinese government insists on the continuous intensification of animal production, more and more household-scale farms will expand to medium-scale farms (rather than reduce farm size). Therefore, ecologizing medium-scale farms becomes critical in achieving increased production and environmental protection. Our simulations show that biogas subsidies and information provisioning are the policies that work best for medium-scale farms.

Last but not the least, examining the policy interventions with an ABM allowed the study of policy effects by incorporating farmers' heterogeneity and interactions. The perspective of individualization possibly provides new knowledge concerning policy effects. This becomes clear in, for instance, the distinct performance of interventions using information diffusion. The force of such instruments is amplified through autonomous observations, learning and imitation among farmers. The ANEM captures such technology diffusion through interactions among individuals, which is usually ignored in approaches that function on the aggregate level. However, in current local policies, information provisioning is more an additional instrument, attached to subsidies or antiepidemic services. The simulation shows that instruments that increase information on pollution mitigation technologies should be given considerably more attention in environmental management in rural China. A second policy implication follows from manure markets. In this simulation, "selling manure" is assumed to be the best choice for individuals aiming to maximize economic profitability and/or environmental benefits. This assumption is made because selling manure results in economic profit without investment (e.g., in technologies) and emission reduction on the farm; therefore, pollution fees are avoided. Manure pricing can stimulate the expansion of animal production, which does not show effects in the simulation on the individual level because of high heterogeneity within the model. The simulation results at an aggregate level, however, reveal high nutrient emissions and thus make the manure market much more problematic. There are other options commonly used worldwide for mitigating livestock nutrient emissions. For instance, livestock diet adjustment to decrease manure nutrients is practiced in Northern Ireland and the US, among others (CBC, 2004; Ferris et al., 2006). In many European countries, seasonal and quantity standards for manure application to arable areas and grassland are established to reduce nutrient losses from farmland (De Clercq, 2001). Furthermore, consumer choices can to some extent contribute to a reduction in nutrient flows within rural China and can also do so, last but not least, by a moderate or reduced consumption of meat. Although excluded from this research, our simulation can be applied to examine the effects of such policy interventions.

The livestock production in Western developed countries seems to have largely finished its intensification process and is now turning to more environmentally sound and sustainable forms of production (Thornton, 2010). So, what should be the strategies for a more environmentally sound future livestock sector for China? This research proves that Chinese livestock production can insist on its process of further

intensification, as long as it initiates a paralleling "ecological reform" of manure management. There is a phase of attaining a 'crucial mass' in innovation diffusion, after which the diffusion will be significantly accelerated (Rogers, 2003). Consequently, the government should create opportunities for farmers to get over the tipping point of 'crucial mass' of environmental sound technologies, by applying various instruments. For instance, it is important for the government to overcome the barriers of farmers' limited capability in seeking information and economic investment for environmental reform. In addition, this research shows the inappropriateness of making and implementing policies which are not tailored to the specific characteristics of livestock production. For instance, the performance of market-based instruments for environmental protection, however, is not always superior compared to regulatory instruments, but dependent on the relative significance of incentives in cost–benefit evaluations. Whichever policy instrument the governments would like to use, it should be modified according to its target group and hence might differ in final operationalization between household, medium and large scale farmers. There are hardly permanently and universally effective strategies to ecologically develop Chinese livestock production. When the intensification of livestock production is inevitable, government has to adjust policy making on the basis of different phases of intensification, various targeted farmers and adoption of diverse measures.

The ANEM has some limitations. This model simplifies the implementation of policy intervention by local governments. In the model, biogas production is easily adopted by farmers due to governmental subsidies; however, biogas digesters in reality can be too difficult for Chinese farmers to operate well for long periods without governmental service (Bluemling et al., 2012). Therefore, the nutrient emission mitigation performance of biogas subsidies may be overestimated. Second, since the parameters of the model were valued with literature review and empirical research, the findings and policy implications concluded above more lie on the case study. Panel or time series data in the same area would have been of great help to calibrate and validate ANEM in a more profound way, such as Brown et al. (2005) did in their research. More case study investigation and interviews, not necessarily in the form of large sampling questionnaire-surveys, would make a better confirmation possible of the generalizability of assumptions in our model or discover other possibilities of farmers' decision-making processes. Third, the policy instruments in the ANEM do not "learn". All the policy scenarios show maximum penetration rates for new technologies, and over the ten years that were simulated in the scenarios, no policy instrument provides more efficacy than that initially achieved with the intervention. Thus, "learning" policy intervention may be necessary, possibly in the form of transforming either farmer groups or kinds of technologies it aims to, in order to overcome the adherence to current practices and enable alternatives to diffuse further. These shortcomings and concerns should be part of a future research agenda. Furthermore, the policy instruments of this research are dealing with a redirection of manure flows, not with their diminution. The collection of manure in biogas digesters makes it better available and suitable for fertilization of the land; manure markets make manure better available where it is needed. The overall nutrient load remains the same, although better distributed across space and time. Whether such redistribution will be adequate to prevent environmental pollution remains to be seen.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.scitotenv.2014.09.004>.

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