Assessment of nitrate leakage and N₂O emission from five environmental-friendly agricultural practices using fuzzy logic method and empirical formula

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Abstract Agricultural nonpoint source pollution in China has been the major environmental problem, so environmental-friendly agricultural practices (EAPs) must be promoted to improve environmental quality. However, the most suitable practices for each agricultural region must first be identified. Thus, in the presented study a fuzzy-logic method and a revised empirical formula were used to assess nitrate leakage and N₂O emissions, respectively, and to compare five EAPs in Xinxiang, a major grain-producing county in Henan Province, China. The required information was collected in face-to-face interviews with 10 extension service experts from the county, using a questionnaire to explore their opinions of the EAPs currently adopted by smallholder farmers, as well as the amounts, frequencies, varieties and proportions of nitrogen fertilizers applied annually. The results indicate that reduced tillage, soil testing and fertilizer recommendations would be the most appropriate practices to initially promote on a large scale in Xinxiang.

Keywords Fuzzy logic method · Empirical formula · Nitrate leaching · N₂O emission · Environmental-friendly agricultural practices

Introduction

Nitrogen applications have played an important role in increasing Chinese crop yields in recent decades (Di and Cameron 2002). However, excessive application of nitrogen fertilizers can cause several environmental problems, including agricultural nonpoint source pollution (ANPSP) (Delgado et al. 2008; Jones and Olson-Rutz 2011). China's first national pollution census bulletin highlighted that combined emission from agricultural sources (i.e., excessive use of fertilizers, especially nitrogen fertilizers) has been identified as the main culprit (Fredrich et al. 2010). Nitrogen emissions and associated processes, notably nitrate leaching and Nitrous oxide emission, are particularly severe environmental issues in dryland plains, where ameliorative action is urgently required. While the prevention and effective control of ANPSP present major challenges, due to the diffuse and varied nature of nonpoint sources, as well as difficulties related to their identification.

Thus, there is high interest in EAPs that could reduce nitrate leaching and N₂O emissions, as well as in practical methods or approaches for evaluating their mitigating effects. Several studies have addressed the mitigating effects of individual environmental-friendly agricultural practice on nonpoint source pollution in China (Duan et al. 2011; Ning et al. 2011; Wang et al. 2015;

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Zhang et al. 2012b), but few have compared effects of multiple practices. Moreover, many previously promoted EAPs are only effective within specific regions. Technology scenarios can help choose the best technology for a given area (Fleskens et al. 2013), then when several EAPs could potentially help to reduce ANPSP in a region, comparative evaluations are required to provide local authorities with the information they need to issue robust recommendations and promote effective practices in their region.

There are three main approaches to assessing nitrate leakage: (i) calculating indices, which are often easy to understand (Bockstaller et al. 1997), (ii) applying a farmland ecosystem water and nutrient balance model, which can incorporate complex parameters and be used to quantify emissions of pollutants at various spatial and temporal scales (Donatelli et al. 1999; Luo et al. 2011), and (iii) long-term experiments, which can generate more reliable results, but are time consuming, costly and yield results with limited general applicability, due to climatic and edaphic variations (Buczko et al. 2010; Huang et al. 2011). In contrast, farmland N_2O emissions are generated from plant-available soil N during nitrification and denitrification (Shi et al. 2012) and are affected by temperature, pH, moisture, and agricultural management practices (Xie and Li 2002; Xing and Yan 1999). There are increasing numbers of approaches for assessing N_2O emissions, including laboratory and field experiments (Zheng et al. 2004; Guo et al. 2013), an empirical formula method (Freibauer 2003; Lv et al. 2005) and a denitrification and decomposition (DNDC) model (Li et al. 1992a, b). However, none of these

approaches are universally applicable and they all have limitations, e.g., laboratory and field experiments are time consuming and expensive, while the DNDC model requires numerous input parameters, such as commonly recorded climate, soil and agricultural practice data (Kröbel 2009). Due to the uncertainties associated with estimates of direct emission coefficients, it remains difficult to accurately assess N_2O emission at a regional or global scale, despite the publication of direct emission factors for various soil types by the IPCC (2006).

The aim of the study presented here was to assess the mitigating effects of five EAPs on nitrate leakage and N_2O emissions in an important grain-producing area (Xinxiang County, Henan Province, China) using two promising methods. Nitrate leakage was assessed using an indicator-based, fuzzy-logic method (Zander and Kächele 1999; Mertens and Huwe 2002; Zander 2003; Pierr et al. 2009). Fuzzy logic is based on the idea that the boundary between suitability and unsuitability (or acceptance and rejection) of an agricultural practice is not clear, but rather blurred or ‘fuzzy’ (Phillis and Andriantiatsaholainaina 2001). Nitrous oxide emissions were assessed using an empirical formula method (Lv 2007), based on annual precipitation and suitable for dryland soils. The empirical formula method benefits from being simple and having known precision. All five EAPs (Table 1) have been previously promoted nationally, but implemented by smallholder farmers to limited extents (Zhang and Zhang 2005; Cai et al. 2006; Li et al. 2008; Shen and Du 2009; Shi et al. 2011; Qiu et al. 2014). This highlights the importance of considering both farmers’ attitudes and likely environmental impacts

Table 1 Advantages and disadvantages of the five assessed environmentally-friendly agricultural practices

Practices	Advantages	Disadvantages	References
No or minimum tillage (M1)	Soil moisture conservation, labor and fuel savings, improvement of soil structure	Overuse of chemical fertilizers, pesticides and herbicides	Cai et al. 2006
Soil testing and fertilizer recommendation (M2)	Balanced fertilization based on soil fertility	High cost of formulated fertilizer, soil testing limited to a subset of sites	Xu et al. 2014
Use of slow- and controlled-release fertilizers (M3)	Nutrients released when needed by crops, reduced fertilizer applications and amounts	Costly, variable nutrient release rates	Zhang and Zhang 2005
Combined application of organic and inorganic fertilizers (M4)	Reduced amounts of inorganic fertilizer, improvements in soil fertility and texture	Labor intensive, time-consuming, space required for mixing, costs of transport from composting site to field, variable nutrient release rates	Zhang 2008
Returning crop straw to field (M5)	Lower air pollution than burning straw, improved soil fertility, subsidies for buying machinery	Required machinery often not compatible with local cultivation patterns.	Ji et al. 2012

when deciding whether a specific agricultural practice should be promoted. Both advantages and disadvantages are associated with any environmentally-friendly agricultural practice (Table 1) and the mitigation potential will differ between practices. Those that are both convenient for farmers and have substantial mitigating effects on environmental problems should be prioritized for evaluation and subsequent promotion. This approach would help local governments to select suitable practices to include in locally-run programs, and meet the long-term goal of preventing, or alleviating, ANPSP cost-effectively, while maintaining (or even increasing) crop production.

Materials and methods

Study area

The case study area, Xinxiang County, is situated in the center of Henan province, an important grain-producing area in Northern China. It covers about 382 km² with a cultivated area of 233 km². The climate is temperate, with four distinct seasons. The main soil types are loam, mixed fine-grained soil and mixed brown earth. The main farming system is wheat–maize rotation. The typical fertilization level is 495 kg N ha⁻¹ y⁻¹, which is higher than the national average, thus the local government is continuously promoting various EAPs.

Data collection

Face-to-face interviews were held with 10 agricultural technical extension specialists in Xinxiang County regarding the EAPs currently promoted for wheat and maize rotation cultivation systems in the region. The most common fertilization regime for wheat–maize

rotation in the region consists of base fertilization followed by a single topdressing each crop season, giving a total of four applications per year (except during the maize growing season, when slow- and controlled-release fertilizers are used). Basic agricultural production data, e.g., amounts of N added and frequencies of fertilizer applications, were also collected (Table 2). Both mineral and organic fertilizers were included in calculations of overall amounts of N applied. Annual precipitation data needed for the two assessment models were collected from the local meteorological agency.

Nitrate leakage risk assessment using fuzzy logic

Fuzzy logic provides highly flexible frameworks enabling integration of various types of information (including words, and thus qualitative human thought processes) in the analysis of complex systems and decisions (Sattler et al. 2010). It has already been used to evaluate fertilizers' environmental impact, and specifically nitrate leakage (Sattler et al. 2010; Uthes et al. 2011), using a MATLAB and Fuzzy Logic Toolbox Release XXX model (The MathWorks, Inc., Natick, MA, USA). Briefly, input data are translated by the fuzzy-logic model into a consistent language, processed according to rules and fuzzy membership functions, then the results from the rule-based assessment are translated into output values through a final defuzzification step (Fig. 1) (Chen et al. 2008).

(1) Determination of assessment parameters (*inputs*)

Nitrate leakage to groundwater is one of the most difficult environmental problems to address in agricultural practices. It is influenced by soil type, precipitation, agricultural management regime, fertilizer type (mineral or organic), numbers

Table 2 Summary of the current, conventional farming practice in Xinxiang County and five alternative environmentally-friendly practices for a wheat–maize rotation system

Type of agricultural practice	Nitrogen (kg ha ⁻¹ y ⁻¹)	Applications (numbers y ⁻¹)
Conventional management (CK)	495	4
No or minimum tillage (M1)	474	4
Soil testing and fertilizer recommendation (M2)	435	4
Slow- and controlled-release fertilizers (M3)	466.5	3
Combined application of organic and inorganic fertilizers (M4)	457.5	4
Returning crop straw to field (M5)	525	4

Fig. 1 The main components of the fuzzy-logic system

of applications and amounts applied (Nylinder et al. 2011). Since soil types and climatic conditions are often similar within a region, the two parameters included in this study were the numbers of applications per year and amounts of fertilizers applied. Effects of these two parameters on nitrate leakage under the five local EAPs (Table 2) were assessed.

(2) Assignment of membership functions (fuzzification)

Due to the uncertainties surrounding nitrate leakage from agricultural land and the complexity of factors involved, the impact of land use-related factors on nitrate leakage can often only be expressed as generalizations, rather than using specific values (Sattler et al. 2010). Thus, interrelations can only be described by approximate rules, e.g., *if the amount of applied nitrogen is 'large', then the risk of nitrate leakage is 'high'*, rather than quantitatively, e.g., *if the amount of applied nitrogen is 200 kg/ha, then 50% of the applied amount of N will be leached to groundwater*. Here, the fuzzy set 'Low', 'Medium' and 'High' was used for fuzzification of the parameter *amount of applied N* used (Fig. 2), while the fuzzy set 'Few', 'Some' 'Many', was used for the parameter *number of applications* (Fig. 3).

(3) Formulation of rules using IF–THEN conditions

The Mamdani fuzzy inference method (Mamdani 1977), the most commonly used multi-input single output fuzzy reasoning method, was deemed the most appropriate for this study. The fuzzy reasoning rules can be formulated as *IF input1 is X AND input2 is Y, THEN output is Z*. Input1, input2 and output are variables; X and Y stand for different input parameters, Z is the fuzzy

set. Input parameters are combined by AND/OR-operators and rule aggregation is achieved using MAX or SUM methods. Four rules were used in our model of the risk of nitrate leakage (Fig. 4):

- Rule 1: If the amount of applied N is 'high' and the frequency (times) of N application is 'few', then a dimensionless index value of nitrate leakage risk is 'low' (If the index is closer to 0 (i.e., low), the nitrate leakage risk is higher).
- Rule 2: If the amount of applied N is 'medium' and the frequency (times) of N application is 'many', then a dimensionless index value of nitrate leakage risk is 'high'.
- Rule 3: If the amount of applied N is 'high' and the frequency (times) of N application is 'many', then a dimensionless index value of nitrate leakage risk is 'medium'.
- Rule 4: If the amount of applied N is 'low' and the frequency (times) of N application is 'medium', then a dimensionless index value of nitrate leakage risk is 'high'.

(4) Defuzzification to generate precise output values

Defuzzification is a procedure that generates precise results (values) describing the outcome of an assessment, using the areas under the output membership functions. Here, a widely accepted defuzzification method, called *the center of gravity method* (Cao 2004; Liu 2007), was used to yield representative values by calculating the abscissa value of the central area of the fuzzy set output. The result is a dimensionless index value ranging from 0 to 1 that represents the risk of nitrate leakage. The closer the index is to one, the

Fig. 2 Screenshot showing fuzzification of the assessment parameter ‘amount of applied nitrogen’

lower the nitrate leakage risk. Thus, the promotion of EAPs should focus on those assigned high index values (Sattler et al. 2010). As an example, the calculation of nitrate leakage risk for the M1 (Minimum and no tillage) practice is presented in Fig. 5.

Method for assessing N₂O emissions

The emissions of N₂O were calculated using a revised empirical formula based on annual precipitation, which is regarded as the most suitable method for assessing dryland N₂O emissions (Lv 2007):

$$\text{N}_2\text{O-N} = 1.49 \times P + 0.0186 \times P \times N$$

Where, $\text{N}_2\text{O-N}$ is the annual N₂O emission per unit area ($\text{kg N}_2\text{O-N} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$), P is the precipitation per year (mm yr^{-1}), N is the amount of applied nitrogen ($\text{kg N} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$), 0.0186 is the N₂O emission coefficient for the applied nitrogen fertilizer for a given agricultural practice.

Results and discussion

Spatial scales used when assessing effects of actions to mitigate environmental impacts of agricultural practices range from local to global. Consequently, information passed to policy-makers may not always provide appropriate evidence-bases to ensure that environmentally sustainable practices are adopted (Kates et al. 2001). The selection of evaluation method can also affect assessments, since different evaluation methods are based on different parameters. In addition, many evaluation methods are specific to certain environmental processes or problems. Thus, the environmental conditions in the study area should be considered when selecting methods (Heller and Keoleian 2003; Ness et al. 2007). Due to the geomorphic type (plains) of the study area, nitrate leakage and N₂O emission are the main environmental problems, rather than soil erosion. Therefore, they are good candidates for environmental indicators that, if appropriately assessed, could aid local governments and farmers to identify the most suitable EAPs to promote and adopt.

Fig. 3 Screenshot showing fuzzification of the assessment parameter ‘number of applications’

Nitrate leakage risk

Nitrate leakage risk indices were calculated for five EAPs (Fig. 6). The practice with the highest index in this study was M2 (0.542), followed by M4 (0.536), M1 (0.529), M5 (0.512) and M3 (0.500). Differences in index values between agricultural practices tested in the same region indicate that nitrate leaching would be affected by the type of agricultural practice adopted. Additionally, an agricultural practice with a higher index is more likely to be successfully promoted for nitrate leakage mitigation.

Due to similarities in climate conditions and soil type within a region, the main factors influencing nitrate leaching in drylands are essentially the amount of N applied and the frequency of application. Based on these two parameters, all five EAPs would change the nitrate leakage risk compared with the conventional production practice (CK), and provide sufficient nutrient supplies to ensure stable crop yields. However, the effect varied between practices and some would apparently increase rather than reduce nitrogen leakage risks.

The risk of nitrate leaching leakage was lowest for M2, largely because this practice (based on soil testing and fertilizer recommendation), stresses the importance

of adjusting N supplies to the local soil’s fertility to avoid overusing fertilizers. Our results corroborate findings by Oenema et al. (2009) that balanced fertilization is effective for enhancing nitrogen use efficiency (NUE) and decreasing N leaching to groundwater and surface water. The application of slow- and controlled-release fertilizers (M3) can reduce numbers of fertilizer applications, but does not alter the total amount of applied N fertilizer, explaining why the nitrate leakage risk was highest for M3. Theoretically, the slow release of nutrients over time in M3 can save time and labor inputs. However, in practice the release of nutrients is affected by several factors, such as pH, soil moisture content and temperature. This might be why some studies have reported good results with M3, while in others farmers did not approve of it (Shi et al. 2011). In this study, the higher risk of nitrate leakage in M3 was also partly a result of the fuzzy logic method, which does not integrate the N-supply characteristic of slow-release fertilizers. The nitrate leakage risk for practice type M5 (returning crop straw to field) was similar to that of M3, because the returned crop straw increased the carbon load, so additional mineral N fertilizer was required to adjust the C/N ratio. The combined application of organic and inorganic fertilizers (M4) and no or

Fig. 4 Four fuzzy rules included in the model of nitrate leakage risk

Fig. 5 A and B are the amounts and frequencies of N applications, respectively. Calculate four rules (C1...C4). N leakage risk is the abscissa value at the mid-point of area C5

Fig. 6 Comparison of nitrate leakage risks associated with the five agricultural practices, described in Table 2, in the wheat–maize rotation system in Xinxiang County

minimum tillage (M1) practices appeared to have lower risks of nitrate leakage than CK. In M4, the lower risk is attributable to the application of an organic fertilizer, which effectively reduces the need for inorganic fertilizers, while M1 reduces over-cultivation, protects the soil structure and conserves soil nutrients.

Nitrate leaching is influenced by several factors, including soil texture, applied fertilizer type, quantity of irrigation water used, and agricultural management practice (Kirchmann and Johnston 2002; Nylander et al. 2011). However, previous studies have shown that the timing of fertilizer application and the amount of nitrogen applied are the main factors affecting it (Malone et al. 2007). Thus, appropriate timing and optimal fertilizer rates are keys to reducing N losses from farmland (Randall and Mulla 2001).

N₂O emissions

Nitrous oxide fluxes associated with the five EAPs were assessed using the revised dryland N₂O emission formula (Fig. 7). Values of the fluxes ranged between 4.90 and 5.75 kg N₂O-N·ha⁻¹·yr⁻¹, with an average of 5.25 kg N₂O-N·ha⁻¹·yr⁻¹. The difference between the maximum and minimum flux was over 5 %. Four of the EAPs had mitigating effects on N₂O emissions: soil testing and fertilizer recommendation (M2) most strongly, followed by combined application of organic and inorganic fertilizers (M4), no or minimum tillage (M1), and application of slow- and controlled-release fertilizers (M3). However, returning crop straw to the

Fig. 7 N₂O emissions (kg N₂O-N·ha⁻¹·yr⁻¹) associated with the five agricultural practices, described in Table 2, in the wheat–maize rotation system in Xinxiang County

fields (M5) yielded higher emissions than the control (CK).

The five EAPs included in this study can be divided into two types: one based on tillage management (M1 and M5), and one based on fertilizer management (M2, M3 and M4).

In the tillage management type, N₂O emissions increased when crop straw was returned to the fields (M5), but decreased when tillage was reduced (M1). There are conflicting reports on effects of returning crop straw to the field on N₂O emissions. Baggs et al. (2003) suggested that it would increase N₂O emissions from the soil, but Zhang et al. (2012a) found no significant difference in total N₂O emissions over the growing season between fields where crop straw had been returned and fields under conventional tillage. Thus, the effectiveness of this practice appears to be sensitive to several factors, including soil conditions, soil C/N ratio and the amount of straw applied (Baggs et al. 2003). Similarly, Bai et al. (2010) found that reduced tillage could increase N₂O emissions. However, others have found that long-term implementation of minimum or no tillage can lead to decreased N₂O emissions (Six et al. 2004; Ussiri et al. 2009). Sui (2006) found no significant differences in N₂O emissions associated with reduced tillage and normal tillage. The effectiveness of reduced tillage appears to be affected by soil water content and soil density, as well as climate conditions (Gregorich et al. 2005).

Several studies have confirmed that N₂O emissions from agricultural soils can be decreased by improving fertilizer management (McTaggart and Tsuruta 2003; Wang et al. 2012) and our findings corroborate this conclusion. We found that the soil testing and fertilizer recommendation practice (M2) was more effective than the application of slow- and controlled-release fertilizers (M3) or the combined application of organic and inorganic fertilizers (M4) in mitigating N₂O emissions in

Xinxiang County. This is consistent with expectations because use of balanced fertilizers increases NUE and reduces N losses (Gordon 2005), while use of slow-release fertilizer reduces N₂O emissions from agricultural systems (Shoji et al. 2001; Halvorson et al. 2009; Ji et al. 2012), but the size of the reduction varies depending on land use and soil type (Akiyama et al. 2010). Fertilizers (mineral or organic) are the main anthropogenic sources of N₂O emissions (Meng et al. 2005), with synthetic fertilizers contributing 60 % of N₂O emissions (Anand et al. 2006). Moreover, there is a linear relationship between the amount of N fertilizers applied and N₂O emissions (Gregorich et al. 2005). Partially substituting organic fertilizer for inorganic fertilizer resulted in lower N₂O emissions. The addition of readily decomposable organic carbon leads to a reducing soil conditions, enhanced denitrification and promotion of the conversion of NO₃⁻ into N₂, rather than N₂O (Hao et al. 2012). However, compared to a single application of inorganic N fertilizer, the combined application of organic and inorganic fertilizers can occasionally result in increased N₂O emissions. The organic carbon in organic fertilizers changes the C/N ratio of the soil and provides energy and carbon sources for soil microbial activity, thereby stimulating nitrification and denitrification, resulting in increased N₂O emissions (Zhang et al. 2004; Dambreville et al. 2008). Therefore, the impact of practices involving applications of both organic and inorganic fertilizers on N₂O emissions requires further study.

Conclusion

Here, two approaches for using fuzzy logic and an empirical formula to assess the EAPs are presented. Key environmental indicators can be incorporated into the assessment and the methods can be applied to data from any region. The results can be used to rank production alternatives according to their relative effectiveness (Sattler et al. 2010; Lv 2007). This is the first time these approaches have been used to assess multiple EAPs in China. Both the fuzzy logic method and the empirical formula describe tendencies in a dataset, rather than giving precise values, and can be used to simplify highly complex problems. Although inherent errors are associated with both methods, they produced very similar rankings for the practices included in this study. The three best EAPs for the local area were found

to be soil testing and fertilizer recommendation (M2), combined application of organic and inorganic fertilizers (M4) and no or minimum tillage (M1). These results could provide valuable reference data for extension service experts in their considerations of regional characteristics in the promotion of EAPs. The results could also assist in the formulation of guidelines and policies to mitigate nitrate leakage and N₂O emissions, and thus more sustainable land management regimes.

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