Analysis of Reactive Nitrogen Emissions from Maize Ethanol Production Based on the DNDC Model

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Abstract—Agricultural system is an important source of reactive nitrogen (Nr) emissions. In this study, DNDC model was established for analyzing Nr emissions in maize planting and maize ethanol production under climate change scenarios (i.e., RCPs 4.5 and 8.5). The DNDC model was applied in maize fields of Shandong Province. The Nr emissions in 2025 and 2030 under the RCPs 4.5 and 8.5 scenarios would range from 2869.24 to 2969.18 kg N/ha. An inventory of Nr emissions in maize ethanol production was obtained in this study. The results showed that compared with maize planting in other cities, maize fields in Linyi would release the biggest amount of N₂O and NO, as well as the smallest amount of NH₃. The study can support decision making for Nr emissions reduction in agricultural systems.

1. Introduction

Agriculture production, fossil-fuel combustion, and other human activities have generally increased the emission intensity of reactive nitrogen (Nr), and then have a great impact on earth's nitrogen cycle [1]. Anthropogenic Nr release would be 270 Tg N yr⁻¹ by 2050, negatively affecting human and ecosystem health [2-3]. Agricultural system is an important source of Nr emissions [4]. Reasonable fertilization management, as well as water and soil conservation measures can effectively reduce Nr release in nitrogen fertilizer [5]. In order to mitigate Nr emissions, energy crops were paid attention to in many previous studies. As a traditional energy crop, maize ethanol was also a potential source of Nr emissions. In light of energy consumption in the process of maize ethanol production, maize ethanol, produced from 1 hectare of maize, generally consumed 61.32 kg of diesel, 1103.20 MJ of electricity, and 1134.72 kg of coal [6]. Concurrently, Nr emissions of maize ethanol production were influenced by varied climatic conditions, especially under the changing climate conditions [7]. Thus, Nr emissions from maize ethanol production under changing climate conditions need to be paid attention to.

Several models have been developed to assess the nitrogen cycle in agricultural sector. Among them, Denitrification-Decomposition (DNDC) model has been widely applied to agricultural systems in China [8]. For example, Zhang et al. [9] analyzed N₂O emission in maize ethanol production. Crutzen et al. [10] analyzed N₂O emission from the maize biofuel production to explore the impact of N₂O on global warming.

Analysis of Nr emissions from maize ethanol production is of great significance. Therefore, the objective in this study is to propose the DNDC-based model for evaluating Nr emissions from maize ethanol production in 2025 and 2030 under the climate change scenarios of RCPs 4.5 and 8.5 in Shandong Province. Also, the Nr emissions inventory of maize planting and maize ethanol production in Shandong province will be obtained. The study can support decision making for Nr reduction in agricultural systems.
2. Methodology

2.1. DNDC model
DNDC model is a rain-event driven and process-oriented simulation model to identify nitrogen and carbon biogeochemical cycles in agricultural soils. It is used to predict \(\text{Nr}\) emissions from agricultural fields during the growing season [11]. DNDC model (version 9.5) was applied in this study, regarded as one of the most complete versions [12].

2.2. \(\text{Nr}\) emissions from maize ethanol production process
Ethanol is produced through the processes of liquefaction, saccharification, fermentation, distillation and dehydration of maize [13]. The functional unit was one hectare of maize field. Referred to Yang and Chen [6], 1 kg maize can produce 0.32 kg ethanol. The energy consumption in the process of maize ethanol production is 15.2 MJ/L [14]. The \(\text{N}_2\text{O}\) emission factor of raw coal is 0.0015 g \(\text{N}_2\text{O}/\text{MJ}\) [15]. It was assumed that the concentration of ethanol produced by maize was 95%, and the density of ethanol was 0.8 kg/L. Thus, the \(\text{N}_2\text{O}\) emission of 1 hectare maize in ethanol production process was described in Equation 1.

\[
A = (M \times 0.32/0.8) \times 15.2 \times 0.0015
\]

where \(A\) is the emission of \(\text{N}_2\text{O}\), and \(M\) is the unit yield of maize.

3. Case Study
Shandong Province is located at 114°48’–122°42’ east longitude and 34°23’–38°17’ north latitude. It is warm temperate monsoon zone. The average annual light hours in Shandong are 2290–2890 hours. The amount of average precipitation is generally varied from 550 to 950 mm. As one of major producing areas for maize, cropland in Shandong support 9.73% maize production in China in 2019. Maize field accounted for more than 27% of the sown area of crops from 2010 to 2019 (Table 1).

Maize plating in 17 cities of Shandong Province was simulated based on DNDC model. The main input data include soil, climate, and farmland management, which were described in Tables 2 and 3. Some statistic data were obtained from NBS [16]. Climate change data from Wang and Huang [17].

| Year | Sown area (10^4 ha) | Total output (10^4 tons) | Yield (kg/ha) | Total sown area of crops (10^4 ha) | Percentage |
|------|---------------------|--------------------------|--------------|----------------------------------|------------|
| 2010 | 296                 | 1932                     | 6538         | 1082                             | 27.36%     |
| 2011 | 300                 | 1979                     | 6605         | 1087                             | 27.60%     |
| 2012 | 302                 | 1995                     | 6609         | 1087                             | 27.78%     |
| 2013 | 306                 | 1967                     | 6427         | 1098                             | 27.87%     |
| 2014 | 313                 | 1988                     | 6360         | 1104                             | 28.35%     |
| 2015 | 317                 | 2051                     | 6462         | 1103                             | 28.74%     |
| 2016 | 406                 | 2614                     | 6439         | 1128                             | 35.99%     |
| 2017 | 400                 | 2662                     | 6655         | 1111                             | 36.00%     |
| 2018 | 393                 | 2607                     | 6626         | 1108                             | 35.47%     |
| 2019 | 385                 | 2537                     | 6594         | 1093                             | 35.22%     |
Table 2 Data Sources of DNDC Model

| Parameter categories | Detailed parameters |
|----------------------|---------------------|
| Terrain data         | Longitude, latitude, area, slope length, slope |
| Meteorological parameters | Daily maximum temperature, daily minimum temperature, rainfall, N wet deposition |
| Soil parameters      | Soil bulk density, PH, soil organic matter content, saturated hydraulic conductivity, permeability, field water holding capacity |
| Crop                | Vegetation type, optimal yield, biomass ratio, plant N content, plant water requirement |
| Management parameters | Farming system, cultivation date, harvest date, fertilization, irrigation, surface coverage, etc. |
| Hydrological parameters | Runoff curve CN value |

Table 3 Farm Management Data

| Parameter categories | Contents                  | Data                                   |
|----------------------|---------------------------|----------------------------------------|
| Planting             | Planting date             | May 1                                  |
|                      | Harvest date              | Oct 1                                  |
| Plowing              | Date                      | April 20                               |
|                      | Depth                     | 30 cm                                  |
| Inorganic fertilizer | Fertilization date        | May 10, June 1, and August 1           |
|                      | Fertilizer amount         | Urea: 100 kg/ha                        |
|                      |                           | Ammonium Phosphate: 60 kg N/ha         |
| Organic fertilizer   | Fertilizer date           | May 5                                  |
|                      | Fertilizer amount         | Farmyard manure, soil C / N=13         |
| Dry farming irrigation | Irrigation date          | April 20, May 20, June 10, July 2      |
|                      | Amount                    | 20 cm/time                             |

Considering the changing climate conditions, two scenarios of future climate change (i.e., RCPs 4.5 and 8.5 scenarios) were introduced in this study. The scenario of RCP 4.5 corresponds to radiative forcing at 4.5 Wm$^{-2}$ in the year 2100, and RCP 8.5 corresponds to radiative forcing at 8.5 Wm$^{-2}$ in the year 2100 [18]. The crop yield and Nr emissions can thus be obtained in this study.

4. Results and Discussion

4.1. Maize yield analysis
The maize yield under the scenarios of RCPs 4.5 and 8.5 in 2025 and 2030 were simulated by DNDC model (Figure 1). The maize yield per hectare in Shandong Province would be a) 7325 and 5672 kg/ha in 2025 and 2030 under RCP 4.5 scenario, respectively; and b) 7483 and 6922 kg/ha under RCP 8.5 scenario, respectively. The maize yield per unit in Linyi would be higher than that in other cities of Shandong Province. Also, because of varied climate conditions, maize yield differentiated among cities. The maize production in each city would show slight downward trend from 2025 to 2030.
RCP4.5 2030
QD
TA
RCP8.5 2030
DY
dz
rz
jna
wf
rz
ta
ly
ta
RCP8.5 2025
zb
HZ
emission
DZ
wh
jna
zz
Mean
RCP8.5 2025
qd
wf
jni
RCP4.5 2030
lc
emission
lc
RZ
jni
hz
YT
lw
zb
zz
Daily
yt
ZZ
hz
JNA
LC
ZB
RCP8.5 2025
lw
JNI
yt
3
LY
dy
RCP4.5 2030
11x50
NH
(\text{kg N/ha/yr})
Yield
10000
12000
3
NH
(\text{kg N/ha/day})
NO emission
(\text{kg N/ha/yr})
3
2000
4000
6000
8000
120
130
140
150
160
170
180
200
210
N
2
O emission
(\text{kg N/ha/day})
0.2
0.4
0.6
0.8
1.2
1.4
2
0.1
0.2
0.3
0.5
0.6
0.7
0.8
50
100
150
200
250
350
400
450
2
10
12
14
16
180
200
210
25
5
10
15
20
25
0
5
10
15
20
25
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
50
100
150
200
250
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400
450
2
10
12
14
16

Figure 1 Maize yield under scenarios of RCPs 4.5 and 8.5 in Shandong Province (Unit: kg/ha).
*Notes: BZ-Binzhou, DZ- Dezhou, DY- Dongying, HZ- Heze, JNA-Jinan, JNI-Jining, LW-Laiwu, LC-Liaocheng, LY-Linyi, QD-Qingdao, RZ-Rizhao, TA-Taian, WF-Weifang, WH-Weihai, YT-Yantai, ZZ-Zaozhuang, ZB-Zibo.

4.2. Analysis of Nr emissions during maize planting
The Nr emissions in each city would be basically the same under the two scenarios (Figure 2). Among then, the N$_2$O emission in Laiwu, Linyi, and Zaozhuang would be greater than that in other cities. While the NO emission in Laiwu, Linyi, Qingdao, Rizhao, and Weihai would be relatively higher than that in other cities. The amount of NH$_3$ emission would be 140 to 200 kg N/ha/yr. Under the both scenarios, the Nr emissions in 2030 would be slightly higher than those in 2025. Compared with maize planting in other cities, maize fields in Linyi would release the biggest amount of N$_2$O and NO, as well as the smallest amount of NH$_3$. The total Nr emissions in Shandong Province are shown in Figure 3.

Figure 2 Nr emissions in Shandong Province. Figure 3 Daily Nr emissions in Shandong Province.

Nr emissions were merely analyzed in the growing period of maize (i.e., from May 1 to Oct 1). The trend of Nr emissions under two scenarios were almost the same. Nr emissions in May, June, and August, influenced by fertilizer application, would be higher than those in other months. NH$_3$ volatilization is also influenced by some climatic factors (e.g., temperature, wind speed, and moisture). For example,
NH₃ and N₂O emissions in fertilized soil tend to be obvious in high air temperature, because of simulating the process of nitrification and denitrification. Influenced by crop absorption, the amount of N₂O emissions gradually decreased in fertilized soil. Compared with the amount in other cities, the maximum amount of N₂O emission would be 19.34 and 19.20 kg/N/ha/day on June 10 in 2030 under the RCPs 4.5 and 8.5 scenarios, respectively.

4.3. N₂O emissions during ethanol production process

The N₂O emission during ethanol production process under RCP 8.5 scenario was higher than that under 4.5 scenario (Figure 4). The N₂O emissions in 2025 would be greater than those in 2030, influenced by maize yield per unit. Among the 17 cities, Linyi would have the largest N₂O emission and Heze would have the least. The inventory of N₂O emissions in the processes of maize and ethanol production are shown in Table 4.

Table 4  Inventory of NR Emissions from the Processes of Maize and Ethanol Production

| Areas      | N₂O       |          |          |          |          |          |          |          |
|------------|-----------|----------|----------|----------|----------|----------|----------|----------|
|            | RCP4.5    | RCP8.5   | RCP4.5   | RCP8.5   | RCP4.5   | RCP8.5   | RCP4.5   | RCP8.5   |
|            | 2025      | 2030     | 2025     | 2030     | 2025     | 2030     | 2025     | 2030     |
| Binzhou    | 7.04      | 7.69     | 5.98     | 6.03     | 0.36     | 0.36     | 0.35     | 0.38     |
| Dezhou     | 6.78      | 8.46     | 6.92     | 8.90     | 0.32     | 0.36     | 0.35     | 0.37     |
| Dongying   | 6.73      | 7.35     | 5.05     | 5.66     | 0.35     | 0.37     | 0.35     | 0.39     |
| Heze       | 6.32      | 6.77     | 8.04     | 7.31     | 0.34     | 0.34     | 0.34     | 0.35     |
| Jinan      | 7.31      | 8.20     | 7.01     | 9.38     | 0.36     | 0.38     | 0.35     | 0.38     |
| Jinling    | 9.00      | 9.76     | 10.21    | 10.65    | 0.59     | 0.58     | 0.55     | 0.51     |
| Liaocheng  | 10.17     | 11.12    | 8.63     | 12.06    | 1.09     | 1.16     | 1.19     | 1.14     |
| Lanyi      | 14.69     | 14.11    | 11.16    | 13.48    | 1.31     | 1.25     | 1.29     | 1.13     |
| Qingdao    | 8.70      | 9.40     | 6.53     | 10.02    | 1.11     | 1.21     | 1.11     | 1.15     |
| Rizhao     | 9.89      | 8.24     | 7.86     | 8.26     | 1.12     | 1.25     | 1.13     | 1.12     |
| Tai'an     | 8.18      | 9.61     | 8.07     | 10.37    | 0.79     | 0.82     | 0.89     | 0.85     |
| Weifang    | 7.21      | 7.43     | 5.81     | 7.50     | 0.39     | 0.36     | 0.36     | 0.38     |
| Weihai     | 7.46      | 7.77     | 6.89     | 7.81     | 1.03     | 1.09     | 1.08     | 1.12     |
| Yantai     | 7.22      | 8.03     | 6.52     | 9.69     | 0.55     | 0.62     | 0.59     | 0.63     |
| Zaozhuang  | 12.51     | 11.60    | 10.13    | 11.65    | 0.72     | 0.61     | 0.64     | 0.53     |
| Zibo       | 7.67      | 8.10     | 5.86     | 9.90     | 0.38     | 0.37     | 0.36     | 0.39     |
| Mean       | 8.48      | 8.92     | 7.51     | 9.30     | 0.66     | 0.68     | 0.66     | 0.66     |
| Total      | 144.10    | 151.66   | 127.64   | 158.06   | 11.16    | 11.50    | 11.28    | 11.14    |

Figure 4  N₂O emission during ethanol production process.

5. Conclusions

Agricultural system is one of important sources of Nr emissions, potentially influencing the climate change effects. DNDC model under climate change scenarios was applied for simulate the Nr emissions during the processes of maize and ethanol production in 2025 and 2030. Application in Shandong...
Province indicated that the amount of Nr emissions in these processes would range from 2869.24 to 2969.18 kg N/ha. The results showed that maize yield per unit under RCP 8.5 scenario would be higher than that under RCP 4.5 scenario. Influenced by climate change effects, maize yield per unit would slightly decrease. The N2O emission under both scenarios would be higher in June than that in other months. Compared with maize planting in other cities, maize fields in Linyi would release the biggest amount of N2O and NO, as well as the smallest amount of NH3.

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