Co-benefits of intercropping as a sustainable farming method for safeguarding both food security and air quality

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Abstract

Large-scale, industrialized farming has contributed significantly to the increased global food supply to feed the fast-growing world population over the past few decades, but it also comes with severe threats to the environment. In particular, the excessive application of chemical fertilizer has led to large emissions of reactive nitrogen compounds into the atmosphere, where they become significant components of fine particulate matter (PM2.5) air pollution. Intercropping has been considered as a sustainable agricultural practice that can reduce the environmental impacts of agriculture, but its potential benefits beyond the farm scale have rarely been examined. Here we develop a new parameterization scheme for belowground mutualistic interactions between intercropped crops in the DeNitrification-DeComposition biogeochemical model, which is then used to simulate and quantify the benefits of nationwide adoption of maize–soybean systems in China in terms of gains in crop production, decreases in fertilizer consumption, and reductions in ammonia (NH3) emission. We further examine how such a decline in NH3 emission could lessen the downwind formation of PM2.5 using the GEOS-Chem chemical transport model. We show that annual mean inorganic PM2.5 concentrations can be reduced by up to 1.5 μg m−3 with the nationwide adoption of maize–soybean intercropping, with a corresponding annual net economic benefit of US$67 billion, of which US$13 billion arises from saved health costs from reduced air pollution. This study demonstrates the economic and environmental values of intercropping systems in dually promoting food security and environmental health, which can serve as a basis for policy consideration as governments and stakeholders explore more sustainable farming options.

1. Introduction

Global food security is one of the most pressing issues affecting human wellbeing. The United Nations has projected that the world population will exceed 9.5 billion by 2050 (United Nations 2014), which is expected to double the global demand for food crops due to the rising population, a worldwide shift toward a more meat-intensive diet, food waste and food surplus-deficit disparity inherent in the current food distribution system (Tilman et al 2011, FAO et al 2012, Lam et al 2013, Hiç et al 2016). It is crucial to enhance the production of food and animal feed to cope with the rising demand, but the associated environmental costs could be substantial. Farmland expansion has already displaced more than half of grasslands and more than 30% of forests globally, with tremendous impacts on wildlife habitats, biodiversity and ecosystem services (Foley et al 2011, 2012, Tai et al 2013). If no measures are taken to reduce the global food
demand, current trends in people’s meat and dairy intake habit and food waste would raise the demand for croplands further by ~19% and ~6%, respectively, by 2050, despite higher crop production enabled by conventional agricultural intensification (Bajzelj et al 2014).

A particularly environmentally detrimental aspect of conventional farming is the intensive fertilizer use, which degrades water and soil quality, and disrupts the global nitrogen (N) cycle by promoting the emissions of reactive nitrogen gases including ammonia (NH$_3$) and nitrogen oxides (NO$_x$ and N$_2$O). In 2007 alone, more than 33 Tg-N of fertilizers are used to boost crop production, nearly triple the amount used in 1981 (Guo et al 2010); such usage could be raised further by 45%–73% to attain sufficient production to fulfill the global demand by 2050 (Pradhan et al 2015). A study estimated that about 11 Tg-N of NH$_3$ was released from China in 2005 and 95% of those emissions were attributable to excessive fertilizer and manure from farms and animal operations (Gu et al 2012). Volatile NH$_3$ released from the fields can react with other acidic pollutants (e.g. oxidation products of anthropogenic NO$_x$ and SO$_2$) to form sulfate–nitrate–ammonium (SNA) particles, which are important constituents of fine particulate matter (PM$_{2.5}$) particles with a diameter of 2.5 μm or below (e.g. Wang et al 2013). High PM$_{2.5}$ concentration in turn causes haze and smog that lower local visibility and severely harm human health. The Chinese government needs to spend up to an estimated amount of US$3.3 billion to compensate for the health impacts of 1 Tg-N of emitted NH$_3$, including the costs of hospital care and rehabilitation (Gu et al 2012, 2014). Without ambitious mitigation, global agricultural NH$_3$ emission in 2050 could rise by ~12% relative to year-2010 level (Bodirsky et al 2014). Therefore, it is critically important to develop sustainable farming practices that can enhance crop production without excessive fertilizer use or further cropland expansion to safeguard both our future food supply and air quality.

Intercropping is a type of sustainable farming practice that entails two or more crops growing in the same field side by side in the same or overlapping growing season (not necessarily sown or harvested simultaneously). It can improve land-use efficiency, whereby fewer land areas are required in intercropped systems to yield the same quantities of monoculture crop grains in China (Li et al 2013, Wang et al 2014) and other countries (Malhi 2012, Franco et al 2015, Layek et al 2015, Martin-Guay et al 2018). Typically, farmers intercrop legumes and non-legume crops. Legumes host symbiotic rhizobia bacteria in their root nodules, which perform biological nitrogen fixation (BNF), i.e. converting atmospheric nitrogen (N$_2$) gas to ammonium (NH$_4^+$) or organic nitrogen for plant assimilation (Foyer et al 2016). Intercropping allows competition between legumes and other crops for soil nutrients, which potentially limits the nutrient supply for the legumes and thus triggers the symbiotic bacteria to undergo faster BNF (Burris and Roberts 1993, Casper and Jackson 1997, Liu et al 2014). Since the fixed nitrogen in excess is also accessible by other crops in the intercropping systems, the same yields of non-legume crops can be maintained with less fertilizer input than their monoculture counterparts, leading to an enhancement in nitrogen-use efficiency. Yong et al (2015a) conducted an experiment in the Renshou County, Sichuan Province, China to study the benefits of such crop–crop interactions between intercropped maize and soybean. They employed relay-strip intercropping, whereby soybean was added into the interval spaces between rows of maize, and found that the benefits of intercropping are threefold: it required only ~75% of the fertilizer use of a monoculture maize system to produce the same quantity of maize grain, generated an additional batch of soybean, and emitted nearly 40% less NH$_3$.

Although the yield advantages of intercropping have been observed in China, the acreage of intercropped lands for cereals has declined from >50% of total farm areas in the 1980s to only ~20% nowadays because of its lower profitability due to the labor-intensive nature of intercropping, increasing labor costs, and inefficient traditional practices of intercropping (Feike et al 2012, Huang et al 2015, Du et al 2018). In their production decision making, farmers typically do not account for externalities, e.g. external costs of monoculture on the environment, or external benefits of sustainable farming practices in mitigating environmental problems. Due consideration of these externalities is a crucial element of policy planning for sustainable food production.

In this study, we evaluate whether the economic benefits of intercropping, including its external environmental benefits arising from air pollution mitigation, are higher than its costs. We make use of a coupled modeling framework based on the DeNitrification-DeComposition (DNDC) soil biogeo-chemical model and the GEOS-Chem global chemical transport model. To mimic crop–crop interaction under intercropping that leads to enhanced BNF, we implement into DNDC a new nitrogen distribution algorithm to, for the first time, represent the competition of resources among intercropped legumes and non-legume crops (Tonitto et al 2007). We use the modified DNDC to conduct model experiments to calculate the amounts of fertilizer necessary to maintain the same maize production when all farmlands in China are converted from maize or soybean monoculture to maize–soybean intercropping. We estimate the corresponding changes in NH$_3$ emission and downwind air quality using GEOS-Chem. Our study concludes with a cost-benefit analysis to quantify the economic and environmental values of intercropping in China, which can serve as a scientific basis for Chinese policymakers and farmers to consider intercropping as a sustainable farming option that can
secure food supply without compromising environmental health. Here we focus on maize–soybean intercropping, but due consideration is also given to wheat-soybean intercropping in the appropriate context.

2. Methods

2.1. DNDC model description and new intercropping scheme

DNDC is a process-based biogeochemical model to simulate agricultural soil emissions of such important gases as nitrous oxide (N$_2$O) and carbon dioxide (CO$_2$). It consists of several sub-models to simulate soil microclimate, microbial decomposition, fermentation, nitrification, denitrification, and crop growth (Li et al 1992, 1994, 2000, Zhang et al 2002, Gilhespy et al 2014). The model is widely used for estimating crop yields, greenhouse gas emissions, fertilizer use and NH$_3$ volatilization for maize, wheat, and soybean (Li et al 2006, Giltrap et al 2010, Li et al 2014, Balasubramanian et al 2015, Zhang and Niu 2016). Crops in DNDC take up soil nitrogen in the form of nitrate (NO$_3$) and NH$_4$ according to their relative abundance. The remaining NO$_3$ and NH$_4$ are denitrified and nitrified, respectively, and then immobilized by microbes. NH$_3$ volatilization is estimated based on the ratio of soil NH$_4$ to aqueous NH$_3$, soil texture and pH, and wind speed. If a legume exists in the cropping system and is under nitrogen stress, DNDC would consider an extra source of soil NH$_4$ via biological fixation, depending on a preset BNF index. DNDC’s default sequential nutrient uptake scheme for multiple crops in a field, however, falls short of realistically represent crop–crop competition and the associated stimulation of BNF. We therefore implemented a new scheme that disables sequential uptake but represents the belowground competition among intercropped crops and distributes nutrients accordingly, whereby the competitive advantage of a crop in obtaining soil nitrogen is quantified by a newly introduced ‘competition factor’ based on its relative root biomass and nutrient depletion zone. Technical details of our parameterization are included in supplementary information A is available online at stacks.iop.org/ERL/14/044011/mmedia.

To validate the new intercropping scheme, we made use of the data from the field experiment performed in the Renshou County, Sichuan, China by Yong et al (2015a) in March 2012–October 2013. Three cropping systems were cultivated: monoculture maize, monoculture soybean, and maize–soybean intercropping. We used the revised DNDC to replicate their field experiments with matched meteorological conditions, soil properties, planting and harvesting dates, fertilizer use, tillage and irrigation practices, and phenological parameters for maize and soybean. We compared in particular the crop yields and emissions of various reactive nitrogen species between DNDC simulations and the observations by Yong et al (2015a) to ascertain model validity and identify key discrepancies.

2.2. Provincial simulations of monoculture and maize–soybean intercropping system in China

Using the revised DNDC model, we performed a series of simulations for the whole China to estimate the effectiveness of intercropping in improving land-use and nitrogen-use efficiencies as well as mitigating air pollution problems, in comparison with the monoculture status quo. Input data for DNDC were extracted from a composite of databases of meteorological, soil properties, crop and farming variables and parameters for the croplands of China. The input data were compiled to represent the most common meteorological and environmental conditions in each Chinese provincial-level administrative division (including province, municipality or autonomous region; hereinafter ‘province’) following the methods tabulated in table S1 for each provincial representative site. We conducted simulations for each of the three cropping systems (monoculture maize, monoculture soybean and maize–soybean intercropping) at various levels (0 kg-N, 20 kg-N, 40 kg-N, ..., 800 kg-N) of urea fertilization under well-watered conditions typical of most irrigated farms. In general, crop yield is higher (+37% to +38% for maize, +62% to +110% for soybean compared to the no-irrigation case) if their water demand is satisfied to a higher extent in DNDC, and the simulated results for water-stressed conditions are included in supplementary information B. Following the spin-up practice employed in Fumoto et al (2008), each simulation was run for 30 years to reach a quasi-steady state, and the results for the last 10 years were averaged and used for further analysis.

From the DNDC-simulated results, we first determined the yield of monoculture maize (‘the conventional yield’) corresponding to the conventional amount of fertilizer applied in each representative site. We then searched for the lowest amount of fertilizer needed in the corresponding intercropping system to produce the same conventional maize yield. The difference in fertilizer use required between monoculture and intercropping to produce the same conventional non-legume crop yield and the corresponding reduction in NH$_3$ emission were determined in each province. These provincial NH$_3$ reductions were then used to further investigate the effects of intercropping on Chinese air quality. To represent a nationwide adoption of maize–soybean intercropping in China, we assumed that all croplands cultivating maize or soybean (figure 1), are replaced by the maize–soybean intercropping system.

To validate the default model with monoculture, we compared the DNDC-simulated total annual provincial crop production and NH$_3$ emission of the monoculture systems with observational data and an optimized emission inventory, respectively. Observed annual crop
production and crop-specific harvested areas are provided in 5 min × 5 min longitude–latitude resolution by Monfreda et al. (2008), which were derived by disaggregating national/provincial totals. Observed NH$_3$ emission in each grid cell is derived from the Magnitude And Seasonality of Agricultural Emissions (MASAGE) inventory (Paulot et al. 2014) at 2006 level, which provides site-by-site transient emission data related to crop-specific fertilizer application. We then scaled up the monthly emission rate associated with the cultivation of maize and soybean in each grid cell from MASAGE by total area and time length to obtain the total annual provincial NH$_3$ emission. Simulated annual crop production and NH$_3$ emission are the product of the DNDC-simulated crop yield and crop-specific total NH$_3$ emitted per hectare, respectively, under the 'conventional fertilizer use' from Monfreda et al. (2008) in that provincial representative site scaled up by the corresponding harvested area.

2.3. GEOS-Chem simulations based on DNDC-simulated reductions in NH$_3$ emissions

Based on the DNDC-simulated provincial NH$_3$ reductions, we estimated the downwind changes in PM$_{2.5}$ concentrations using GEOS-Chem v10-01 (www.geos-chem.org), driven by reanalyzed meteorological data from the NASA Goddard Earth Observing System, Version 5 (GEOS-5) with a horizontal resolution of 2° × 2.5° and 72 vertical layers. We adopted the model standard chemical mechanisms for NO$_x$-ozone-hydrocarbon-aerosol-bromine chemistry (Bey et al. 2001, Pye and Seinfeld 2010) to simulate the formation of PM$_{2.5}$ components including SO$_4^{2-}$, NO$_3^-$, NH$_4^+$, organic carbon, black carbon, sea salt, and mineral dust. Other model details and emission inventories relevant to PM$_{2.5}$ simulations are described in supplementary information C.

To represent the effect of intercropping on PM$_{2.5}$ air quality, we scaled up or down the MASAGE NH$_3$ emission rates associated with the cultivation of maize and soybean in each province by the relative increase or decrease in NH$_3$ released after adopting intercropping as simulated by DNDC and kept other emission rates unchanged. For example, if DNDC estimates that NH$_3$ is reduced by 10% when intercropping is adopted in a province, the corresponding MASAGE NH$_3$ emission rates in that province will be reduced by 10%. GEOS-Chem simulations were driven by meteorological and land surface inputs from October 2005 to December 2006 with the first three months as spin-up. The simulation with the original MASAGE emissions served as a control.

2.4. Cost-benefit analysis of the intercropping systems

To compare between the economic values of intercropping in terms of both internal and external costs/benefits, we monetized the effects of intercropping on crop productivity, land-use efficiency, fertilizer-use efficiency, and NH$_3$ emission, and perform a cost-benefit analysis. We adjusted all values in the following discussion to 2006 US dollars value by assuming a constant 3% annual interest rate. We also applied inflation rates based on the relative purchase power parities in China with the baseline in 2006 (Organization for Economic Co-operation and Development, or OECD; https://data.oecd.org/). Unit prices/costs of the crops, fertilizer, labor, and machinery in China are extracted from data published by the Food and Agriculture Organization of the United Nations (FAO; http://www.fao.org/faostat/) and other sources (see table 1). Since labor and machinery costs may vary geographically depending on the wealth status and soil conditions, we assumed each hectare of intercropped cropland requires, at most, a doubling of the labor and machinery costs of monoculture, similar to double-cropping the two crops on the same land. We did not consider the possible shift of equilibrium unit prices/costs due to the changes in crop production and other

Figure 1. Maps showing provincial harvested areas of maize and soybean in year 2000 according to Monfreda et al. (2008). The harvested area of maize in China is ∼3 times that of soybean. Most maize croplands are found in East China while soybean croplands are mostly in Northeast China. The total harvested area for maize–soybean intercropping would be 33 Mha, the total harvested area of maize and soybean combined.
external factors affecting those prices/costs, e.g. investor speculation on the commodity markets and demand for biofuels (Lagi et al 2015). The health cost associated with inorganic PM$_{2.5}$ pollution was estimated following the method presented by Paulot and Jacob (2014) as the multiplicative product of the time-lagged change in premature mortality rate induced by a current change in PM$_{2.5}$ concentration, and the present value of statistical life in China (see supplementary information D for details).

3. Results

3.1. Implementation of competition factors in DNDC

Figure 2 shows the simulated crop yields and NH$_3$ emissions using the default and the revised DNDC based on the experimental field setup of Yong et al (2015a). For the original scheme, we show the average yield and NH$_3$ emission rate of both orders with soybean as the first modeled crop and maize as the first modeled crop. Black arrows in the top right figure indicate how we estimate the fertilizer for intercropping (120 kg-N ha$^{-1}$) to yield the same amount of monoculture maize at the conventional fertilization (180 kg-N ha$^{-1}$). In the bottom right figure, the black arrows indicate the corresponding change in NH$_3$ emission.

Table 1. Inflation rates and unit prices/costs in China used in the cost-benefit analysis.

| Item         | Inflation rate | Source       | Unit price/cost (adjusted to 2006 US$) | Source                  |
|--------------|----------------|--------------|----------------------------------------|-------------------------|
| Urea fertilizer | 14% (2010 versus 2006) | OECD         | US$ 0.274 kg$^{-1}$                   | Kahl et al (2010)       |
| Labor        | 19% (2011 versus 2006) | OECD         | US$ 186.5 ha$^{-1}$                   | Zhang et al (2015)      |
| Machinery    | 19% (2011 versus 2006) | OECD         | US$ 40.0 ha$^{-1}$                    | Zhang et al (2015)      |
| Maize        |                 |              | US$ 0.252 kg$^{-1}$                   | FAO                     |
| Soybean      |                 |              | US$ 0.413 kg$^{-1}$                   | FAO                     |
intercropped maize. When the competition factors are implemented in the revised scheme, however, the intercropped soybean yields are lower when nitrogen is limited because part of its fixed nitrogen is now used up by the intercropped maize. In turn, intercropped maize has a much higher yield than monoculture maize. Monoculture maize yield reaches 9000 kg ha\(^{-1}\) in dry mass (‘the conventional yield’) with the conventional fertilizer use of 180 kg-N ha\(^{-1}\). Intercropping requires 120 kg-N ha\(^{-1}\), i.e. 33% less fertilizer to produce this conventional yield while reducing NH\(_3\) emission by 26%, which is similar to the experimental results found by Yong et al. (2015a). They showed that the conventional yield (6400–7300 kg ha\(^{-1}\) for maize and 1900–2000 kg ha\(^{-1}\) for soybean) was generated by intercropping with 150 kg-N ha\(^{-1}\) fertilizer, equivalent to a 17% reduction in fertilizer use, and the corresponding NH\(_3\) emission was reduced by 44% in their experiments. In consideration of the possible experimental errors, e.g. ~8% in grain yield (Yong et al. 2015b) and ~10% in NH\(_3\) emissions (Liu et al. 2014), as well as our model uncertainties, the new nutrient distribution scheme is at least capable of qualitatively capturing the belowground competition of intercropped crops and representing the beneficial effects of intercropping better than the original sequential algorithm in default DNDC.

3.2. Provincial simulations with revised DNDC

We compared the DNDC-simulated production of monoculture maize and soybean with observed data from Monfreda et al. (2008), and simulated NH\(_3\) emission with the MASAGE inventory. In general, we find that the DNDC-simulated production of both monoculture maize and soybean at the provincial level based on representative sites compares reasonably well with observations, with a model-observation correlation of \(r = 0.94\). Simulated maize and soybean production are 110% and 70% higher than the observed production on average, respectively. DNDC-simulated and inventory NH\(_3\) emissions compare less well (see supplementary information E for detailed comparisons). The ratio of simulated NH\(_3\) emission to fertilizer-nitrogen input is 14.1% ± 9.2% for monoculture maize, which is similar to a reported value of 14.2% ± 8.6% for maize croplands in the US (Balasubramanian et al. 2015) although our simulated maize emissions are lower than those from MASAGE for most provinces. Soybean emissions are substantially higher in our simulations with an emission to input ratio of 37.1% ± 15.7%, likely because soybean BNF in DNDC always provides sufficient nitrogen for soybean growth and hence soil nitrogen is in excess under soybean monoculture, favoring NH\(_3\) volatilization. The incongruence in magnitude between DNDC-simulated and MASAGE NH\(_3\) emissions on a provincial scale is expected due to the high spatiotemporal variability of soil properties, topography and hydrometeorological conditions that could be lost in our upscaling approach. For example, DNDC predicts that croplands emit 3.6%–8.5% more NH\(_3\) per °C of soil temperature increase when the baseline is within 10 °C–20 °C, and 1.8%–10% per m s\(^{-1}\) of wind speed increase when the baseline is within 2–5 m s\(^{-1}\), representing large sensitivities of NH\(_3\) emission to changing meteorology. Hence, instead of directly using the DNDC-simulated absolute values that may be prone to systemic biases, we use the simulated percentage reduction in NH\(_3\) emission for intercropping relative to monoculture for most provincial representative sites as the basis to represent the beneficial effects of intercropping in alleviating nationwide air pollution.

Figure 3 shows that the quantity of fertilizer required for the intercropping system to generate the conventional yields of the non-legume crop in its monoculture counterpart is reduced in all representative sites (by 16%–84% of their corresponding monoculture counterparts; see supplementary information F for the result for each province); on average, only 58% of the conventional quantities of fertilizer are needed in maize–soybean intercropping to generate the conventional maize yield. With these quantities of fertilizer, intercropped soybean yield is lower (by ~4.5% to ~24% depending on the province) than its monoculture counterpart. As monoculture maize is replaced by maize–soybean intercropping, the extra batch of intercropped soybean produced in the same piece of land over the growing season represents an overall enhancement in crop production (as opposed to only a single batch of monoculture maize) and improves land-use efficiency. Since the original total harvested area of monoculture maize is higher than monoculture soybean, this additional soybean yield produced (2800–5000 kg ha\(^{-1}\)) when monoculture maize is replaced by intercropping is more than enough to compensate the production loss from the slightly reduced soybean yield (~15% on average) when monoculture soybean is replaced by intercropping, leading to an overall higher soybean production (+220% grain mass nationwide).

Figure 4 further shows the ratios of DNDC-simulated NH\(_3\) emissions from the intercropping system to the combined amounts released by monoculture maize and soybean. Maize–soybean intercropping lowers total NH\(_3\) emissions from 28 provinces by 45% on average. Zhejiang was the only province with increased emission (by 32%) after conversion to intercropping, mostly because there is more land cultivating soybean (113 kha), which emits 20 kg-N ha\(^{-1}\) of NH\(_3\), than maize (32.7 kha), which emits 45 kg-N ha\(^{-1}\) of NH\(_3\), resulting in a provincial total NH\(_3\) emission of 3700 Mg-N. When all maize and soybean croplands are converted into maize–soybean intercropping, which emits 34 kg-N ha\(^{-1}\) of NH\(_3\), the provincial total increases to 4900 Mg-N.

We also examined how these benefits of intercropping would be affected by water stress (see
supplementary information B for summary). The production gain (relative to monoculture) of maize is not sensitive to water deficit and that of soybean only decreases when there is no irrigation. The NH$_3$ emission reduction enabled by intercropping is largely offset when <25% of crop water demand is met.

3.3. Downstream effects of ammonia reduction on air quality in China
To estimate the potential benefits of intercropping in terms of air pollution alleviation, the MASAGE NH$_3$ emissions were provincially scaled up or down according to the ratios of NH$_3$ changes in figure 4 to simulate the emission changes induced by intercropping, leaving the excluded provinces and other countries unchanged. We then compared the simulated results with the unscaled control. As the mutualistic effect and thus NH$_3$ emission would change only after soybean is planted, the changes in PM$_{2.5}$ concentrations only over the growing period of soybean (May–December) are shown for maize–soybean intercropping (figure 5). Agricultural NH$_3$ is released mainly
from the central and northern provinces of China (Gu et al. 2012, 2014). In the maize–soybean intercropping simulation relative to the control case, the largest reduction in NH3 gas concentration (by up to 8.5%) is found in Henan province in central China. The corresponding changes in major SNA aerosol components, (NH4)2SO4 and NH4NO3, are the largest in the downwind regions to the east (following the prevailing westerlies) that overlap with high anthropogenic NOx emissions (Wang et al. 2013). The largest improvement in air quality is found around Hebei, Henan, Shanxi, Shandong and Shaanxi. Mean concentrations of total inorganic PM2.5 and its major components, NH4+ and NO3−, in Hebei are reduced by up to 1.5 μg m−3 (2.3% compared to the control case), 0.35 μg m−3 (3.9%) and 1.2 μg m−3 (5.0%) respectively. The largest SO42− changes are found in the major SO2-emitting regions (South China and Sichuan Basin), though the reductions are smaller than 1.2% relative to the control.

3.4. Economic feasibility of nationwide adoption of intercropping

We further performed a cost-benefit analysis for intercropping in China. Based on the DNDC-simulated production and NH3 emissions of monoculture versus intercropping systems and the subsequent differences in PM2.5 air quality, we find that converting the current monoculture croplands into intercropped ones can raise the annual net economic benefit by US$67 billion (93% more than current practices; see figure 6 for breakdowns). Although the ratio of labor and machinery costs to the revenues from grain sales increases from 7.3% to 8.5% under our high-end assumption that intercropping requires double labor and machinery, the additional costs will still not be significant financial burdens compared to the additional benefits of intercropping, which include extra grain revenues, reduced fertilizer expenses, and saved health costs associated with improved air quality. It is found that high fertilizer savings are seen in the intensive farming provinces while savings on health costs mainly benefit the downwind provinces of these intensive agricultural regions.

It is noteworthy that food price fluctuations, which are controlled by many external factors in addition to production enhancement (Lagi et al. 2015), may interfere the profitability of grain sales, but are not considered in this study. Another potential caveat of our analysis is that indeed ~20% of Chinese cereal croplands already adopt intercropping (Huang et al. 2015), so that our estimation based on pure monoculture being converted to intercropping likely represents a maximum possible gain, part of which has already been realized. However, even if we take into account of the current prevalence of intercropping by converting ~20% less current cropland area, the net gain can still be 77% higher than the current practices.

Figure 5. Mean changes in concentrations of major inorganic PM2.5 components under nationwide replacement of monoculture maize and soybean fields with maize–soybean intercropping in continental China over the growing period of soybean (May–December) in 2006.
4. Conclusions and discussion

In this study, we implemented into DNDC with a new belowground nitrogen competition scheme and combined it with GEOS-Chem to investigate the net benefits brought about by implementing nationwide intercropping in China. Our findings show that maize–soybean intercropping systems have the potential to save 42% of fertilizer application, compared with their monoculture counterparts, while producing...
the same quantities of maize (4300–16000 kg ha\(^{-1}\) on average) and an additional batch of soybean (2800–5000 kg ha\(^{-1}\)), improving both fertilizer-use and land-use efficiencies. Furthermore, the corresponding NH\(_3\) emission is cut down by 45% on average, mostly observed in central and northern China. Noticeable air quality improvements are seen in these regions but also, indeed more significantly, in downwind regions in northern and northeastern China that overlap with high anthropogenic NO\(_x\) emissions from industrial activities, power generation, and transportation (Fu et al. 2015). The reduction in PM\(_{2.5}\), over those areas can be up to 1.5 \(\mu\)g m\(^{-3}\) over the growing seasons of soybean, which is equivalent to \(~4.3\%\) of the national daily average PM\(_{2.5}\) limit of 35 \(\mu\)g m\(^{-3}\) (Ministry of Ecology and Environment of the People’s Republic of China; http://www.mee.gov.cn). We also find that the nationwide adoption of maize–soybean intercropping can lead to an increase in net economic benefits by US$67 billion per year (of which US$13 billion is from the health cost saving with less air pollution). This study can serve as a scientific basis for policymakers and other stakeholders to explore the feasibility and effectiveness of employing sustainable farming practices to safeguard our food supply while alleviating environmental pollution in China.

We also found from the cost-benefit analysis that there is an uneven distribution of costs versus benefits across different provinces. Provinces with intensive agriculture benefit more from the gains in crop production but suffer less from the health damage costs associated with PM\(_{2.5}\), while the populated downwind cities are affected more severely by the air pollutants but gain less from the enhanced crop production. Such information is useful for Chinese policymakers to establish an integrated agricultural and air quality management strategy that is fair to most of the provinces. They may also refer to our results (e.g. figures 3 and 4) to identify which province could benefit from intercropping the most, set out pilot programs to test adopting intercropping in croplands there, and use the framework of this study to evaluate the effectiveness of the conversion in safeguarding air quality and food productivity.

We estimated the economic and environmental benefits above necessarily under present-day market conditions, assigning to crops, fertilizer, labor and machinery unit prices/costs that are insensitive to long-term market changes. Taking food prices as an example, we did not consider price volatility due to long-term production changes, seasonality, investor speculation on commodities, growing demand for biofuels, new government policies and subsidies, and international trade (de Gorter and Just 2010, Gilbert 2010, Clapp and Helleiner 2012, Lagi et al 2015). Substantial food price fluctuations due to these economic factors may interfere with the favorability and efficiency of intercropping (as well as other sustainable farming methods) to the farmers. Although economic modeling (e.g. partial equilibrium model) to predict demand-supply-driven price changes in the commodity market is beyond the scope of this work, our (mostly) physical modeling framework can be used concurrently with such economic models that include the market factors mentioned above, e.g. food price decline due to crop production increase after the conversion to intercropping.

One major difficulty in evaluating the benefits of large-scale intercropping adoption arises from the time-consuming and resource-demanding nature of field experiments. Model simulation (e.g. using DNDC) is thus an excellent alternative approach as we have pursued here, albeit with various sources of uncertainties. One of such uncertainties concerns that capturing the daily variability in both models and field measurements is difficult since NH\(_3\) volatilization is sensitive to meteorological anomalies and irrigation practices. Some studies found that the 25 d cumulative NH\(_3\) emission can range between 17% and 64% of the applied fertilizer nitrogen when comparing DNDC-simulated results and observations from a field experiment with three events of 5 mm artificial rainfall (Rochette et al 2009, Dutta et al 2016). Such variability may raise or reduce our estimated downwind PM\(_{2.5}\) concentrations. The sensitivity of NH\(_3\) emission to interannual variability of hydroclimatic conditions certainly warrants further investigation. Model representation of soil nitrogen biogeochemistry represents another major challenge. In DNDC, for instance, crops absorb different nitrogen species from soil solely according to their relative abundance, but studies have found that some crops prefer either NO\(_x\) or NH\(_4^+\) over the other depending on the crop and growing stage (Boudsocq et al 2012). Better parameterization of legume BNF index that depends on crop nitrogen demand, growth stage, and the abundance of various soil nitrogen content, instead of using constant values as in our study, is also called for in future work (Liu et al 2011).

Our simulated yields of monoculture maize and soybean are generally slightly higher than observations (figure S3), and this may lead to an overestimation of revenue gains from extra grain production under intercropping. Yet, the estimated labor and machinery costs take up only a small fraction of the grain revenues even at the maximum level of conversion, and thus despite the possible biases our results still attest to the potential economic advantage of large-scale intercropping, which is a feasible measure to safeguard food production, air quality, and the environment. According to the MASAGE inventory, maize, wheat and soybean production together contributes to only \(~16\%\) of the total agricultural NH\(_3\) emission in China. Our revised DNDC nitrogen distribution scheme will be useful in further examining the beneficial effects of adopting intercropping systems of other crop pairs, which will likely yield even larger total benefits than found by this study. For instance, as we replicated our experiment in China for the intercropping of winter
wheat and soybean, we showed that wheat-soybean intercropping can also be both profitable and environmentally friendly: lowering national NH3 emission by 86% and PM2.5 concentration by up to 1.7 μg m⁻³ (2.2%), and bringing a net annual increase in economic benefits of US$64 billion (380% more than monoculture) (see supplementary information G for details).

Intercropping is a labor-intensive practice. With increasing labor costs over time and decreasing machinery costs for monoculture, intercropping involving cereals has experienced a sharp decline in prevalence in China from being implemented in more than 50% of farmlands in the 1980s to only about 20% nowadays (Huang et al. 2015). The net rural-to-urban migration of the younger generations further limits the agricultural labor supply. Moreover, the traditional layout of intercropping is neither convenient for mechanization nor optimized for light-use efficiency, which in turn raises the conversion costs from monoculture and reduces the marginal profits (Du et al. 2018). Governmental subsidies on fertilizer also reduce the economic favorability of intercropping as far as the farmers or farm owners are concerned. In such economic decisions, however, the potentially large external environmental and health costs of monoculture are typically ignored, unless they are internalized and institutionalized by governmental agencies. This study assesses the environmental values of more widespread adoption of intercropping in terms of alleviating air pollution and providing a scientific basis for governments and agencies to consider diverting their current resources from subsidizing fertilizer to modernizing and popularizing this and other sustainable farming practices in the country or at least in certain provinces. Our assessment framework could also be useful to identify potential agricultural regions around the world where large-scale adoption of intercropping is feasible.

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