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A Nitrogen Physical Input-Output Table (PIOT) model for Illinois☆

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ABSTRACT

Nitrogen (N) presents an important challenge for sustainability. Human intervention in the global nitrogen cycle has been pivotal in providing goods and services to society. However, release of N beyond its intended societal use has many negative health and environmental consequences. Several systems modeling approaches have been developed to understand the tradeoffs between the beneficial and harmful effects of N. These efforts include life cycle modeling, integrated management practices and sustainability metrics for individuals and communities. However, these approaches do not connect economic and ecological N flows in physical units throughout the system, which could better represent these trade-offs for decision-makers. Physical Input-Output Table (PIOT) based models present a viable complementary solution to overcome this limitation. We developed a N-PIOT for Illinois representing the interdependence of sectors in 2002, using N mass units. This allows studying the total N flow required to produce a certain amount of N in the final product. An Environmentally Extended Input Output (EEIO) based approach was used to connect the physical economic production to environmental losses; allowing quantification of total environmental impact to support production in Illinois. A bottom up approach was used to develop the N-PIOT using Material Flow Analysis (MFA) tracking N flows associated with top 3 commodities (Corn, Soybean and Wheat). These three commodities cover 99% of N fertilizer use in Illinois. The PIOT shows that of all the N inputs to corn farming the state exported 68% of N embedded in useful products, 9% went to animal feed manufacturing and only 0.03% was consumed directly within the state. Approximately 35% of N input to soybean farming ended up in animal feed manufacturing. Release of N to the environment was highest from corn farming, at about 21.8% of total N fertilizer inputs, followed by soybean (9.2%) and wheat farming (4.2%). The model also allowed the calculation of life cycle N use efficiency for N based on physical flows in the economy. Hence, PIOTs prove to be a viable tool for developing a holistic approach to manage disrupted biogeochemical cycles, since these provide a detailed insight into physical flows in economic systems and allow physical coupling with ecological N flows.

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1. Introduction

While benefitting society through enhanced agricultural production and manufacturing of goods, human intervention in the global nitrogen (N) cycle has also led to an overabundance of reactive forms of N in the environment. This release has resulted in issues such as eutrophication (Chaffin et al., 2013), impacts to human health (Peel et al., 2013) and alteration of ecosystem function (Camargo and Alonso, 2006; Moss et al., 2013). Nitrogen is also associated with climate change as N_2O is a potent greenhouse gas (Pinder et al., 2013) (Pinder et al., 2011) and damages to ecosystem services (Compton et al., 2011; Van Grinsven et al., 2013). As a result of these critical impacts, N use is one of the critical planetary boundaries that has transgressed the safe operating space (Steffen et al., 2015). Hence, several efforts have been made to track and quantify N inputs to various ecological systems in order to provide an insight into reducing the human impact on N cycle transformations (Hale et al., 2015). The N paradox necessitates optimizing the use of N while reducing losses and associated negative impacts that have been the major focus of analysis in recent years for N management

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(Zhang et al., 2015). According to an estimate for Europe, if the environmental cost of N were internalized into social benefits of N use in Europe then the use of N fertilizer would be reduced by at-least 50 kg/ha or approximately 25–50% of current fertilizer inputs (Van Grinsven et al., 2013). The magnitude of these impacts highlights the need to inform producers and consumers about the negative impacts upstream and downstream of the agricultural products being considered. Thus, strategies to develop integrated management plans such as vertical integration (as supply chain), horizontal integration (such as N cascade approach in a region), interactions with other chemical species (such as SO_2 from combustion sources), stakeholder involvement and regional integration (Oenema, 2011) may be beneficial for reduction of impact. Systems analysis, N budgeting, integrated assessment modeling and logistics management are some of the suggested tools for sustainable management of N (Oenema, 2011). These tools provide useful insights for sustainable management of N in specific systems such as farm scale N losses (Cameron et al., 2013; Zhang et al., 2015), losses from combustion processes (Reis et al., 2016), supply chain losses on product basis such as in N footprint (Leach et al., 2012; Galloway et al., 2014) and studies of nitrogen-related impacts across the life cycles of products (Costello et al., 2015). However, these approaches contribute to the systems scale quantification of reactive N losses attributed to a specific product or process, they do not capture the full network of N flows across different products and processes. Such insight is necessary for coupling the economic and environmental N flows to more efficiently use and manage N at the full system scale while considering the harmful effects, which is not feasible through single product or process analysis.

In this work, a comprehensive view for N flows in coupled economy and ecological system is demonstrated by a physical flow model based on a Physical Input-Output Table (PIOT) approach. PIOT goes beyond other available modeling approaches by including linkages between multiple sectors of the economy in physical units and tracking N flows across sectors. Thus, the PIOT approach extends the description of a vertically integrated management approach as it provides insight into structural interaction among industries of an economy along with physical insight into opportunities for improving resource utilization efficiently. PIOT also quantifies the direct and indirect impacts on environmental and resource flows through the integrated system. Developing these detailed insights at regional scale for multiple regions will also be useful for optimizing N use since regional shifts of production have been suggested as a strategy to improve food production while reducing N pollution (Van Grinsven et al., 2013).

This work specifically addresses the need for integrated regional models that relate physical N flows in production with the N losses to environment. Physical flow based models will allow development of regional economic strategies that meet both economic production and environmental objectives as the physical dependence of production sectors are accounted in these models. Therefore, using the physical analogue of the Environmentally Extended Input-Output (EEIO) framework, a model based on Physical Input-Output Table (PIOT) approach is developed for tracking the N flows of the Illinois economy. Illinois was chosen as representative Midwestern state where economy is strongly connected to agricultural systems, hence provides a good case study for coupling of economic and ecological N flows. PIOT is developed using a "bottom up" approach that tracks the physical flows for each contributing commodity at fine scale (Marco et al., 2009). This approach provides insights into the N flow structure among the industries in the Illinois economy. The connection with ecological systems is established using the EEIO approach of tracking the N losses to water and air from each sector. Thus, this PIOT can be used to quantify the total direct and indirect emissions related to a particular production activity in the state. Further, the model provides a way to calculate life cycle nitrogen use efficiency (NUE) for each production sector in Illinois.

2. Method

The N-PIOT framework proposed in this work is inspired by the PIOT framework (Hoekstra and van den Bergh, 2006), with variables adopted to reflect the unique requirements of N-PIOT. The framework provides the structure of PIOT, which is combined with a "bottom up" approach to obtain relevant data for the PIOT. A bottom up approach uses the material flow analysis (MFA) at the commodity level that corresponds to N flows in the economy. There is a strong relationship between MFA and IO resulting from the physical connection that MFA at inter-sectoral scale can provide inputs to IO analysis (Marco et al., 2009). The top-down approach that uses the statistical information of the economic IO table to construct material flow suffers from the limitation that it is not based on mass balance principle, thus resulting in biased results because some products have higher economic valuation but do not directly correspond to amount of mass flows. This provides motivation for using bottom-up approach for building N-PIOT based on mass balance principle. Marco et al. (2009) have used a sectoral level mass balance principle to build PIOT bottom up. Our work uses a much finer scale, using commodity level information for N flows to build the PIOT. This method mimics the process scale LCA that is aggregated to build the IO scale model. The limitation of truncation error that occurs frequently in process scale models is not a problem here because each of the N flows are followed from cradle to gate within the state. This ensures that none of the sectors related to N flows are missed while maintaining a N mass balance. Any effects of non-N related sectors on N flows, can be addressed using a hybrid method with mixed units (Hawkins et al., 2007), but is beyond the scope of this study.

2.1. Conceptual framework for N-PIOT

Table 1 shows the basic structure of the N-PIOT. The PIOT for N is a partial IO model since it includes only the economic sectors that are involved in processing of N from the point of "reactive N" (*Nr*) formation to various products and flow to final consumption point. The N emissions during various processing steps are captured using the EEIO framework. In this respect, the N-PIOT provides a physical coupling model for flow of N between ecosystems and economic system with PIOTs tracking N flows in economic systems. There are a total of **Y** economic sectors in the IO table that represent the economy of the region. Out of these there are **m** sectors that can be identified as the processing sectors for N based commodities. The type of flows for the N-PIOT are processing flows (Z), new N input (fixed from atmospheric N_2) as raw materials (R), demand which captures consumption (C), exports (EX) and imports (I), residuals production (RP), residuals use (RU), stock changes (ΔS) and emissions (E, losses to environment). These flows are used to balance the PIOT by imposing a mass balance constraint between total input (TI) and total output (TO) in form of N, both individually for each sector and the overall state. Z_{ij} indicates flow of N from the i_{th} processing sector to the j_{th} processing sector. Additional rows for new N input as raw materials (R) to the regional economy and emissions (E) from the economy to nature is also included in the PIOT to account for interaction of N flows with natural systems. This is based on the concept of an EEIO model that couples economic and environmental flows. Hence, N-PIOT establishes the connection of N flows in the economy to the impact of N flows in the ecosystem. The row R of N input to the economy includes fixation from natural processes (such as legume N fixation) and the Haber Bosch process. Nitrogen emissions, row E, includes emissions to air, water

Table 1
General Framework for Physical Input-Output Table.

		To Processing Sectors							Demand			Total Outputs from Sector
		1	2	3	...	j	...	m	Cons (C)	Export (E)	Import (I)	
From Processing Sectors	1	Z_{11}	Z_{12}	Z_{13}	...	Z_{1j}	...	Z_{1m}	C_1	EX_1	I_1	TO_1
	2	Z_{21}	Z_{22}	Z_{23}	...	Z_{2j}	...	Z_{2m}	C_2	EX_2	I_2	TO_2
	3	Z_{31}	Z_{32}	Z_{33}	...	Z_{3j}	...	Z_{3m}	C_3	EX_3	I_3	TO_3
	...	...	...	...	...	...	...	...	...	...	...	...
	i	Z_{i1}	Z_{i2}	Z_{i3}	...	Z_{ij}	...	Z_{im}	Ci	EXi	Ii	TO_i
	...	...	...	...	...	...	...	...	...	...	...	...
	m	Z_{m1}	Z_{m2}	Z_{m3}	...	Z_{mj}	...	Z_{mm}	C_m	EX_m	I_m	TO_m
Raw Materials	Nr Fixation (Soybean) R1	$R1_1$	$R1_2$	$R1_3$	...	$R1_j$	...	$R1_m$				
	Nr Fixation (Haber-Bosch) (R2)	$R2_1$	$R2_2$	$R2_3$	...	$R2_j$	...	$R2_m$				
	Natural Nr Fixation (R3)	$R3_1$	$R3_2$	$R3_3$	...	$R3_j$	...	$R3_m$				
Residuals Production		RP_1	RP_2	RP_3	...	RP_j	...	RP_m				
Residuals Use		RU_1	RU_2	RU_3	...	RUj	...	RUm				
Stock Changes		ΔS_1	ΔS_2	ΔS_3	...	ΔS_j	...	ΔS_m				
Emissions		E_1	E_2	E_3	...	E_j	...	E_m				
Total Inputs to Sector		TI_1	TI_2	TI_3	...	TI_4	...	TI_m				

and land in organic or inorganic forms. There is also a stock change (ΔS) row that records the beginning and ending stock to account for N in products as stocks carried over from one year to the next. The demand of N from a particular N processing sector is captured by F_i which indicates the final consumption of N in the economy from i_{th} sector. The final consumption here includes the consumption (C_i) of N based commodities directly by consumers and net exports for consumption in other regions. The term for net exports is calculated by difference of exports and imports ($EX_i - I_i$) for the processing sector that imports some of the sector products from different region. Using these flows and notation, the sectoral level balance is given by Eqs (1.1) and (1.2)

Eq. 1.1: Total Input to Sector j (Column Balance)

$$TI_j = \sum_{i=1}^{m} Z_{ij} + R_j + RU_j + \Delta S_j - RP_j - E_j$$

Eq. 1.2: Total Output from Sector j (Row Balance)

$$TO_j = \sum_{i=1}^{m} Z_{ji} + C_j + EX_j - I_j$$

For the overall balance of PIOT, first a sector level mass balance is ensured by equating Total Input (TI) to Total Output (TO) for each sector. Note that even though emissions and residuals production are "outputs" from a sector, these flows are not included in the output balance equation. This is because the output side balance only captures the useful output from a sector activity. Emissions and residuals are a form of waste output that are not immediately incorporated in the products and are utilized or wasted further down in production systems. Residuals are unintended flows from a sector that can have value addition with or without further processing, however is not a desired product from the sectors and have insignificant economic value. Each row of the N-PIOT in physical units describes the flow of N from the processing sector in the row to those in columns and to the final consumers. Thus, each row sum indicates total output of useful N from each sector, and the column sum indicates the total input to each sector. The emissions are deducted from each column sum to indicate total input that can be used by each sector to provide the output to other sectors and also to final consumers. Ideally, a balance of input and output needs to be met for an IO table. To ensure mass balance of the PIOT, reasonable assumptions can be made about the flows that have missing information such as exports, imports, etc.

Approach for balancing PIOT: One of the necessary requirements for validation of IO model is the balance of input and output flows. In case of PIOT if several variables have missing data then it can be a misrepresentation of resource flows in the economic system, but the direction of the imbalance can give information about the additional data needs. This direction of imbalance was utilized to balance N-PIOT in this work. To balance the N-PIOT, a balancing row or column is added based on a positive or negative value after subtracting output from input, respectively. If input value of N for a sector is higher than output (i.e., Output-Input = negative), then it is assumed that the balancing needs to be done on the output side and an output column is added. These columns are chosen to be auxiliary flows such as exports, consumption or imports on output side. Alternatively, if an input value is lower than the output side (i.e. Output-Input is positive), it is assumed that balancing needs to be done on input side for missing flow and an input row is added. In this work, the input side balancing row has been chosen to be the beginning stocks. The use of auxiliary flows to balance PIOT (such as imports, exports, beginning stocks etc.) ensures that the structure of the PIOT due to interaction of sectors is not changed by adding rows and columns. This minimizes the impact of overbalancing on the structure of the PIOT, especially if the uncertainty of data used to build the PIOT is high. This approach is particularly suitable for regional scale PIOT, since detailed trade statistics needed for this analysis are generally not available at the regional scale, whereas for national scale these values are well reported and have lower uncertainty. Recycling in a regional economy was accounted for by adding specific rows for residual supply and use. The supply of residuals provides an accounting method to assess any N that is not converted into useful products in the processing sector and is collected as residual for later use.

2.2. Steps to build the N-PIOT

A generic flow diagram for building a N PIOT is shown in Fig. 1 of SI. The bottom up approach at fine scale for building the PIOT model in this work starts with identification of the major commodities that are associated with N flows, for example corn, soybean etc. The next step is the construction of material flow analysis (MFA) diagrams for these commodities, which is then mapped to the corresponding economic sectors. These MFA diagrams track the flow of N as the major N driving commodities are converted into various products and end in consumption or waste flow (see Fig. 2–4 in SI). These N flows are then converted from MFA diagrams into the PIOT format. This entails aggregating flows from the MFA diagrams for specific commodities in the mapped IO sector. The PIOT of sectoral N flows is then augmented with information regarding interactions with the environment such as N fixation and emission. Each row and

column (individual sectors) is then independently validated for the input vs output mass balance using Eqs. (1.1) & (1.2). If the rows and columns do not satisfy the mass balance then assumptions about exports or imports are made to achieve the mass balance as discussed previously. The choice of exports and imports for balancing help in avoiding alteration of industrial interactions structure significantly, however impacts the overall balance at state scale due to assumed exports or imports.

Estimation of Flows in the N-PIOT

There are mainly three types of N flows in the developed PIOT: a) flows in between the sectors or intersectoral flows (Z_{ij}) b) flows to and from natural systems such as emissions to ecosystems (E) or Nr fixation from atmosphere (R) and c) flows of N directly being consumed by humans or exported/imported outside the state boundaries (C, EX, I).

a *Intersectoral flows:* The intersectoral flows of N are based on the physical flow of commodities in between sectors. Each physical commodity mass is then converted into actual N flows based on N content of each commodity. The conversion factors for mass to Nr is shown in Table 11 of SI and all the converted flow values are shown in SI Tables 2 (Soybean), 6 (Corn) and 7 (Wheat).

b *Emissions and Nr fixation:* Emissions from each sectors present in the PIOT model are added to study the interaction of these sectors with environment, represented in row E (Table 1). N data for emissions E from sectors related to farming was obtained from the Fertilizer Emissions Scenario Tool for CMAQ (FEST-C) version 1 (http://www.cmascenter.org) as described in (Cooter et al., 2012; Bash et al., 2013) for the state of Illinois or literature. Environmental Policy Integrated Climate (EPIC) model provided the data for emissions for Wheat and Soybean in our PIOT. The emissions data for corn was directly obtained from literature, including the USGS SPARROW model (Alexander et al., 2008) and field studies (Ogle et al., 2008). N fixation for soybean was obtained by calculation (See SI, Table 3) and for fertilizer manufacturing sector N fixation was assumed to be equal to the consumption of fertilizers.

c *Export/Import/Consumption flows:* For some of these flows, data were found in reports (USDA, 2012). The consumption data were calculated by assuming the same per capita consumption for each commodity as the national average per capita consumption. The resulting values were multiplied with population of the state to get total state-level consumption for the specific commodity. Some of the export and imports number are assumed values for sectoral level balance. Though these numbers are highly uncertain, they do not impact the structure of N-PIOT model for sector interactions.

2.3. Strength and applications of N-PIOT

PIOTs are used to conduct Life Cycle Assessment (LCA) in a similar way as other LCA approaches based on input-output tables. The equations for LCA based on IO table depend on the objectives of LCA. For N management, one of the most important objective is to obtain total useful output required by the sectors to meet final demand from sectors. As a reminder, the final demand (f_i) of N from each sector here includes the actual demand for N consumption (Ci) and Exports (EX_i) from the sector and excludes any demand met by imports (I_i). Thus, LCA based on N-PIOT will provide the overall output (TO_i) for each sector i.e. the useful form of N flows from a sector. This TO_i in the built original PIOT is also referred to as TO_{old} later in the paper to emphasize that this is the original flows of total output of N in the economy to support production from the specific sectors.

To calculate a new total output (TO_{new}) to support a new final demand (f_{new}) given in physical units from sectors in the economy, a direct requirements coefficient for each sector is defined as $A_{ij} = Z_{ij}/TO_j$ where A_{ij} is the "direct requirements coefficient" that captures the flow from i_{th} sector to j_{th} sector per unit output from sector j. The coefficients A_{ij} in matrix A, provide information about relationship between N flows from one processing sector in useful form to support total output of other sector and is based on the built N PIOT i.e. use TO_{old} for each sector in the built PIOT. Eq. (3) is used to calculate TO_{new} for a given f_{new} using the direct requirements matrix A:

$$TO_{new} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{f_{new}} \tag{3}$$

Eq. (3) provides total N output required from the sectors in economy to meet a particular final demand of N based products from the sector. I in this equation is an identity matrix of same dimension as A which is derived from the built PIOT. These analysis of N for Illinois are discussed in Section 3.2

Total life cycle emissions (analysis for Illinois discussed in Section 3.3) to meet a final demand from a sector are calculated using the Environmentally Extended Input Output (EEIO) model given in Eq. (4).

$$\phi = \boldsymbol{E}\hat{\boldsymbol{q}}^{-1}(\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{f_{new}} \tag{4}$$

In this equation, E is N emissions for each sector based on N-PIOT and q is the total useful N output (TO or TO_{old}) from the sector as products in physical units from the original PIOT. Hence, $\boldsymbol{E}\hat{\boldsymbol{q}}^{-1}$ is the emissions per N output by sector. The N-PIOT framework allows users to track the change of emissions and TO together due to the physical relationship between E and TO being captured in PIOT. In the case of N flows, the emissions can have significant uncertainty based on the source of emissions information. The reliability of these emissions factor is high in our model since the emission estimates for wheat and soybeans derive from process-based FEST-C vq simulations that provide spatially complete, consistent estimates reflecting regional-scale patterns of soil and weather. Subsequent FEST-C refinements and literature suggest the values used in this example are conservative, but can be updated as improved estimates become available. For other sectors that do not have significant land and water emissions, the major emissions source is auxiliary N through fuel combustion. All of these emissions factors can easily be updated if management practices change that impact the N emissions at the farm scale or energy utilization changes. The calculations of emissions in N PIOT is thus similar to the methodology elsewhere (Suh, 2004), however slightly different than in (Giljum and Hubacek, 2010) where the main interest is primary materials in PIOT. In this work, the whole PIOT is in units of N, so all primary material here is N flow. Hence Eqn 4 captures the waste generated to support final demand along with Eqn 3 capturing total physical N output from all sectors to meet final demand.

3. Results

The developed N-PIOT model captures N flows associated with top 3 commodities (corn, soybean and wheat) in Illinois for the year 2002, which accounts for about 99% of N fertilizer input to the state. Fig. 1 shows the N balance for the state of Illinois based on these major crops. In 2002, total N input was 1.27E+06 Mt. of N in the form of fertilizers, other goods such as feed, seeds, manufactured food products and biological N_2 fixation by soybeans. Of these inputs, about 27% was the share of N mobilization (i.e. conversion of inert N to reactive N in the soil) whereas 70% was the share of fertilizer imports. The "other" portion was 3%, which includes imports of N embodied in other products. About 14% of total N inputs to the state were lost to the environment as air, water and land emissions. These emissions value were calculated based on FEST-C v1 simula-

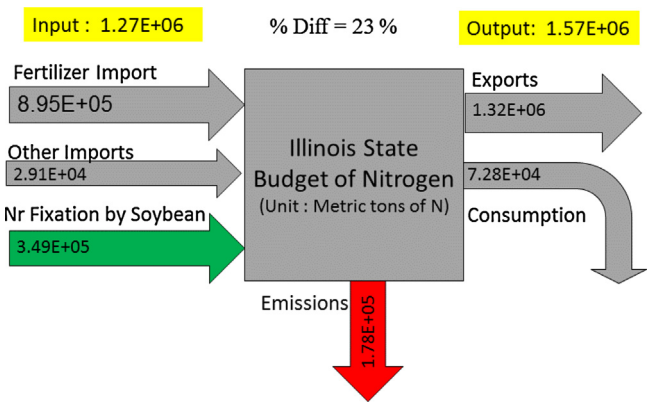

Fig. 1. Nitrogen Balance for State of Illinois.

tion and literature for corn, thus includes all the field scale N losses that forms 20% of N inputs as fertilizer being lost to ecosystems. In the developed PIOT, emissions do not include the fossil fuel combustion based air emissions however, it does include emissions to the atmosphere from N fertilizer application on agricultural soils. This is because the N emissions related to combustion are considered to be new N inputs (i.e. are auxiliary N) and do not come from the N mobilized in other forms being included here (i.e. the N that gets used to make products). The consumption of N based products such as manufactured food within the state is only about 6% of the total N entering the state. Finally, N leaving the state was 23% higher than inputs, displaying an imbalance in the PIOT. This suggests that some input flows were missing in the accounting and/or the individual sector balance for exports may have been overestimated, or a combination of both. The 23% discrepancy in N flow accounting was attributed to the data uncertainty for balancing PIOT. Since the aim of this work was to develop a general framework for PIOTs of N flows in the economy, the discrepancy in mass balance highlighted the need of detailed data collection on imports and exports at state level to further improve the accuracy of this approach. Other frameworks that also attempt to account for N balance are at the watershed scale or farm scale, including the approach using Net Anthropogenic Nitrogen Inputs (NANI) and riverine exports (Zhou et al., 2014; Hong et al., 2013). Similarly, national scale N balances have also been attempted (Houlton et al., 2013). These approaches have also found N imbalances. However, these N balances could not be directly compared with our balances since the PIOT framework is accounting for N flows in the economic system in state boundaries whereas the watershed balances look at ecosystem boundaries and national balances look at country boundaries. All these framework highlight the need of better data collection in order to manage N as a resource and uniquely provide understanding of N flows in different systems.

3.1. *N PIOT for Illinois*

The constructed N-PIOT for Illinois was based on MFA diagrams for major commodities: Corn, Sweet Corn, Soybean, Wheat, Livestock farming and fertilizer manufacturing. The MFA diagrams are shown in SI Figs. 2–4). Tracing the flows of each commodity through various sectors provides the map of flow of N in the PIOT format. Based on the major N flow drivers (corn, soybean and wheat), the PIOT developed for the state of Illinois has 22 sectors (shown in Table 2, sector descriptions given in Table 13, SI) as compared to 427 sectors in a full NAICS sectors of IO table in year 2002. These 22 sectors represent important areas of focus for sustainable management of N. After identifying the flows in the MFA for each commodity, these flows were estimated to build a PIOT based on the relationship of these flows with the PIOT as discussed below. Details of each flows being estimated is provided in SI.

Balancing N PIOT: For Illinois, there was high imbalance found in the inputs and outputs for the sectors which may be due to lack of accounting/reporting of exports, stocks and/or losses of N to the environment. In some sectors, the discrepancy was as high as 87%. The sectors such as “Dog and Cat Food manufacturing” showed 100% discrepancy because consumption or export values for these products have not been reported. The assumption made for such case was that all the N that enters in these product manufacturing end up being consumed in the economy. Since no information was available on the export of these products from Illinois, all the N was allocated to within state consumption. Similar approach was used for the food manufacturing sectors such as “Bread, Bakery & Product Manu.”, “Cookie, Cracker & Product Manu.”, “Snack Food Manu.”, “Tortilla Manu.”, “Breakfast Cereal Manu.”, “Frozen Food Manu.” and “Vegetable, Fruit Canning & Drying”. Assumption made on exports, imports and stocks do not alter the intersectoral interaction, hence does not limit the analysis based on PIOT discussed in next section. The details of balancing process applied for each sector is shown in Table 2.

3.2. *Life cycle nitrogen flows using N-PIOT*

Fig. 2 shows the life cycle N throughput (TO_{new}) for a final demand (f_{new}) of 1 unit of N from each of the sectors using Eq. (3). This value can be interpreted as the total N required to meet the demand of 1 unit of N in product from the specific sector. For example, the figure shows that to obtain 1 unit of N product from “Oilseed farming” (Soybean in this work), a total of 1.22 unit of N is required from the economy itself. The breakdown of this 1.22 unit of N throughput through the oilseed farming shows, 1.036 unit from Oilseed farming and 0.186 unit of N from “Fertilizer Manufacturing sector”. The 1.036 unit flow from Oilseed farming includes the N embedded in the seed being used in the same sector and N fixation by Soybean farms. Thus, this figure shows the economic interdependency of various sectors in terms of N flow to support a unit of N output.

The highest interdependency among sectors to support a unit of N output is shown for “Poultry Processing” and “Animal (Except Poultry) Slaughtering & Processing”. These sectors are dependent on N produce from various sectors, thus making a long supply chain to provide the final output. For 1 unit of N product from “Poultry Processing”, the economy needs a total flow of 5.88 units of N. Thus the NUE of the economy in producing useful output of N through poultry processing is about 17%. Other animal slaughtering such as pork and beef production also has similar efficiency. In a recent study for beef and pork production in France, an efficiency of 11% and 7% was found for production of retail products of beef and pork (Chatzimpiros and Barles, 2013). The breakdown shows that for each unit of N output as product from “Poultry Processing” in Illinois, it needs 0.42 units of N output from “Oilseed farming (Soybean)”, 0.45 unit of N from Soybean processing, 0.61 unit of N from Corn Farming, 0.2 unit of N from Wet Corn Milling, 0.35 units of N from Dry Corn Milling, 0.0047 units from Wheat Farming, 1 unit from Animal Food Manufacturing, 0.86 unit of N from Nitrogenous fertilizer manufacturing and finally 1 unit of N embodied in poultry being transferred to processing sectors. It is to be noted that the efficiency of poultry processing to produce meat has been implicity assumed 1 here, due to lack of data for efficiency at the time of this study.

The strength of using PIOT for studying the throughflow of N for each product is that it clearly shows the steps that contribute to low N use efficiency. A plant-based food item such as “Breakfast Cereal Manufacturing” certainly has a lower N release than Poultry meat. This results from fewer transformation steps in pro-

Table 2
N PIOT Sectors and Flow Balance (Unit: Metric tons of N).

Sectors	Total Input (TI)	Total Output (TO)	Balance (I-O)	% Off By Input	Assumed Flows to Balance N PIOT	
					Balancing Flow	Flow Type
Oilseed farming	5.30E+05	7.09E+05	-1.79E+05	33.75	1.79E+05	Imports
Soybean and Other Oil Seed Processing	4.10E+05	4.60E+05	-4.98E+04	12.14	4.98E+04	Stocks
Corn Farming	6.04E+05	7.63E+04	5.28E+05	87.37	5.28E+05	Exports
Wet Corn Milling	2.42E+04	2.42E+04	0.00E+00	0	NA	NA
Dry Corn Milling	4.33E+04	4.33E+04	0.00E+00	0	NA	NA
Wheat Farming	2.64E+04	1.03E+04	1.61E+04	60.99	1.61E+04	Consumption
Flour Milling & Malt Manu.	1.01E+04	5.51E+03	4.62E+03	45.62	4.62E+03	Exports
Other Animal Food Manu.	1.24E+05	5.01E+04	7.38E+04	59.56	7.38E+04	Exports
Dog & Cat Food Manu.	2.20E+02	0.00E+00	2.20E+02	100	2.20E+02	Consumption
Cattle Ranching & Farming	3.28E+03	3.28E+03	0.00E+00	0	NA	NA
Animal Production Except Cattle & Poultry Eggs	4.40E+04	4.40E+04	0.00E+00	0	NA	NA
Poultry & Egg Production	2.82E+03	2.82E+03	0.00E+00	0	NA	NA
Poultry Processing	2.82E+03	2.82E+03	0.00E+00	0	NA	NA
Animal (Except Poultry) Slaughtering & Processing	4.73E+04	4.73E+04	0.00E+00	0	NA	NA
Nitrogenous Fertilizer Manu.	0.00E+00	8.95E+05	-8.95E+05	100	NA	NA
Bread, bakery and product manu.	2.89E+03	0.00E+00	2.89E+03	100	2.89E+03	Consumption
Cookie, cracker and pasta manu.	9.64E+02	0.00E+00	9.64E+02	100	9.64E+02	Consumption
Snack food manu.	1.47E+03	0.00E+00	1.47E+03	100	1.47E+03	Consumption
Tortilla manu.	1.82E+02	0.00E+00	1.82E+02	100	1.82E+02	Consumption
Breakfast cereal manu.	1.86E+02	0.00E+00	1.86E+02	100	1.86E+02	Consumption
Frozen food manu.	2.55E+02	2.55E+02	0.00E+00	0	NA	NA
Vegetable and fruit canning & drying	2.14E+02	2.14E+02	0.00E+00	0	NA	NA

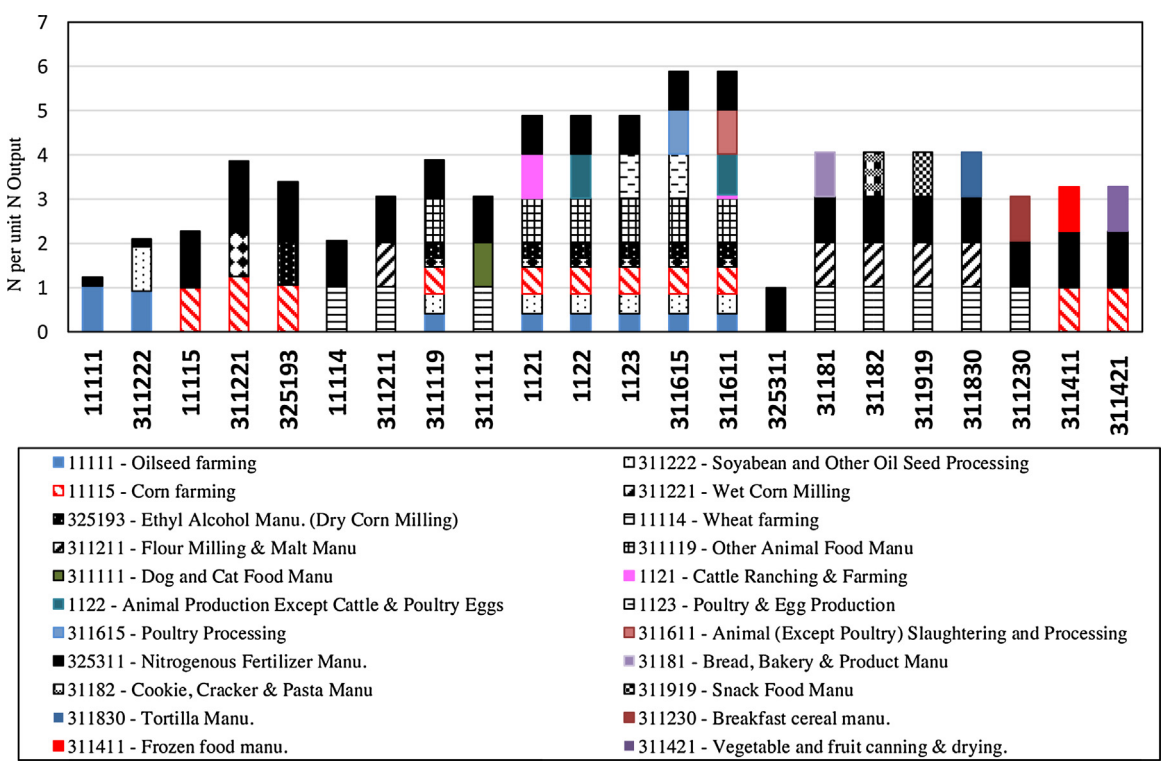

Fig. 2. Life Cycle N Throughput per Unit N Demand.
*Each bar shows TO_{new} for f_{new} = 1 from the respective sector using Eq. (3). TO_{new} is the total life cycle N required to support 1 unit of N product demand (f_{new}) from the sector.

ducing an unit of output from "Breakfast Cereal Manufacturing" than poultry. Information regarding the contributors of high N use can then be used to strategize improving the NUE of high N intensity products. In the case of Poultry meat (produced in sector 1123, Fig. 2), for example, reuse of manure in place of fertilizer can reduce the N demand by 0.86 unit of N per unit of output. However, the availability of manure is regionally concentrated (Yang et al., 2016), hence proves to be a logistic and economic challenge due to costs along with application restrictions to crop for human consumption

to avoid contamination (United States Department of Agriculture, 2017; Abdel-Mohsein and Mahmoud, 2015).

Similarly, switching to grass fed beef from corn fed beef (product of sector 1121) can reduce the N requirement by 1 unit per unit of output because replacing the N input from Animal Food Manufacturing (see contribution of sector 311119 to sector 1121) will have cascading impacts on requirement of N output from other farming sectors or milling sectors. Such PIOTs for various geographic regions can provide insights into optimizing N use regionally based on the specific NUE of a product in the region, which generally differs owing to production efficiency and operations of a particular region.

3.3. Life cycle emissions

Fig. 3 shows the total life cycle emissions to support 1 unit of final demand from each of the sectors in the current PIOT for Illinois, calculated using Eq. (4). The emissions that were included in the PIOT are: on farm N_2O Emissions from Corn, NO_3^- leaching and runoff from corn, soybean farming and wheat farming, N volatilized (AVOL) as NH_3 from Wheat and Soybean farming (See SI, Section 4 Table 9) and NO_3—N attached to sediment loss from Soybean farming and Wheat farming. The emissions from energy consumption in these sectors were not included, since the focus was on understanding the N losses that were input to the economy for production of N based products. N mobilization and loss by energy consumption is an auxiliary input for N economy, since the emissions are directly lost to environment and are not incorporated into any final product. Nonetheless, N emissions from energy consumption should be included for future studies, to provide a complete picture of damage caused by N losses to support the production.

4. Discussion

The N-PIOT developed for 2002 shows that corn, soybean, and wheat production consumes 86%, 11% and about 3% of N fertilizer, respectively. The share of release to the environment is highest during corn production, with about 21.8% of N fertilizer inputs being lost to water and air whereas the emissions share of the fertilizer inputs from soybean is 9.2% and from wheat is only 4.2% of emissions. The analysis on fate of N use entering the economy through these farming activities shows that corn farming exports 68% of N out of state embedded in products, 9% goes to animal feed manufacturing within the state and only 0.03% gets directly consumed as corn products within the state. Approximately 35% of the N input to soybean farming went to animal feed manufacturing within the state. The data also shows higher outputs of N from state than N input which is different than usual N balances on the farm or watershed scale where outputs are usually lower than the inputs reflecting N storage or postulated denitrification (Breemen et al., 2002). This is because the PIOT data collected was only for one year, the data on previous year stocks or imports were not available for all flows that contribute to production and exports possibly showing lower inputs than outputs. The current analysis of N flow structure (shown in Fig. 4) also revealed lack of recycling of N in Illinois that may be due to lack of reported re-use of manure on small scale farms or complete lack of recycling. There has been some estimation of livestock manure application rates at the county-scale, these values are generally "potential" manure application rates and do not reflect actual farm practices, hence we did not include these data for recycling estimates. As the economy moves towards better reutilization of waste, the PIOT can be updated accordingly to incorporate these feedback loops. Further, as the emissions from corn is larger than soybean, upstream industries can shift to lower emissions option such as soybean for products like animal feed manufacturing to derive same product benefits at lower ecological costs.

Due to a lack of availability of other N-PIOTs at state scale, the PIOT results and structure could not be directly compared to other existing work for N management. However, analyses based on N-PIOT have similar interpretation as studies that look at material flows in the production supply chain such as reactive N flows in the agriculturally-based production chain. A recent study for drivers of N footprint found about 7.1 unit of N flows per unit N output in grass fed beef (Liang et al., 2016), which is similar in magnitude to our values of 5.9 unit of N flow in Illinois economy per unit of N product from the Animal slaughtering sector. Even though these systems approaches are very different, it represents the high N intensity of animal meat production system. Another study reports about 3.9 kg of reactive N use/kg protein in beef production system for US (Eshel et al., 2014). This translates to about 24.37 kg Nr/kg N product in beef for US, which is much higher as compared to our intensity of about 6 units of N per unit of N output. This difference can be attributed to non-inclusion of pasture land contribution to N inputs in the animal farming system in our study, since the built PIOT only focused on feed from crop farming (corn, soybean and wheat). However, our efficiency numbers of about 17% is much closer to another recent study for beef and pork production in France, that reported an efficiency of 11% and 7% for production of retail products of beef and pork (Chatzimpiros and Barles, 2013). Since the commercial farming production systems track the flow through concentrated feed flow, these comparable numbers pertain to N flows due to concentrated feed inputs but ignore the pasture land inputs. The pasture land N inputs to beef production is almost equal to the concentrated feed inputs in US, as reported in (Eshel et al., 2014). The fertilizer consumption in Illinois calculated in this work was 8.95E + 05 Mt-N which was about 28% higher than the fertilizer sales data of 6.46E + 05 Mt-N (based on 11% growth from 2002 to 2003, and 2003 data was 7.17E + 05 Mt-N) reported by US-EPA (2017). However, the fertilizer consumption reported by USGS on county level gave total of 7.68E + 05 Mt-N (Gronberg and Spahr, 2012) which is about 14% lower than the value calculated in this work. The discrepancy can be attributed to lack of stock data for fertilizers which may also be used by farmers for consumption, but are reported in sales during a previous year. Also, the sales data from US-EPA do not report out of state purchase which also contribute to consumption near the state borders and accounted in the fertilizer consumption. Since, in our work, the consumption data for fertilizer is calculated based on USDA-NASS dataset (see SI), this estimate was assumed to be more accurate for N entering the economy than sales data. Hence, the N-PIOT numbers need further refinement to improve the accuracy of N intensity for production systems and current underestimation can be attributed to lack on inclusion of other livestock feed. Alfalfa is a significant source of livestock feed which was not included along with imports of livestock feed. Further, the intent of this work was to provide the interconnected physical flow model for N as resource in economy, rather than accurate N use in supply chain of single commodity, hence this discrepancy can be improved in future work as more data is collected. Regional boundary selection implies that the N-PIOT developed here is limited to analyzing environmental impact within the region boundaries. For example, the impact on total N flows in region 2 for consumption of meat in region 1 cannot be accounted by the PIOT model developed in this work. Since the focus here is on single region PIOT, the impact associated with imports that occur in the region of origin is not included. Such impacts can be captured by developing multiregional PIOTs which is out of scope for this work.

This work demonstrates use of N-PIOT as a technique for extending the vertical integration of economic and ecological systems for decision making in physical resource management such as N. A framework combining bottom up approach with MFA has been

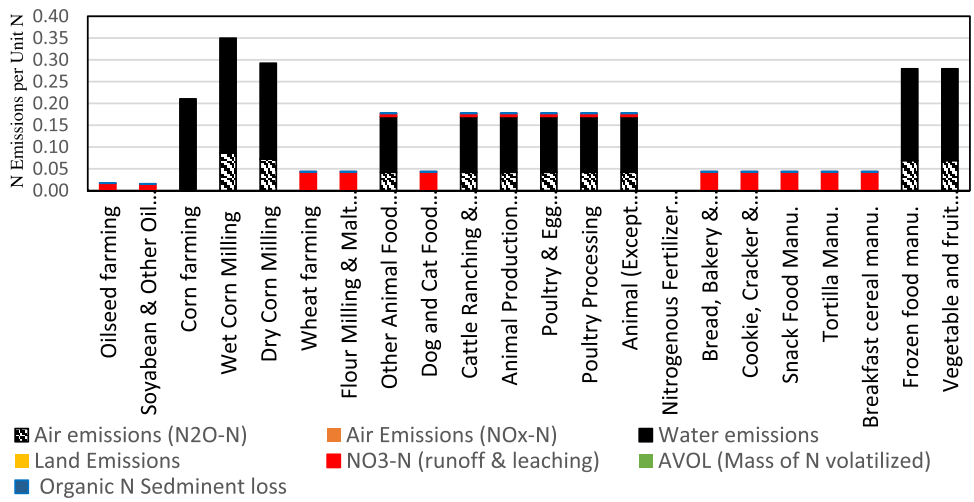

Fig. 3. Total Emissions for Per Unit N Demand from Sectors.
*Life Cycle Emissions include both direct and indirect emissions to support production from a sector. In this case, we only included farm scale emissions from corn, soybean and wheat, emissions from energy combustion is not included. This is the reason that some production sectors have only the indirect emission included, such as "Flour milling" only showing the indirect emission that comes from wheat farming due to consumption of wheat as input to flour milling.

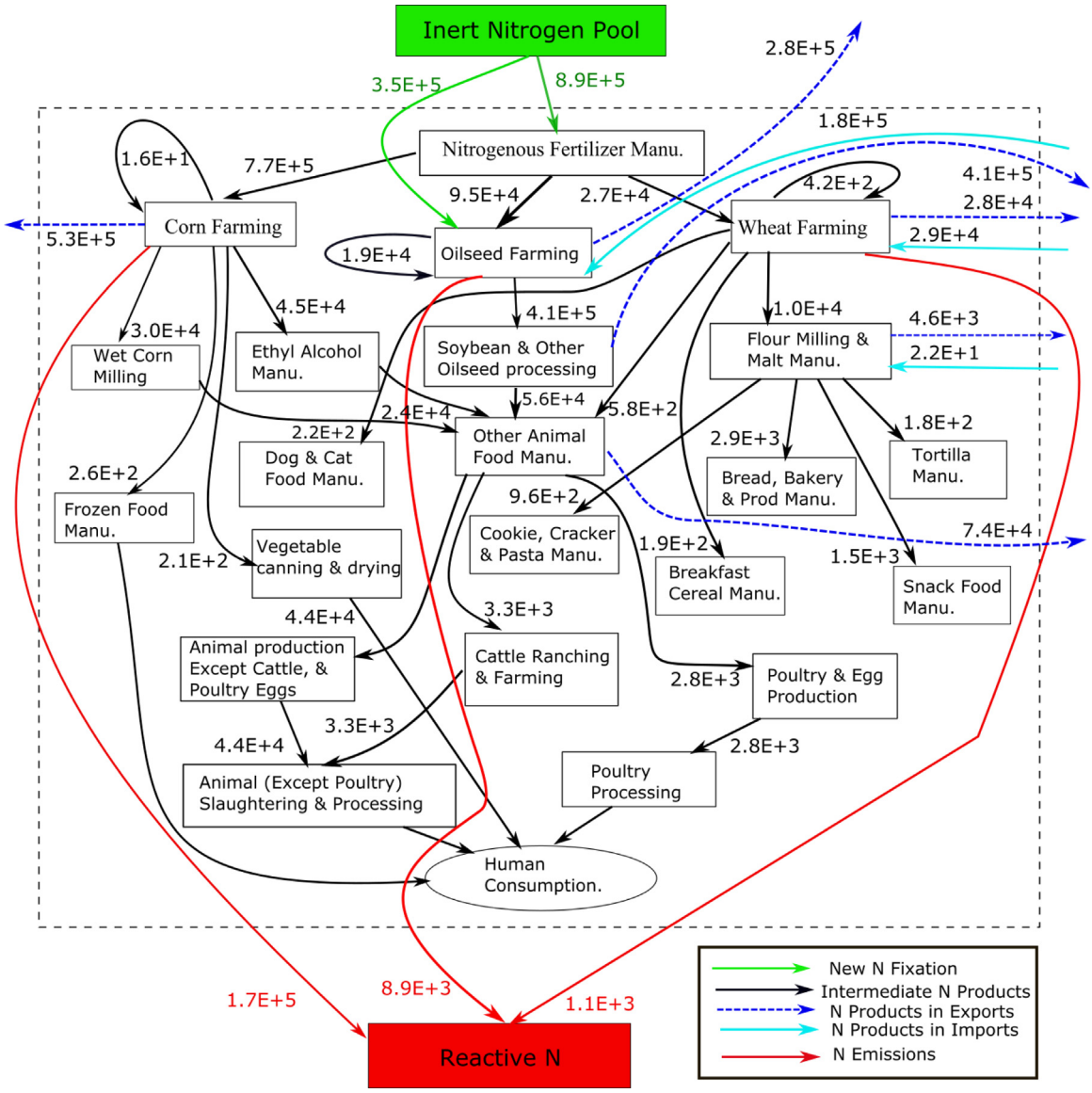

Fig. 4. Structure of N Cycle in Illinois Economy based on PIOT (N Flows linked to arrows in Mt-N/yr).

established for transparent development of regional N-PIOTs with Illinois as case study. This framework can also be adopted for development of N-PIOT in other states using similar flow sheets and adopting it for state specific economy. One of the limitations of the approach developed in this work is that PIOT developed by "bottom up" approach has not been mapped to Monetary Input-Output Table (MIOT) for Illinois; thus does not allow economic and physical analysis together. This would be a useful next step. Further, it also misses the indirect connections of these 22 sectors with the rest of the economy which occurs in form of other resource exchange. PIOTs can be criticized for this limitation because it only presents a partial picture of the economy in terms of the physical flow selected. For this reason, many researchers rely on mixed unit IO models (Hawkins et al., 2007). This limitation of partial representation is not an issue if the goal of developing PIOT is to focus on a particular resource management such as N here. However if the PIOT needs to be combined with MIOT, a mixed unit approach is suggested to enhance PIOT with "non-nitrogen" additional sectors. Despite the limitation of partial picture of the economy, N-PIOT provides a comprehensive insights into N utilization which allows to understand the opportunities for optimizing resource use.

The results from this work highlight that the potential benefits of developing N PIOT outweighs the time and effort cost because it provides detailed insights into the structure of N flows in the economic systems based on actual physical flow similar to the biogeochemical cycles of N in ecological systems. Improvement in methods to develop PIOT would enable adoption of these models to couple the production systems with ecosystems. This would enable physical coupling of ecological and economic systems in order to inform integrated management of N by decision makers.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolmodel.2017.06.015.

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