Economies of scale in farms and environmental inequalities through the lenses of nitrogen fertilizer use: Concept development

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Abstract
In this paper, we develop the framework of a system dynamics-based model for future studying the equity of resource distribution in rural areas, at a country scale and farm resolution. Our main hypothesis for conceptual development of the model is the following: the unequal spatial distribution of N fertilizer availability and use within a country might be linked to an unbalanced distribution of income to farms (in terms of farm size, i.e. economies of scale), which at the same time, might lead to exacerbated pollution. In such a context, our target variables are: nitrogen fertilizer use, farm size (both in land area and herd size) and emissions of NH_3, N_2O and CH_4, all disaggregated in a per-country basis. The Causal Loop Diagram (CLD) approach was used for this study, for visual representation of our 'model concept' on how target and intermediate variables are related. In order to allow future calibration and/or validation of the dynamic model, all variables utilized in construction of the CLD are commonly used indicators of social and rural development, economies of scale at farm level and environmental impacts. The representation of our model into a CLD revealed that a more sophisticated representation of wealth distribution in farms may be needed to extend beyond trivial outcomes in modelling effects of N fertilizer use.

Key Words
Smallholder farm; industrial farm; Gini index; pollutant emissions; causal loop diagrams; system dynamics modelling.

Introduction

The Haber-Bosch process for synthetic production of nitrogen (N) fertilizer is considered by many the most important invention of the 20th century (Smil, 2002). It is currently responsible for the production of more than 99% of all synthetic N fertilizer produced globally. The growth in world population is strongly linked to the increase in production and application of synthetic N fertilizer to soils, due to the greatly enhanced agricultural production it allowed (Erisman et al., 2008).

The growing availability of N fertilizers has been nurtured by ever decreasing marketing costs and rising food demand. This, combined with the fact that agricultural systems present, by nature, relatively low N use efficiencies led to excessive fertilizer use that is environmentally damaging (Sutton et al., 2013). According to the planetary boundary framework introduced by Rockström et al. (2009) and updated by Steffen et al. (2015) out of the nine planetary boundaries which describe the risk of human perturbations capable of destabilizing the Holocene state of Earth system, N losses due to human (especially agricultural) activities have by far transgressed the high risk zone.

Yet, the application of N fertilizer into crop fields, and the wealth benefits arriving from it, are currently unevenly distributed socially and geographically (Steffen et al., 2015). Multiple regions of the world face the deleterious effects of excess N use, while others perish with the lack of it. The unequal spatial distribution of N fertilizer availability and use might be linked to an economically unbalanced distribution of wealth among farms, which, in its turn, might lead to exacerbated pollution. For instance, the excessive application of N fertilizer in many European countries have led to deleterious consequences such as eutrophication of water bodies (Sutton et al., 2011) due to high levels of ammonia (NH_3) emissions, while the poor quality pasture systems in tropical developing regions, i.e. South America and Africa, lead to higher emissions of methane (CH_4) and nitrous oxide (N_2O) (Thornton and Herrero, 2010).

We consider economies of scale in farms as a proxy for assessing the social equity issue in rural areas, because small farms, or smallholders, critically differ from larger commercial farms in terms of access to capital, technology and resources that enhance operation efficiency of their agricultural systems.

Hence, the aim of this paper is to describe the framework of a system dynamics-based model for assessment of (un)equal distribution of N fertilizer as related to: (1) the (un)even distribution of income to farms (smallholders versus commercial farms) and (2) environmental pollution in terms of NH_3, N_2O and CH_4, emissions. Ultimately, the farm size-related difference in effects should, in turn, be integrated into desired models such as the GAINS model (Amann et al., 2011).

Method

First, a number of indicators of social and rural development, economies of scale at farm level and environmental impacts were listed, based on the availability of historical data disaggregated by country. The considered sources were the World Bank, FAOSTAT and EUROSTAT databases.
Next, a Causal Loop Diagram (CLD) was built, as to graphically represent the 'model concept' of which selected indicators are related and then, mathematical relationships were developed among the variables in the CLD.
The system dynamics software Vensim PLE ×32® has been utilized through the development stages of the model in this study.
In this study, we hypothesize that the scale (size) of a crop or livestock farm is directly proportional to income. Hence, one core aspect of this work is to represent farm size as a function of the distribution of income in the rural area. The Gini index (Ceriani and Verme, 2012) was chosen as a basis to calculate the percentages of the rural population belonging to three social strati: the rich or class 1, the medium and poor classes (classes 2 and 3, respectively).

Results and discussion

The disaggregation of the rural population into the three classes as a function of the rural Gini index is presented in Figure 1, and the mathematical relationships utilized are presented by equations 4 to 6 in Table 1. The relationships in Figure 1 are hypothetical and were created to fit the concept of Gini index in three income classes.

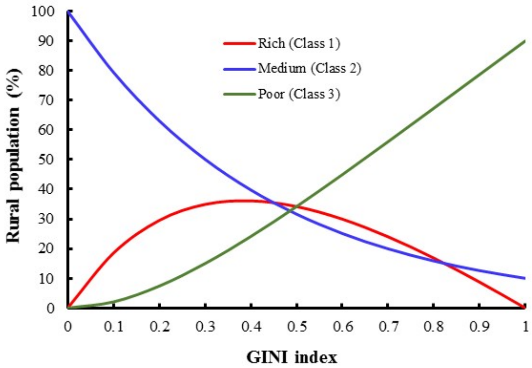

Figure 1. Disaggregation of total rural population into rich, medium and poor classes as a function of the Gini index.

The patterns of Figure 1 indicate that lower Gini values led to a higher percentage of the population belonging to class 2 (equal income distribution). At around 0.5, equal amounts of the population were allocated to all three social classes, while at higher Gini values, poverty prevails. These outcomes indicate that the chosen modelling approach for social stratification agrees well with the concept of inequality embedded in the Gini index.

A CLD was developed, and presented in Figure 2. We started by disaggregating country agricultural land into permanent cropland and pasture land. Both the number and area of farms in a certain income class are explained as a proportion to the total available cropland area and the rural population allocated in each class, as defined in the previous paragraph. A similar procedure was applied to pasture lands, for ruminant farms, i.e., the number and average herd size of a ruminant farm in each class was a function to the respective class population and the available pasture land area. Because monogastric animals are usually kept under confinement, the calculation of herd size was done independent from the livestock farm area.

We then relate livestock manure production in each class to livestock farm size and number, from both ruminant and monogastric species. From the crop farms, we derive the total amount of synthetic N fertilizer utilized from number and size of crop farms. We then connect manure and synthetic N to a single box for total fertilizer applied. From this variable, we flow into total crop production in each class. For the pasture land size we derive livestock production per class. Both crop and livestock productions are connected to food and feed stocks.

Gaseous emissions of CH_4 per class are linked to livestock production and emissions of N_2O and NH_3 to fertilizer use. Accounting for gaseous emissions in a per-size class basis will allow to examine whether or not the unequal distribution of wealth is directly or inversely proportional to farm environmental impact.

We consider that the relative cost of synthetic N fertilizer is key to its allocation across the farm classes. Hence, access to this resource per size class will be accounted as a proportion of the agricultural GDP available to each social class, calculated with Gini, similar to what was done with population disaggregation (formulas 7 to 9).

The next step of this study is the conversion of the developed CLD into a Stocks and Flow Diagram (SFD), which will actually allow dynamic quantification of the processes. Quantitative outcomes from the dynamic model will be compared to time series available in published databases.

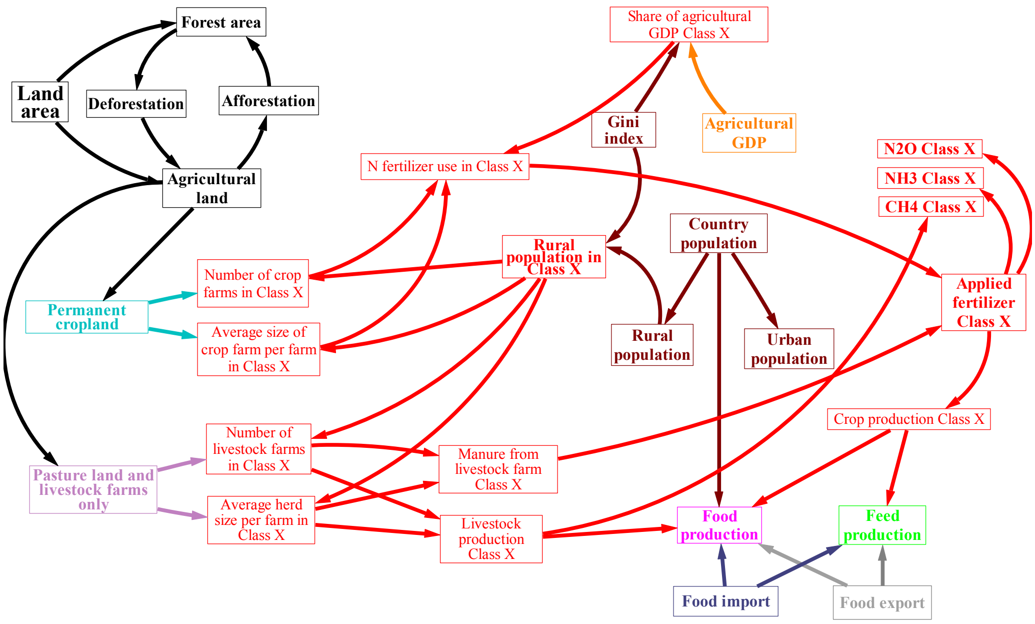

Figure 2. Causal Loop Diagram (CLD) for the relations among considered indicators. Main aspects are farm size in classes 1, 2 and 3 (represented by the letter "X"), N fertilizer input and emissions of the gaseous pollutants NH_3, N_2O and CH_4. Arrows leaving a box indicate the variable as 'explaining' and arrows arriving at a box indicate the variable 'explained by'. The actual mathematical relationships among variables are presented in table 1.

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Table 1. Equations that represent the relationships of the LCD. The equations presented here explain the general relationships, and consistency of units may not hold. Beta coefficients to be determined

$\text{Forest area} = \text{Land area - Agricultural land} \times \left(\text{Deforestation - Afforestation}\right)$	1*
$\text{Agricultural land} = \text{Permanent cropland} + \text{Pasture land}$	2
$\text{Rural population} = \text{Country population - Urban population}$	3
$\text{Medium class rural population} = \text{Rural population} \times 0.1^{\text{GINI index}}$	4
$\text{Poor rural population} = (\text{Rural population} - \text{Medium class rural population}) \times \text{Gini index}$	5
$\text{Rich rural population} = \text{Rural population} - \text{Medium class rural population} - \text{Poor rural population}$	6
$\text{Share Agr. GDP Class 2} = \text{Agr. GDP} \times 0.1^{\text{GINI index}}$	7
$\text{Share Agr. GDP Class 1} = \left(\text{Agr. GDP - Share Agr. GDP Class 2}\right) \times \text{GINI index}$	8
$\text{Share Agr. GDP Class 3} = \text{Agr. GDP - Share Agr. GDP Class 2 - Share Agr. GDP Class 1}$	9
$\text{Number of crop farms Class i} = \beta_{2,i} \times \text{Permanent cropland} / \text{Population Class i}$	10
$\text{Average size of crop farm per farm Class i} = \beta_{3,i} \times \text{Permanent cropland} / \text{Population Class i}$	11
$\text{Number of livestock farms Class i} = \beta_{4,i} \times \text{Pasture land} \times \text{Population Class i}$	12
$\text{Average herd size per farm Class i} = \beta_{5,i} \times \text{Pasture land} / \text{Population Class i}$	13
$\text{N fertilizer use Class i} = \beta_{6,i} \times \text{Number of crop farms in Class i} \times \text{Avg. size of farm per farm Class i} \times \text{Share Agr. GDP Class i}$	14
$\text{Man. prod. livest. farms Class i} = \beta_{7,i} \times \text{Number of livest. farms Class i} \times \text{Avg. herd size per farm Class i}$	15
$\text{Livestock prod. Class i} = \beta_{8,i} \times \text{Number of livest. farms Class i} \times \text{Avg. herd size per farm Class i}$	16
$\text{Applied fertilizer farms Class i} = \text{N fertilizer use Class i} + \beta_{9,i} \times \left(\text{Man. prod. livest. farms Class i}\right)$	17
$\text{Crop production Class i} = \beta_{10,i} \times \text{Applied fertilizer farms Class i}$	18
$\text{Food production} = \beta_{11,i} \times \text{Country pop.} \times \left(\begin{array}{l}\left(\sum_{i=1}^{3} \text{Livestock production Class i}\right) + \\ \left(\sum_{i=1}^{3} \text{Crop production Class i}\right)\end{array}\right) \text{- Food imp.} + \text{Food exp.}$	19
$\text{Feed production} = \beta_{12,i} \times \left(\sum_{i=1}^{3} \text{Crop production Class i}\right) \text{- Feed import} + \text{Feed export}$	20
$N_2O \text{ Class i} = \beta_{13,i} \times \text{Applied fertilizer Class i}$	21
$NH_3 \text{ Class i} = \beta_{14,i} \times \text{Applied fertilizer Class i}$	22
$CH_4 \text{ Class i} = \beta_{15,i} \times \text{Livestock production Class i}$	23

*For the sake of simplicity, we do not consider the share of land use for dwellings or infrastructure.