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PERSPECTIVE

MANURE AND METROPOLES—A GLOBAL FRAMEWORK FOR NUTRIENT CYCLING IN FOOD SYSTEMS

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1 INTRODUCTION

Nutrient supply, in combination with water supply and soil quality are key for efficient crop production. As many of the nutrients, except N, have to be mined and are finite resources, the recirculation of nutrients is essential to maintain soil fertility and food production. Consequently nutrient management in agrifood systems is not only a matter of supply, but also of reusing nutrients.

On a global scale, human and livestock populations are both increasing. For the human population, the strongest increase of population is occurring in urban areas (due to population growth and migration). Large scale livestock systems tend to be developed close to these urban areas, where the markets and the consumers are. Historically, the demand for fresh products (hard to transport) and availability of co-products from the food industry have contributed to this. These days so called agglomeration effects (cluster effects due to specialization and deep labor markets) also have a role[1,2], which makes it attractive to transport feed instead of end products, although it requires large transport volumes. This concentration is enabled by global free trade, in which feed and livestock products are transported around the globe[3].

With the concentration of livestock systems, environmental and health issues arise; excessive manure production and local pollution from nitrogen emission endanger biodiversity, and fine particulate matter $PM_{2.5}$), odor and risk on zoonoses can lead to negative consequences for the welfare of people living in the surrounding area. With the perspective for recirculating nutrients, questions about the concentration and location of livestock production are relevant; nutrients from plant production are transported to livestock production areas which are concentrated spatial, but the return flow of nutrients for fertilization is complicated. However, this is not only valid for livestock, but also for humans; where do the nutrients from human consumption of plant and animal products end up?

This discussion paper tries to understand the driving factors behind livestock and feed production locations and nutrient-transportations around the world. Understanding the driving factors can help to think about potential solutions and their relative merits.

This paper is based on a Dutch report[4] from Wageningen University and Research and was commissioned by the Dutch Ministry of Agriculture, Nature and Food Quality.

2 THE LIVESTOCK REVOLUTION

The so called livestock revolution[3] has occurred in many industrialized countries and is now happening in many emerging and less industrialized countries. The main characteristics of this transition are (1) strong growth in number of livestock, (2) rationalization of production, (3) specialization and agglomeration of livestock systems (especially pigs and chickens), (4) strong increase in trade in feed and livestock products, and (5) strong improvement in feeding and breeding and as a consequence of that a large increase in productivity per animal for a unit of labor input. At a global scale, cattle numbers in 2012–2016 were 150% of those in 1961–1965, while pigs and chickens increased to 249% and 575% respectively, compared to 1961–1965. In the meantime, also population densities and total livestock densities have increased. For example, livestock densities in the Netherlands and China increased faster than population densities, while in Bangladesh and Ethiopia population densities increased faster than livestock densities[5,6] (Table 1).

When comparing population and livestock densities by country for the same time period[6] the following can be observed for 1961–1965 (Fig. 1(a)): (1) most countries have a low population density and low livestock densities (Fig. 1(a), lower left quadrant); (2) a few countries have relative high population densities and high livestock densities; (3) a couple of countries have high population densities, but low livestock densities; and (4) no countries combining a low population density with a high livestock density were identified.

When looking at a more recent snapshot (2012–2016) of these densities, these observations are more pronounced (Fig. 1(b)) than in 1961–1965. All countries seem to have shifted upwards and to the right; higher population densities and higher livestock densities. This can be explained by population growth and an increase in the total number of animals in livestock systems worldwide.

Both graphs are separated into four quadrants, divided by population density of 150 humans km^{-2}, and 150 livestock unit (LSU) km^{-2} of agricultural area[7]. The 150 population density km^{-2} is the average population density worldwide km^{-2} in 2012–2016. The 150 LSU·km^{-2} of agricultural land is based on a closed nutrient cycle of phosphorous, where P-excretion is 40 kg·LSU^{-1} and an average crop uptake of 60 kg·ha^{-1}·yr^{-1}, following a

Table 1 Indexes of human and livestock densities in 2012–2016 by country, with 1961–1965 as a reference period with an index of 100

Country	Index human population density in 2012–2016 compared to 1961–1965	Index livestock density in 2012–2016 compared to 1961–1965
Bangladesh	316	165
China	135	220
Ethiopia	705	330
The Netherlands	175	220

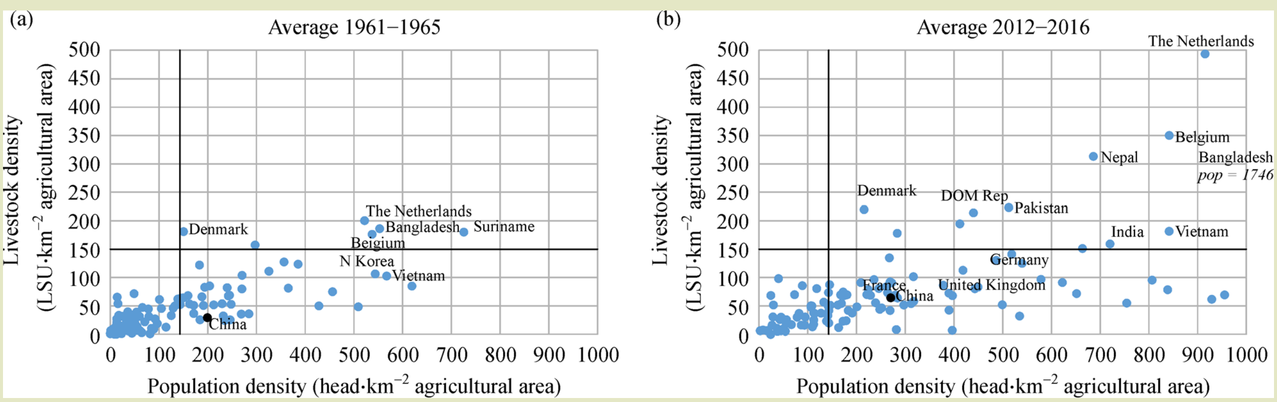

Fig. 1 Livestock and population densities by country: averages for 1961–1965 (a) and the period 2012–2016 (b). The *x*-axis shows the population densities km^{-2} in a country, the *y*-axis the livestock density (in livestock unit, LSU) km^{-2} of agricultural land in a country (authors own graph, based on data from Eurostat[5] and FAOstat[6]).

similar approach as done by Liu and colleagues[8]. At this level of livestock density, all animal manure can be placed on crops while not exceeding the crop requirements. Each of these quadrants can be described based on the characteristics regarding land use, economy and infrastructure of countries that are situated in a specific quadrant. By doing this, the four quadrants can be conceptualized and labeled.

3 A FRAMEWORK OF AGRIFOOD REGIONS

Figure 2 summarizes a global framework for agrifood systems within the four quadrants and the main characteristics of countries in these quadrants.

I Delta. This quadrant is designated Delta, because the countries present in this quadrant are mostly situated in deltas. It is characterized by high population and high livestock densities. Countries in the Delta quadrant have high skilled laborers and an excellent infrastructure due to rivers and seaports, which facilitates the import and export of all sorts of goods. Since countries in the Delta quadrant have an extended livestock industry, but low availability of land due to competition, feed needs to be imported from other regions. Animal products are consumed within the delta itself, but also exported to other regions. There is a strong competition for land, driving up prices and technical efficiency of agricultural production. Environmental problems, due to high livestock densities and accumulation of manure are a matter of concern in industrialized countries, rather than in developing countries. Food security and livelihoods are policy priorities in the latter[9].

II Metropole. Countries in this quadrant have the character of a metropolitan region, with a high population density but a low livestock density. The service economy is extended while livestock production is low. So countries in the Metropole quadrant need to import most of its animal based food.

III Hinterland. Countries in this quadrant have low population and livestock densities. Costs of land and labor are low. The main activity in the countries in the Hinterland quadrant are the production of crops for food, and depending on land productivity and the use of inputs, feed is produced as bulk products for export. The most important exporters are located in North and South America. Due to the low level of fertilizer inputs and the absence of large scale enterprises, African countries are net importers.

IV Intensive livestock. As shown in Fig. 1, in the real world there are no countries situated in this quadrant, with low population density but high animal density. However, we can still describe the characteristics in concept. Countries in the Intensive Livestock quadrant would focus on livestock production for export, fed with its own regional feed production. There would be enough room for feed productions, since relatively little land is required for local food consumption.

When considering the transport of agricultural products between countries, several nutrient flows can be determined:

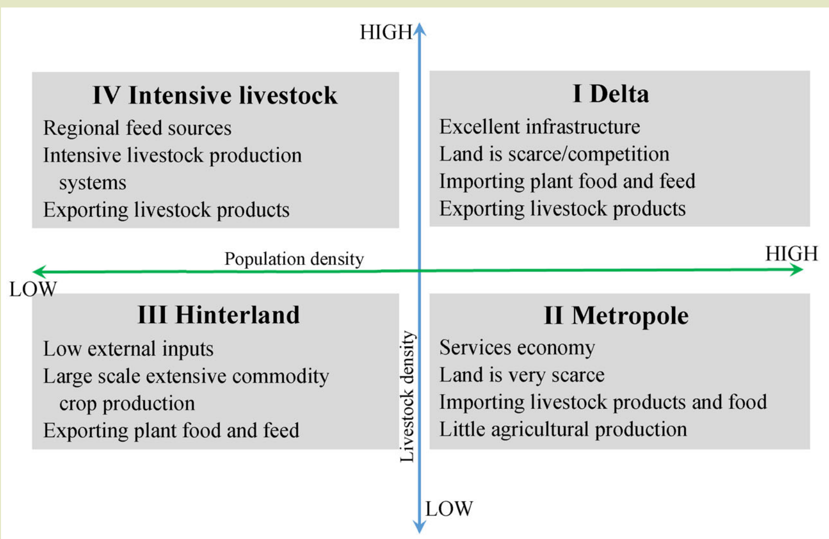

Fig. 2 Global framework of agrifood systems with four quadrants and the main characteristics of countries in these quadrants.

(1) feed transport from the countries in Hinterland to the Delta quadrants,

(2) livestock products from countries in Delta quadrant to (mainly) those in Metropole quadrant, and

(3) livestock products from countries in the Intensive Livestock quadrant to (mainly) those in the Metropole quadrant; this flow is not present in the world, since no countries occur in this quadrant.

The first two flows are present in real life. For example, the Netherlands, a Delta country, imports a lot of feed (mainly soy) from Brazil, a Hinterland country, and exports livestock products to Germany and the UK, Metropole countries. These flows of products (nutrients) is linear and not at all circular. In Delta countries, feed is converted to products and manure. The products are consumed or exported, but most of the manure accumulates and is applied to local soils, leading to water quality issues and biodiversity threats. As a response, manure policies have been developed and manure export is sometimes mandatory.

Nutrient depletion will take place in Hinterland countries since feed is exported and no return of nutrients via livestock manure is organized. In Delta and Metropolitan countries nutrients accumulate from human excreta from the consumption of livestock and plant products. Organizing recirculation and reuse of nutrients implies that nutrients coming from imported feed to the livestock systems, need to be returned to the feed producing areas for fertilization. In addition, the nutrients from the livestock products need to be recovered from the human waste system to close the nutrient cycle and prevent losses. As mentioned above, livestock concentrations are not only a nutrient related matter, but there are also environmental and health issues caused by the intensive livestock production systems, especially close to cities and vulnerable nature areas. These issues are not solved by just recycling nutrients to the feed-producing countries.

4 TWO POTENTIAL DIRECTIONS FOR SOLUTIONS

There are two imaginable but drastic solutions to convert this linear relationship of nutrients into a circular one. For each solutions, it is also the question to what extent the environmental and human health issues can be solved.

4.1 Organizing return flows of manure and excreta

In this technical solution pathway, current flows of nutrients continue, but two extra flows of nutrients are instigated. The first one is in the form of nutrients that are recovered from the livestock manure in Delta countries and transported back to Hinterland countries; the second flow are nutrients recovered from the human waste system in Delta and Metropole countries that are returned to Hinterland countries. The recovery of nutrients from manure and human waste requires large investment in technology to do this efficiently and the organization of the return transport to Hinterland countries will be costly. However, the advantages are that Delta countries, with its high efficient and knowledge intensive livestock sector will remain highly productive and no assets are depreciated. Local environmental and health risks related to gaseous emissions to air may not be solved in this technical solution pathway, since livestock and humans are still living close to each other in high densities.

4.2 Reorganizing trade systems and, with it, livestock systems

In this solution pathway the goal is that intensive livestock systems become self-sufficient regarding feed. This would mean that the volume of the livestock systems in Delta countries become much smaller, since the amount of livestock is dependent on the amount of feed produced in these countries. This amount will be limited, due to land competition and low financial yields of feed crops. So feed import and export ceases, which results in increasing feed supply in Hinterland countries. Assuming worldwide consumption of animal products is stable and transport of these products is widely possible, the Hinterland countries can use there feed supplies to develop their own livestock systems and start producing livestock products for export. These exports would go to countries with high population densities where the products are consumed. The nutrients from human consumptions still need to be recovered and returned to the feed producing countries.

Implementing this solution pathway would mean that regions will shift to another quadrant. The Delta countries would experience a decrease in livestock density, moving them toward the Metropole quadrant. The Hinterland counties would increase their livestock densities, moving them toward the Intensive Livestock quadrant. Positive effects can be found in the reduction of health issues for humans caused by livestock, because livestock is now kept in the low populated Intensive Livestock countries. The Delta countries also solve its manure stocks effectively because the number of livestock is greatly reduced. Whether environmental problems on a global scale will be diminished is uncertain, since it can be expected that in the Intensive Livestock countries, livestock production will be concentrated, such as the current feedlots in the USA. Furthermore, the current livestock system in the Delta countries are economically scaled, knowledge intensive and operated by highly skilled people. It is uncertain whether the same benefits and skilled laborers are available in the Hinterlands/Intensive Livestock countries. Certainly, the Delta countries loses a significant industry, with depreciation of assets as a result, but gains a reduction in health issues and local environmental problems from livestock systems and extensive nutrients stocks.

5 THE WAY FORWARD

Both solutions require the recovery of nutrients from human waste in Delta and Metropole countries to be exported to feed growing Hinterland and Intensive Livestock countries for recycling and reuse. Furthermore, an essential element of the recycling of nutrients in all quadrants and systems is first the collection and storage of manure, and second attention to manure quality and safety. For example, the presence of nutrients in the right amounts and the absence of negative elements, such as heavy metals and pharmaceuticals. This aspect is not elaborated further here, but is considered as key in reusing waste.

To make a profound decision about which solution is most suitable with respect to nutrient cycling, economics, human health and environmental issues, the solutions and their side effects must be thoroughly explored, including:

• Further exploration of economic costs and benefits of the current situation and the two solutions. Think about infrastructure, spreading of risks and economies of scale.

• In depth study of spatial differentiation. In our analysis, countries are taken as entities, while we actually want to look at regional, and sometimes transboundary-regions, in which Delta countries and the other quadrant countries normally occur. This will result in different classification within the quadrants, in which, perhaps examples of Intensive Livestock context will be identified.

• Quantification of the total amounts of transported products, feed and nutrients for the current system and the two solutions, and of the associated broader impacts on the United Nations Sustainable Development Goals.

• Governance; how to arrange these shifts in trade and economies that both solutions require?

Our conceptual framework provides insight in the existing relationships and nutrients flows between very different countries around the world. This concept will also help to understand what will happen if we want to organize the required recycling of nutrients in the agrifood system. It may be clear that both solutions require large structural changes of economies and governance, and that the current system is shown to be unsustainable as well.

Compliance with ethics guidelines

Daan Verstand, Theun Vellinga, Krijn Poppe, and Pieter de Wolf declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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