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Nitrogen metabolism of an Indian village based on the comparative agriculture approach: how characterizing social diversity is essential for understanding crop-livestock integration

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Highlights

- Despite its importance, the integration of social diversity in environmental assessment remains challenging due to the lack of adequate frameworks
- We combined *comparative agriculture* and *territorial metabolism* to study nitrogen flows at village level in Petlad, India
- N surpluses were large, mostly lost to the environment, and crop-livestock interactions remained limited in spite of great potential
- Large socio-economic contrasts, with diverging objectives amongst farmers' categories, hamper developing synergies between systems
- The framework proposed here showed potential to improve research on the environmental impacts of agriculture

ABSTRACT

CONTEXT

Addressing the environmental impact of agriculture requires a comprehensive analysis of the system at stake, and accounting for the social diversity (i.e. social groups involved in farming and relationships between them) is particularly important for designing efficient policies aimed at mitigating these impacts. However, the integration of this diversity in environmental assessments remains challenging, partly due to the lack of frameworks for combining data and concepts belonging to bio-technical and social sciences.

OBJECTIVE

In this study, we aimed at assessing how the combination of the conceptual frameworks of *comparative agriculture* and *territorial metabolism* helps to better understand the environmental impacts of agriculture. In particular, we look at the crop-livestock integration as a possible way to reduce nitrogen losses from agriculture, and study how social diversity shapes this integration.

METHODS

Combining comparative agriculture and territorial metabolism frameworks, we carried out an intensive fieldwork in Petlad (Gujarat, India) organized in four steps so as to successively (i) capture farm diversity at the micro-regional level, (ii) build archetypes representing farming systems, (iii) assess nitrogen flows at farming systems' level and (iv) model nitrogen metabolism at village level.

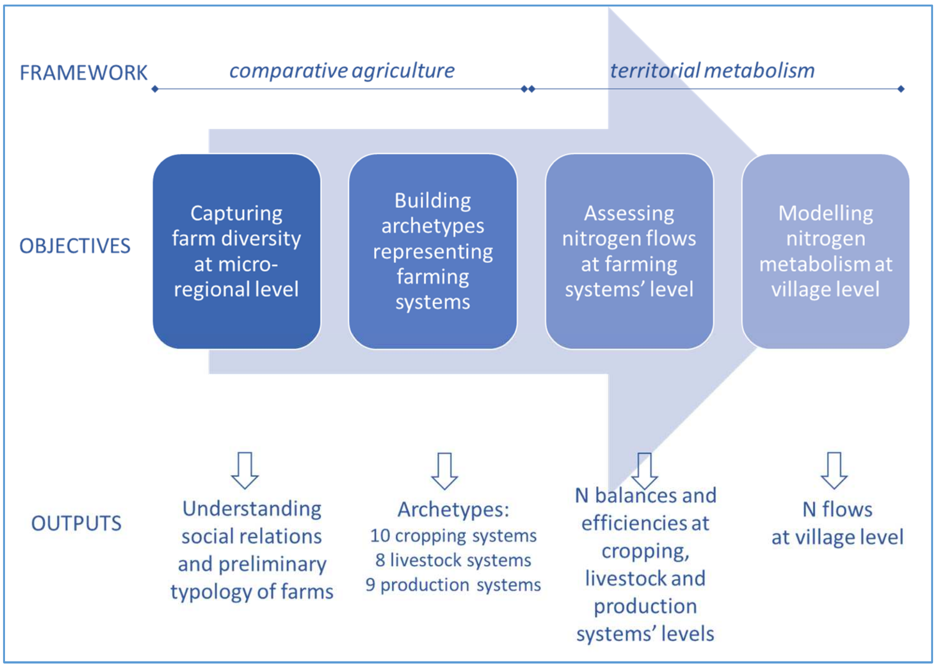
RESULTS AND CONCLUSIONS

We found that despite obvious potential, crop-livestock interactions were limited, accounting for minor nitrogen flows compared to the flow of inputs, mainly synthetic fertilizers and feed concentrates. The output flows, mainly tobacco, cereals and milk, were also low and most of the input nitrogen was lost to the environment (surplus of over 600 kg N/ha from the cropping system balance), contributing to pollution. While large subsidies for synthetic fertilisers had a role in the development of such huge surpluses, our study showed that this environmentally harmful situation was also influenced by the existing socio-economic conditions and social relations in Petlad. Most of the owners who had sufficient access to land (>1 ha) focused on the very profitable tobacco production and tended to abandon livestock, which they no longer needed either technically or economically. Conversely, households with low or no access to land were motivated to raise dairy animals, in order to supplement small incomes from crops, but faced difficulties in feeding them. We conclude that promoting crop-livestock integration as a potential lever to reduce nitrogen surplus would be unlikely to succeed in the presence of such a strong social lock-in.

SIGNIFICANCE

Concurring with certain critiques of socio-ecological systems approaches, this result advocates for a better consideration of social diversity in the analysis of the environmental impacts of agriculture and in the design of interventions.

GRAPHICAL ABSTRACT



Keywords: crop-livestock interaction; comparative agriculture; nitrogen metabolism; farm diversity; Indian agriculture

1. Introduction

Addressing the environmental impacts of agriculture requires taking into account the diversity of farms. Indeed, assessments carried out at the scale of large regions and based on the study of an average farm are well suited for globally characterising a situation and attracting the attention of policy makers to certain issues, but they are inadequate when it comes to defining actions to be implemented at the farm level (Scoones and Toulmin, 1998). For this purpose, analyses at a finer scale and taking into account diversity are needed (Ramisch, 2005; Giller et al., 2011; Chikowo et al., 2014). First, considering farm diversity makes it possible to understand the environmental impacts of different farms and to identify the most effective ones (Bassanino et al., 2007). This then permits environmental analyses to be carried out at the level of a group of farms (Carmona et al., 2010; Righi et al., 2011), taking into account possible flows between farms such as crop residue and manure (Diarisso et al., 2015; Grillot et al., 2018). Finally, as the farm constitutes a key decisional level for changes in production choices and agricultural practices, it is necessary to include this diversity when supporting transitions: differentiated drivers of change between farms can thus be highlighted and serve as a basis to formulate more efficient targeted policies or projects (Andersen et al., 2007).

Accounting for this diversity, however, is not an easy task and can be time-consuming given the complexity of farming systems and the multiplicity of the interactions involved in their functionning (Lacoste et al., 2018; Hammond et al., 2020). Farm typologies are interesting for the global vision of the fabric of the farms they are based on and different methods exist to construct them (Landais, 1998; Righi et al., 2011; Alvarez et al., 2018; Berre et al., 2019; Tittonnel et al., 2020). Nonetheless, because typologies generally consist in stratifying the farming households according to individual attributes (resource endowments, production choices and sources of incomes being the most often considered attributes), they alone are not sufficient to describe the functional and social links between farms. Multi-agent modelling is a step forward in this respect, since it makes it possible, for example, to spatialise material flows between farms (Berre et al., 2021), to consider different levels of social organization in ecosystem management decisions (Bousquet and Le Page, 2004) or to take account of farmers' networks in production choices (Xu et al., 2020). The simplifications made to meet the modelling objective, however, compromise the integration of the often complex social relationships that govern many rural societies. The *comparative agriculture* approach was developed from the 1960s onwards to study and compare agricultural development processes from different parts of the world and different historical periods (Cochet, 2015a). Its main originality is to jointly examine the biotechnical and socio-economic changes that shape agricultural development processes at different scales (Dufumier, 2007). To do so, it has developpped a conceptual framework at the interface between the bio-technical and social sciences. This approach allows not only to grasp the diversity of farms and their functional interactions at the scale of a territory, but also to situate this diversity in the environmental, historical and social conditions under which they were developed (Cochet, 2015a), and thus address what we call “social diversity”. The latter refers to the diversity of farmers who are part of different social groups, and to the social relations that bind them around land, labour exchanges and the resulting levels of remuneration, flows of matter and produce or debt. Comparative agriculture has often been used to understand the relationships between farming societies and their environment (e.g. Torquebiau et al., 2010; Leauthaud et al., 2013; Lacoste et al., 2016), but environmental assessments based on this approach are still scarce (e.g. Moreau et al., 2012).

Crop-livestock integration has long been acknowledged as a major lever to develop agricultural environmental sustainability (Devendra and Thomas, 2002; Herrero et al., 2010; Gonzalez-Garcia et al., 2012). The use of manure and animal power in the cultivation process, of crop residue as feed, and the management of the links between cultivated and grazing areas in a territory can reduce the environmental impact of agriculture (Schiere et al., 2002; Gliessman, 2014; Lemaire et al., 2014; Salton et al., 2014). These practices potentially reduce the consumption of external inputs into the production process and better regulate biogeochemical cycles (C, N, P), thus limiting flows towards the hydrosphere and the atmosphere (Dumont et al., 2013). Crop-livestock integration can be achieved not only at farm level but also at landscape or regional scales by enhancing farm complementarity (Lemaire et al., 2014; Peyraud et al., 2014). However, such scales increase the biophysical and socio-economic complexity of the system, and, going back to the issue of diversity, adequate approaches are required to encompass this complexity (Moraine et al., 2017).

India is a particularly interesting country to study crop-livestock interaction, as historically, the integration of the two activities played a key role (Aubron et al., 2019). The green (for crops) and white (for milk) revolutions of the 1970s (Dorin and Landy, 2009) encouraged more specialized production systems, but the potential for integrating these two dynamics is, *a priori*, vast (Erenstein and Thorpe, 2010). The stakes are high, as agricultural intensification has major environmental consequences, particularly in terms of nitrogen pollution (Agrawal et al., 1999; Buvaneshwari et al., 2017). Besides, rural societies in India are marked by strong contrasts in access to land (Pouchepadass, 2006; Rawal, 2008) that place the issue of social diversity at the heart of its agricultural development.

In this context, we aim at demonstrating the interest of combining the conceptual frameworks of comparative agriculture with that of *territorial metabolism*, a systemic and multi-criteria assessment method allowing qualitative and quantitative analyses of the transfer, storage and transformation of matter within a territory (Barles, 2010; Bonaudo et al., 2016). We applied these combined frameworks to model and analyse nitrogen flows at the scale of a village (360 households, 218 ha of agricultural land) while considering the local diversity of farming systems. In particular, we looked at the crop-livestock integration as a possible way to reduce nitrogen losses from agriculture, and studied how social diversity impacts this integration. The choice of nitrogen was driven by the fact that it is a powerful "marker" of the impact of human activity, agriculture in particular (Billen et al., 2014): losses can occur during the different phases of the "nitrogen cascade" and can affect every compartment of the environment (Galloway et al., 2003).

The study focused on a small region in the northwest of India, Petlad block, in Anand district, Gujarat state. Like most alluvial zones in the Indian subcontinent, Petlad underwent a green revolution from the 70s onwards, which translated into the extension of irrigated crops, particularly tobacco, to the majority of the block's surface. In addition, dairy farming is prominent in Petlad, as it is located in the collection zone of the Amul milk cooperative which inspired the white revolution in India and went on to be a model for the implementation of other milk cooperatives in the rest of the country. Today the animal density – cattle and buffalos – is among the highest in the world (Gilbert et al., 2018).

2. Methods

2.1. Capturing farm diversity at the micro-regional level

The comparative agriculture framework combines three interlocked scales of analysis, using specific concepts for each: the "agrarian system" (Mazoyer and Roudart, 2006) at the village, region or country level; the "production system" (PS) at the farm level; and the "cropping system" (CS) or "livestock farming system" (LFS) at the plot or herd level (Cochet, 2012; see Supplementary materials part I for detailed definitions).

Disparities between farmers in access to resources structure the choices of production and practices and play a key-role in agricultural development processes (Dufumier, 2007). Capturing the diversity of farms is thus an essential step of the research in comparative agriculture. At the regional level, this is done through the combination of: (i) the characterization of ecosystem resources, which at least partly define what can be produced, how, when and where; (ii) the reconstitution of the agrarian history and the farm differentiation process over the last five decades (Cochet and Devienne, 2006; Lacoste et al., 2018). Both analyses were achieved in Petlad through a two-month fieldwork and led to a first typology of farms (figure 1).

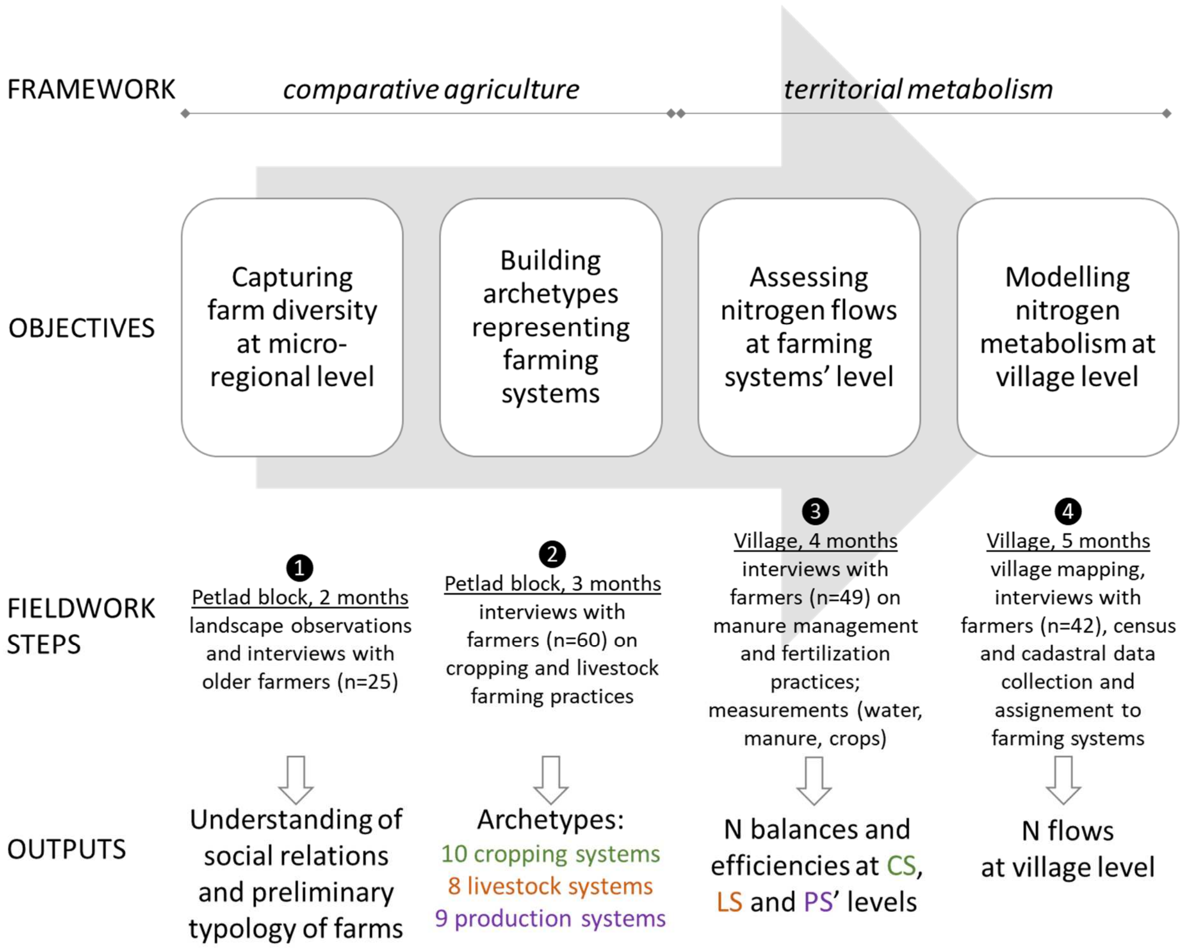


Fig. 1. Research process in Petlad: frameworks, objectives, fieldwork steps and outputs

2.2. Building archetypes to represent and assess farming systems

To gain a more precise understanding of the practices implemented by the different categories of farmers, we carried out in-depth interviews with active farmers during two successive fieldwork steps (steps 2 and 3, figure 1). Respondents were selected progressively so as to cover the pre-identified diversity, which was gradually refined.

This was used to build three kinds of archetypes (Supplementary materials, part I): (i) cropping systems at the plot level (n=10), (ii) livestock farming systems at the herd level (n=8) and, (iii) combining the first two within specific farm structures, the production systems (n=9). A production system is composed of at least one cropping system or one livestock farming system and may combine several cropping systems (or several livestock farming systems, although this is not the case for Petlad's production systems presented in this paper). These archetypes correspond neither to real farms, nor to sample values averages. They result from choices based on the understanding of the bio-technical and socio-economical processes operating locally (Aubron et al., 2016). This methodological choice is justified by the complexity of farming systems, which prevents the selection of variables set beforehand collected through surveys within a reasonable period of time (Lacoste et al., 2018).

The economic assessment included in this paper was based on the structure and the functioning of farming systems as modelled in the archetypes, supplemented by data on prices, equipment lifetime and use of hired labour, collected through the same interviews (figure 1, fieldwork step 2). More details on the methods and indicators used for this economic assessment are available in Cochet (2015a et 2015b) and other results for Petlad in Aubron et al. (2015).

2.3. Assessing nitrogen balances and efficiencies at farming systems' level

The nitrogen flows considered at cropping, livestock farming and production systems' level are shown in figure 2. They arise from the material flows included in the archetypes, be they inputs, i.e. flows entering into the systems, outputs, i.e. flows outing the systems, or internal flows, i.e. flows circulating between the different components of the system in the case of production systems. This knowledge was complemented during step 3 of the fieldwork by focuses on manure production, storage, spreading and sales and on the way it varies between production systems in Petlad. We converted these material flows into nitrogen flows using different sources of data (Supplementary materials part II).

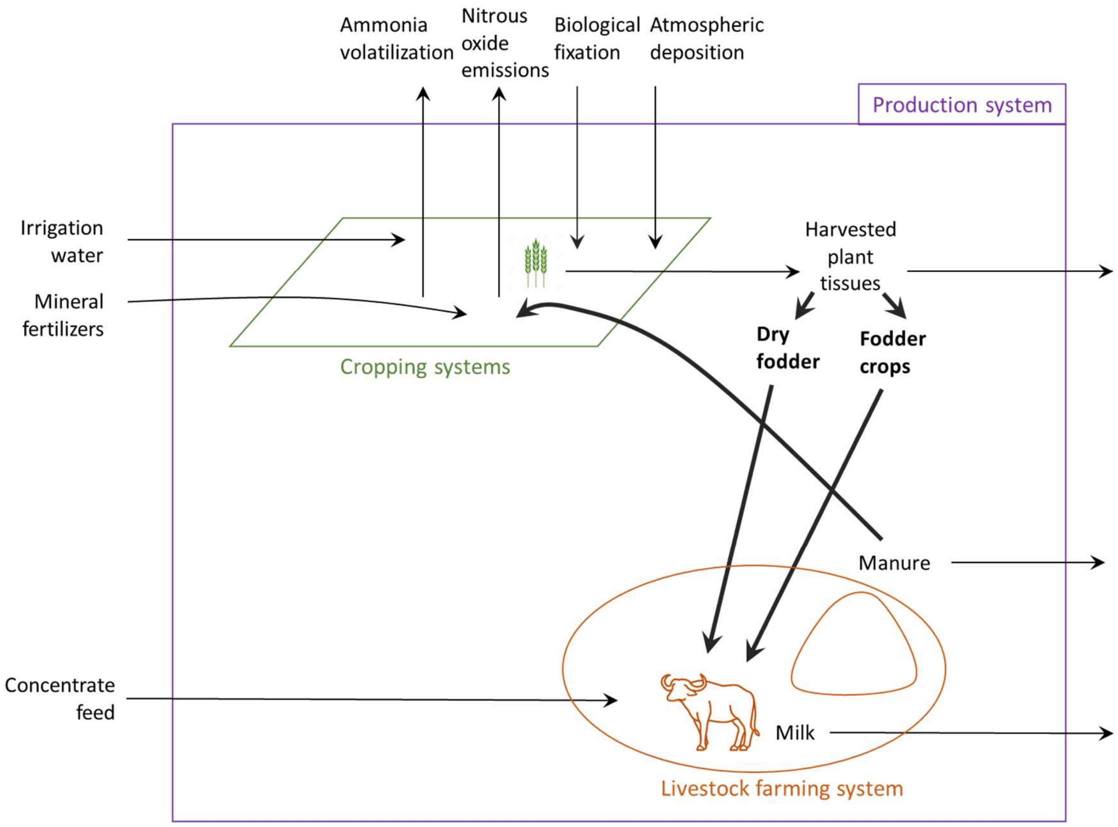


Fig. 2. Nitrogen flows at the cropping, livestock farming and production system scales (example of Production System 5: small diversified farms). Production system internal flows are **in bold**

We then calculated both nitrogen balances and efficiencies indicators at each level: cropping systems, livestock farming systems and production systems.

$$N\ balance = N\ inputs - N\ outputs \qquad \text{(Equation 1)}$$

$$N\ efficiency = \frac{N\ collected\ outputs}{N\ inputs} \qquad \text{(Equation 2)}$$

Nitrogen balance (N balance, Equation 1) is the difference between nitrogen inputs (N inputs) and ouputs (N outputs). Nitrogen efficiency (N efficiency, Equation 2) is the ratio between N collected outputs and N inputs (collected outputs are outputs that are collected by humans, that is to say manure, grains, crop residues or milk but not nitrous oxide for example; for more detailed equations, see Supplementary materials part III).

For cropping systems, balances account for the gaseous N losses of ammonia and nitrous oxide at the time of applications of organic and synthetic fertilizers, which represent most of the emissions for these two polluting gases (Sommer et al., 2004; Gupta et al., 2016). Hence, surpluses of the N balances for the cropping systems correspond either to dinitrogen gaseous losses or to the nitrogen excess in the soil, which is most likely to be leached in the form of nitrate, affecting water quality (Galloway et al., 2003; Garcia-Ruiz et al., 2012). For the livestock farming systems, N balance surplus indicates losses of nitrogen contained in the uncollected excreta (most of the urine in the case studied, given the absence of waterproof flooring at the housing sites), as well as nitrogen losses during manure storage (Rufino et al., 2006). The compacted earth covering on which urine is deposited limiting infiltration and runoff, the major transformation process of uncollected urine is the hydrolysis of urea into ammonia, enhanced by the semi-arid conditions (Moraes et al., 2017). Nitrogen losses during manure storage are also mostly gaseous, partly in the form of dinitrogen (non-reactive) as well as of ammonia and nitrous oxide (Peyraud et al., 2012; Benoit et al., 2015), which are pollutants for the atmosphere. The reasoning in terms of efficiency is complementary to that developed through balances: it makes it possible to measure the capacity of the system to efficiently use a resource, in this case nitrogen (de Wit, 1992; Dawson et al., 2008).

2.4. Modelling nitrogen metabolism at village level

The assessment of nitrogen territorial metabolism at village scale was carried out in a village located in Petlad block, composed of 360 houses according to the 2011 population census. The choice of this geographical entity – the village – was guided by the search of a compromise: this village represented almost the whole diversity of farming systems identified in Petlad block, while considering a number of farms which was not too high (a few hundreds to be compared to the several tens of thousands of farms existing in the block). Working at the scale of a village also enabled access to cadastral and census surveys data, which would have been much more time-consuming, if not impossible, at a broader scale. Based on a fourth fieldwork session (figure 1), the work at village level consisted in articulating this data with the understanding of farming systems generated by the previous steps of the research and modelled in the archetypes.

First, we assigned one cropping system to each of the 915 cadastral plots of the village (218 ha in total), combining three sources of data: (i) interviews with farmers using a village map, (ii) ground observation and (iii) satellite imagery from Google Earth (with images taken at different times of the year to identify crop rotations). As this did not allow us to distinguish different fodder cropping systems, at this stage we settled for referring to them by the generic term of “fodder cropping system”. We thus produced a map of cropping system distribution in the village.

Then, we assigned one production system to the 234 farms of the village. Here, a farm is defined as a household appearing in the 2006 agricultural census (GoI, 2010) with the list of the owned cadastral plots, in the 2012 livestock census (GoI, 2014) with the number of owned animals per category of age and species, or in both agricultural and livestock censuses. To assign production systems to the farms, we defined rules structured in a decision tree. These rules refer to land ownership, number of animals, balance between the two and other information regarding some specific crops or economic activities. For each of the production systems rearing livestock (eight out of nine), the assignment of a production system to a farm entails the assignment of a livestock farming system to its herd. For the farms that cultivate fodder crops, we were able to define the areas under the different fodder cropping systems, applying the proportion in the assigned production system.

After matching each cadastral plot and farm with farming systems, the flows of inputs and outputs were calculated for both entities adjusting the archetypes values to the reported cropped areas and number of animals. The origin of inputs and the destination of outputs, either the village or outside the village, were also defined based on our knowledge of local farming systems and agrarian relationships. Similarly, regarding the internal flows of manure and fodder within the farms, we formulated allocation hypotheses for each production system. These hypotheses are decision rules determining the quantity of manure and fodder used, bought and sold by the farm, according to the quantity produced and the reference values of the assigned archetype (for details on these hypotheses, see Supplementary materials part IV). They also spell out the allocation of manure between different cropping systems, and thus between plots, within the farm. At the village level, the flows of manure and fodder between farms that sell or buy these items were assessed globally, considering that local transfers had priority and that imports only occured when the quantities available for sale in the village were not sufficient to cover the need.

We then converted these material flows into nitrogen flows and used them for assessing: (i) the contribution of each category of inputs, internal flows and outputs to nitrogen flows at village level; and (ii) the contribution of each production system to nitrogen flows at village level.

3. Results

Results are divided into two main sections. The first provides historical trajectories that are key to understand today's production systems and presents their main features and economic results. The second section assesses the environmental implications of this development path considering nitrogen flows at both farming system and village level.

3.1. Petlad's agricultural development: green and white revolutions and the persistence of inequalities

The reconstitution of Petlad's agrarian history carried out in this study showed that, in 1950, Petlad's agriculture was characterised by fairly high crop-livestock integration from a technical point of view. At that time, in this alluvial plain with a semi-arid climate, crops were mainly rainfed (millet, sometimes associated with legumes, rice in the lower zones), with a single crop season during the monsoon (*kharif*). Well irrigation, used to grow tobacco and vegetables, only involved 15 % of the cultivated surface (Shah and Shah, 1950). Ruminant livestock farming (sheep, cattle, buffalos) played an essential role in the fertility management of the cultivated land: animals were fed on uncultivated grazing areas, on cultivated plots during the fallow period and on crop residues. Excreta were used as amendment and for the renewal of the soil fertility by nutrient transfer. Draught animals were also essential for some cultivation operations (tillage), drawing water from the wells, and transportation.

In terms of social organisation, there were strong contrasts. Land was largely concentrated in the hands of owners mainly belonging to the Patel caste, who owned up to 20 ha per household, and was worked by landless labourers from the Solanki, Parmar, Chauhan, Thakor and Vagri castes, who rarely owned animals. Two pastoral communities (Rabhari and Bharvar) completed this picture. The latter did not own cultivated land either, but they had access rights to grazing areas for their herds of ruminants and hence played a role in providing the farmers with draught animals and participated in the fertility management of cultivated land.

In Petlad, from the 1960s onwards, the green revolution took the form of an expansion of irrigated surfaces (figure 3) and an increase in the cropping intensity, like in the other alluvial zones in India that can be easily irrigated by wells and bore wells fitted with motor pumps. Today, the cultivated area represents 90% of the district's territory, and it is entirely irrigated. Tobacco, a very profitable winter (*rabi*) 7-month crop, gradually gained importance in the crop rotation. It is often rotated with a summer crop (millet) or a monsoon crop (rice or millet), and is sometimes part of an annual rotation including three crop cycles. Since the 1990s, banana and chilli cultivation has increased in farms that had the means to purchase the expensive equipment and inputs that these crops require.

In terms of land, the successive agrarian reforms adopted in India (Appu, 1997) had only a limited impact in Petlad: some families who had little or no land were granted plots (often located in zones earlier reserved for grazing, figure 3), but a large number remained landless and continued to work as agricultural labourers. They are particularly present in tobacco cultivation, which is very labour intensive. Some of these landless families have gained access to land *via* sharecropping contracts, where the owner provides the inputs, and the sharecropper provides all the labour and receives 20% of the harvest. Although landowners in Petlad were little affected by the agrarian reforms, the size of their properties has diminished as a result of successive divisions due to inheritance. Few still own up to ten hectares, but today, a 1 to 2 ha farm is considered a "large farm" (table 1).

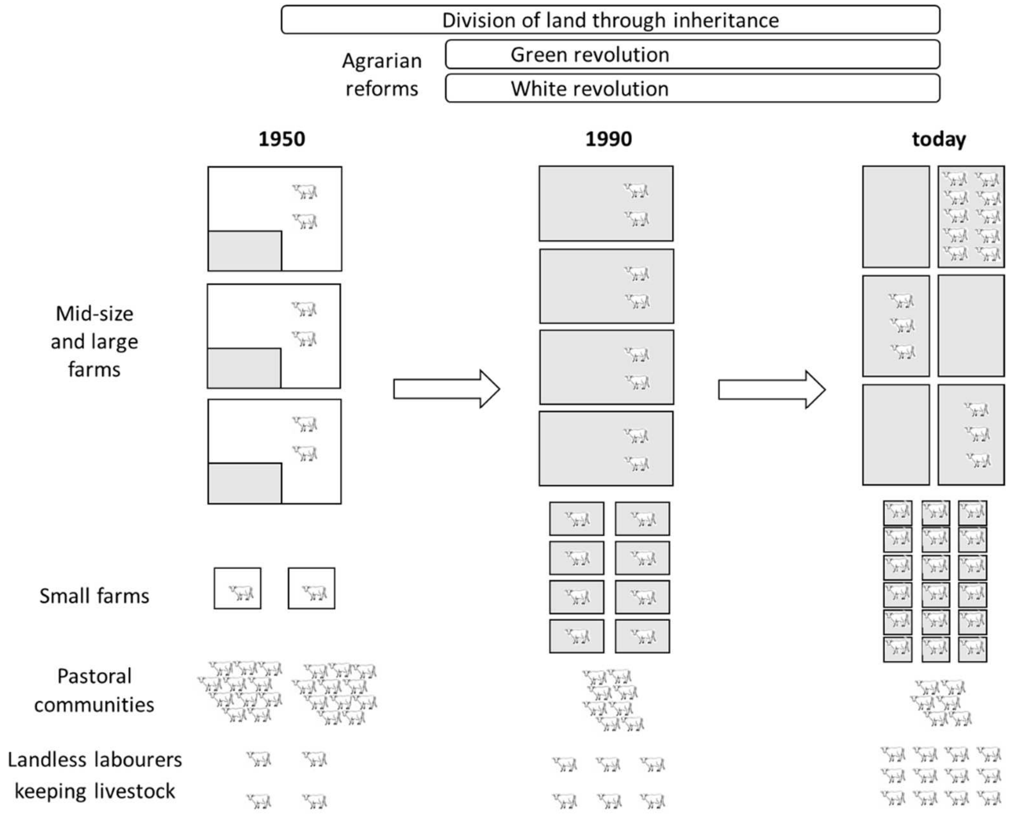


Fig. 3. Diagram showing agricultural change in Petlad. The rectangles represent the cultivated area by different production systems, and are grey when they are irrigated; cows represent the ruminant herds.

As the use of synthetic fertilisers, motor pumps and then tractors increased, livestock lost its importance in crop cultivation, but is far from having disappeared. The white revolution that took place in the 1960s, consisted of structuring the collection, processing and marketing of milk into a large cooperative network, led by the National Dairy Development Board based in Anand, 60 km from Petlad. The Amul milk cooperative that inspired this revolution is also located in Anand, and Petlad falls within the radius of its collection zone. Compared to the the green revolution for cereals, the white revolution sought to be more inclusive with regard to the regions and families involved. In Petlad block, village milk collection was gradually organised by village societies that offered everyone the guarantee of daily sales of their milk production, with payment for quality. Most families began to raise one or two milk animals (buffaloes or cows), including landless agricultural labourers and sharecroppers for whom this represented a means of supplementing their income (figure 3 and table 1). From the 1990s onwards, farms breeding larger herds (from four to six, and up to a few dozen females) began to emerge among those who owned cultivated land. A few investors even set up farms with over 100 cows, making use solely of a hired labour force. The current cattle density is 188 head per km² at the scale of the district and 280 head per km² in the village studied.

Current feeding practices have little to do with those that existed in 1950 and differ from farm to farm (table 1): grazing land and grazing periods have been reduced to almost nothing, and only the pastoral communities continue to graze their animals; straw is now the basic fodder for most herds; a new category of fodder, irrigated fodder crop, has gained increasing importance (Napier grass on the edges of plots or a crop rotation of lucerne, fodder sorghum and corn for larger farms more specialised in milk production). As the labourers find it difficult to access straw or cultivated fodder, they collect natural fodder on the edges of plots or paths, or from the plots themselves (this also provides free weeding for the landowners). Finally, all production systems are now using purchased concentrates, mainly from the cooperative, the cost of which is deducted from the payment for the milk.

The economic results show strong contrasts between farms types (table 1): the income from production systems 5 to 8 owning less than 0.4 ha of irrigated land, is systematically lower than 50 000 Rs (625 €) per worker per year, even including the wage earned by agricultural labourers, and in a certain number of cases it remains below the poverty line. In contrast, production systems 1 to 4 (large landowners who give their land to sharecroppers, large dairy farms and mid-size farms) income is between 56 000 and 820 000 Rs (700 and 10 000 €). Pastoral farmers (SP9) earn a very low income from livestock farming, but their larger herds and their higher historical social status compared to agricultural labourers has enabled them to develop complementary economic activities (farming and non-farming) that generally ensure a higher total income.

Table 1 Petlad's production systems: structural and functional main features and agricultural incomes

Production system	**PS1**	**PS2**	**PS3**	**PS4**	**PS5**	**PS6**	**PS7**	**PS8**	**PS9**
	Large landowners with land in sharecropping	Large dairy farms	Mid-size diversified farms	Mid-size dairy farms	Small diversified farms	Small dairy farms	Sharecroppers with livestock	Day labourers with livestock	Pastoral farmers
Acreage (ha)	1 - 9.5	2 - 6	0.4 - 2	1 - 2	0.1 - 0.4	0.1 - 0.4	0	0	0
Cropping systems	T/F/F T/F/R T/M/F T//B	A/S Ma/Ma/S Napier	T/F/R T/M/F T//B Chili Napier	A/S Ma/Ma/S	T/F/R T/M/F + Napier on field borders	T/F/R A/S + Napier on field borders	PS1 cropping systems in sharecropping + Napier on field borders		
Herd size	0	100 - 200 co	4 - 12 co & bu	12 - 40 co	1 - 2 bu	3 - 4 co & bu	0 - 2 bu	0 - 2 bu	5 - 20 co
Herd feeding (in % DM weight)		Fd: 35 Ffc: 17 C: 48	Fd: 43 Ffc: 15 C: 42	Fd: 33 Ffc: 17 C: 50	Fd: 32 Ffc: 34 C: 34	Fd: 36 Ffc: 28 C: 36	Fd: 32 Ffc: 34 C: 34	Fn: 62 Fd: 3 C: 35	Fn: 23 Fd: 14 Ffc: 25 C: 38
Agricultural income* (Rs per worker per year)	80 k - 820 k	205 k - 645 k	56 k - 135 k	145 k - 330 k	35 k - 46 k	43 k - 49 k	**24 k** - 40 k	**22 k** - **25 k**	**13 k** - 32 k
Number of farms in the village (%)	20%	1%	17%	2%	16%	8%	32%	3%	<1%
Total land use in the village (%)	42%	2%	38%	4%	10%	4%	-	-	-

T=tobacco; F=fallow; R=rice; M=millet; B=banana; A=alfalfa; Ma=maize; S=sorghum; a single slash between two crops corresponds to an intra-annual rotation and a double slash to a pluri-annual rotation.

co=cow; bu=female buffalo

Fn=natural fodder; Fd=dry fodder (straw); Ffc=fodder crops; C=concentrate feed.

* including wages earned as agricultural labourers if any. Incomes **in bold** are below the poverty line (as defined by the Indian government and adapted to family composition: 28 000 Rs/yr).

3.2. Environmental implications of this development path in terms of nitrogen flows

3.2.1. Nitrogen balances at the farming system scale

Table 2 shows N balances and efficiencies for each cropping system, livestock farming system and production system. For more details on inputs and outputs, see Supplementary materials part V.

Table 2 Nitrogen balances and efficiencies at farming systems' level

	N balance	**N efficiency**
Cropping systems	(kgN/ha/year)	
chili	252	0.21
fallow/fallow/rice	207	0.1
Napier grass	-177	1.01
maize/maize/sorghum	-14	0.82
alfalfa/sorghum	230	0.69
tobacco//banana	632	0.09
tobacco/fallow/ fallow	493	0.17
tobacco/fallow/rice	779	0.17
tobacco/millet/fallow	704	0.19
tobacco/millet/rice	880	0.21
Livestock farming systems	(kgN/female/year)	
PS2 – Large dairy farms	84	0.36
PS3 – Mid-size diversified farms	58	0.46
PS4 – Mid-size dairy farms	77	0.42
PS5 – Small diversified farms	67	0.32
PS6 – Small dairy farms	89	0.35
PS7 – Sharecroppers	66	0.32
PS8 – Day labourers	32	0.48
PS9 – Pastoral farmers	68	0.23
Production systems	(kgN/year)	
PS1 – Large landowners with land in sharecropping	1193	0.19
PS2 – Large dairy farms	11863	0.17
PS3 – Mid-size diversified farms	1598	0.15
PS4 – Mid-size dairy farms	3084	0.22
PS5 – Small diversified farms	197	0.25
PS6 – Small dairy farms	481	0.16
PS7 – Sharecroppers	217	0.29
PS8 – Day labourers	64	0.48
PS9 – Pastoral farmers	678	0.23

A single slash between two crops corresponds to an intra-annual rotation and a double slash to a pluri-annual rotation. The values indicated for the cropping systems correspond to the typical technical operations implemented for this rotation. When a given cropping system is inserted in different production systems, the technical operations are adjusted, for example with increased amounts of manure applied in relation to the larger herd size in that production system.

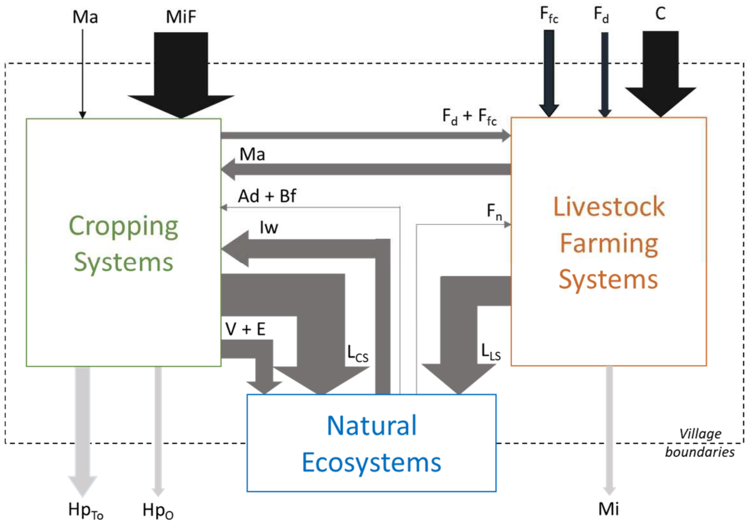
Among cropping systems, fodder cultivation showed the smaller N balance surpluses, with even negative N balances for Napier grass and maize/maize/sorghum rotation. Rice cultivation preceded by a fallow period (fallow/fallow/rice) and chilli cultivation also presented relatively small surpluses, particularly when compared to cropping systems that include tobacco. For the latter the balance surpluses were all above 600 kgN/ha/yr as a consequence of the large N inputs (between 762 and 1398 kgN/ha/yr) and small N outputs (between 269 and 560 kgN/ha/yr). The tobacco/millet/rice rotation shows the largest surplus of 880 kgN/ha/yr. Mineral fertilisation was the main input of N in all the cropping systems (37 to 75% of inputs), with the exception of the fallow/fallow/rice system, where irrigation was the main N input (44%). Organic manure represented only 11 to 40% of the input. The N efficiencies were good for fodder crops and very poor for other crops (between 0.09 and 0.21).

Nitrogen balances for all types of livestock farming system had a surplus (from 32 kgN/adult female/yr in PS8 to 89 kgN/adult female/yr in PS6) linked to poor N use efficiencies. The N inputs were mainly purchased concentrates (from 47 to 73%), and green cultivated fodder, particularly in PS5 to 7 (from 37 to 41%). Milk had a relatively low share in N outputs (between 21 and 29%) in comparison to organic manure (from 71 to 79%).

All production systems (PS) showed nitrogen surplus, that varied greatly from one PS to another. These surpluses were linked to poor N efficiencies, all lower than 0.5. Depending on the PS's technical orientation, the main sources for N inputs varied greatly (from 0 to 69% for mineral fertiliser and from 0 to 71% for concentrates). This was also the case for N outputs, which was mainly milk for PS2 and PS4, manure for PS8 and PS9, or tobacco for PS7.

3.2.2. Nitrogen flows at the village scale

The village flows of inputs, outputs and their internal circulation (figure 4) showed that most of the N input was mineral fertiliser (65%) and to a lesser extent, purchased concentrate feed (25%). The N inputs (1101 kgN/ha/yr) were much higher than the outputs (175 kgN/ha/yr), which were mainly crops exported outside the village, tobacco in particular (58%). This large surplus of nitrogen at the scale of the village (926 kgN/ha/yr) led to a poor global N efficiency (0.16). Crop cultivation was the main contributor, with 626 kgN/ha/yr surplus nitrogen, most probably joining the hydrosphere through leaching. This surplus from cropping systems was not homogeneous across the village territory, with some fields with over 900 kg of surplus nitrogen per hectare per year (see map of N balances, Supplementary materials part VI). Concerning livestock farming, N losses came from excreta management and were mainly gaseous: 78% of the nitrogen excreted by animals in the village was lost through uncollected excreta or during the manure collection, storage or spreading processes.



N flows entering the village
Ma: Manure *(1)*
MiF: Mineral fertilizers *(715)*
F_{fc}: Fodder crops *(75)*
F_d: Dry Fodders *(36)*
C: Concentrate Feed *(274)*

Internal N flows
V + E: NH_3 volatilization & N_2O emissions *(158)*
L_{CS} : Other N losses from cropping systems *(626)*
Iw: Irrigation water *(126)*
Ad + Bf: Atmospheric deposition & N biological fixation *(9)*
Ma: Manure *(108)*
L_{LS} : N losses from livestock systems *(284)*
F_n: Natural Fodders *(7)*
$F_d + F_{fc}$: Dry Fodders & Fodder Crops *(36)*

N flows leaving the village
Hp_{To}: Tobacco *(101)*
Hp_O: Other crops products *(38)*
Mi: Milk *(36)*

Fig. 4. Schematic representation of N flows entering, circulating in and leaving the village with the thicker the arrows the greater the N flows. The text expands the notation for each flow and gives the annual value in KgN/ha/year into brackets.

Milk and crop products self-consumption in the village was considered as negligible and has not been accounted for.

The different PS contributed differently to the input flows from outside the village (Table 3) with PS1 and PS3 being the main contributors *via* mineral fertilisers, and to a lesser extent PS2, *via* the purchase of concentrated feed. Output flows were mainly produced by PS1 (33%) and PS3 (35%), given their large contributions to tobacco and grain output, which are major flows at the territorial scale.

Table 3 PS contribution[a] to input and output N flows of the village (in %)

Categories and Flows	**PS1**	**PS2**	**PS3**	**PS4**	**PS5**	**PS6**	**PS7**	**PS8**	**PS9**
Input flows	**28**	**12**	**38**	**8**	**6**	**6**	**3**	**<1**	**<1**
Mineral Fertilizer	39	1	45	3	8	4	-	-	-
Manure	84	-	16	-	-	-	-	-	-
Feed Concentrates	-	37	20	21	1	10	10	<1	<1
Dry Fodders	-	33	25	18	1	11	11	<1	<1
Fodder crops	-	-	-	-	3	25	73	-	-
Output flows	**33**	**8**	**35**	**6**	**10**	**6**	**2**	**<1**	**<1**
Fruits&Vegetables	49	-	45	-	1	5	-	-	-
Grains	41	<1	38	2	16	3	-	-	-
Tobacco	43	2	38	2	11	4	-	-	-
Milk	-	32	22	22	2	12	9	<1	<1

[a] *The contribution calculated here is the contribution of the whole group of farms falling under the production system. For the contribution of each production system, see Table 2 and Table SM7*

PS1: large landowners with land in sharecropping; PS2: large dairy farms; PS3: mid-size diversified farms; PS4: mid-size dairy farms; PS5: small diversified farms; PS6: small dairy farms; PS7: sharecroppers with livestock; PS8: day labourers with livestock; PS9: pastoral farmers;

Regarding spatial distribution, the differentiation in N surplus between fields was mainly linked to pedoclimatic conditions which were more favourable to rice/tobacco rotations with large N surpluses in the west and south of the village. However, fields located in these areas and yet presenting small surpluses most often belonged to small farms (PS5 and PS6, Supplementary materials part VI).

4. Discussion

In this section, we will first discuss the main biophysical results of the study and compare them with existing literature, then show how socio-economic analysis can help understand the mechanisms at play, and finally discuss the importance of taking into account social diversity in research on the environmental impact of agriculture.

4.1. High nitrogen surpluses and an under-exploitation of the crop-livestock integration potential

Whether at the scale of cropping systems, livestock farming systems or production systems, nitrogen balances in Petlad were mainly high surpluses compared to literature values. The nitrogen balances estimated in long-term socio-ecological research for the pre-industrial period in Europe, which represents a relevant reference to analyse the sustainability of agricultural systems (Garcia-Ruiz et al., 2012), did not rise above 10 kgN/ha/yr, and were sometimes negative (Garcia Ruiz et al., 2012; Gizicki-Neundlinger and Güldner, 2017). The balance obtained from FAO cultivation data for the contemporary period (2009) shows a surplus of 10 kg/ha/yr for Africa (Billen et al., 2014). The annual surplus of 642 kgN/ha/yr for cultivation obtained in the studied village is twenty-two times higher than the French average in 2005 (Peyraud et al., 2012), nearly eight times higher than in the intensive pig and dairy farming region in France (Le Gall et al., 2005), two and a half times higher than the value obtained from the FAO data for China, the region that shows the highest surplus in Billen et al.'s (2014) study, and nearly three times higher than the maximum value obtained in pig farms in Italy (Bassanino et al., 2007). While accounting for losses towards the hydrosphere and the atmosphere, the latter study indicates a farm-gate balance surplus of 486 kgN/ha/yr (Bassanino et al., 2007), i.e. half of the village total surplus value obtained in this study (926 kgN/ha/yr). Such very large nitrogen losses into the ecosystem are likely to generate pollution. Indeed, water contamination by nitrates was confirmed by groundwater analyses carried out during step 3 of the field work in Petlad (11 of the 16 samples taken are over the NO3 potability limit of 50 mg/L), even though part of this contamination could be due to human waste. This is consistent with water quality degradation observed in other regions of India that were also involved in the green revolution (Agrawal et al., 1999; Singh and Singh, 2004; Buvaneshwari et al., 2017).

Looking more closely, cropping practices seem to be the most problematic, because crops contribute far more than livestock farming to nitrogen loss towards the ecosystem (Figure 4). The nitrogen use efficiency in Petlad is also far better in livestock farming systems than in cropping systems, except for fodder cultivation systems. In addition, comparing efficiencies with references found in the literature suggests a larger gap in performance for cropping systems than in livestock farming systems. In Austrian agriculture during the pre-industrial period, two studies estimated that the nitrogen loss linked to the storage and spreading of manure varied respectively between 40 and 60% (Krausmann, 2004) and 27 and 60% (Güldner et al., 2016). In African crop-livestock systems, Rufino et al. (2006) quoted a study carried out in Kenya, where up to 40% of the nitrogen contained in excreta was not recovered due to collection practices, and estimated that 23 to 70% of the nitrogen recovered was then lost during the manure storage process. The nitrogen flows at the scale of large regions described by Billen et al. (2014), based on FAO data and works by Sheldrick et al. (2003) and Oenema et al. (2003), revealed that animal excreta not recovered by man, and the nitrogen lost during the storage or spreading of manure, represented 70% of the nitrogen excreted by animals in India, and 67% in Europe. With 78% of the nitrogen excreted in the village lost through uncollected excreta or during the manure collection, storage or spreading processes, Petlad's livestock farming systems show fairly low performance for these criteria.

In the case of crops, the values obtained can be compared with those provided by Austrian studies which are to our knowledge among the most detailed on this subject with an historical perspective in the literature. While the balances calculated for two large Austrian farms for the pre-industrial period revealed a nitrogen use efficiency of about 30% for crop cultivation, it was far better (54 and 77%) for peasant farms (Gizicki-Neundlinger and Güldner, 2017). In other studies, still in Austria (Krausmann, 2004), the nitrogen use efficiency for crop cultivation was above 63%, both in the pre-industrial and the contemporary period. Finally, in the regional comparison based on FAO data, the efficiency for crop cultivation was ≥ 40% in all the regions studied except for three, including India and China (Billen et al., 2014). According to the same study, the global world efficiency of nitrogen use in crop cultivation was 43%. Thus, with an efficiency of 9 to 21%, Petlad's non-fodder cropping systems seem to be highly inefficient from the perspective of nitrogen use. This poor efficiency in cultivation has been also observed in other works in India (NAAS, 2005; Singh and Singh, 2008; Velmurugan et al., 2008), but the values obtained in Petlad were even lower.

This inefficiency is linked to a very high use of imported inputs, representing 79% of the nitrogen input related to agriculture in the village. Such a dependency on external inputs has been found in livestock farms in Italy (Bassanino et al., 2007), but it was much lower for agricultural systems studied in different regions of Austria (Krausmann, 2004): while imported nitrogen was absent in pre-industrial times, in contemporary times it represented 57% of the nitrogen input in the lowlands, 34% in the uplands and only 8% in the alpine zone of Austria. Crop-livestock integration, which makes it possible to substitute imported nitrogen with internal flows in the territory (Dumont et al., 2013), was largely under-utilised in Petlad: although nitrogen input from manure spreading was almost sufficient to cover the crop needs, farmers applied two to four times more nitrogen in the form of synthetic fertilisers, generating considerable surpluses. As well as this, the large use of concentrates for animal feed can also be explained by the low level of crop-livestock interaction in the territory: although rice and millet straw contributed to animal feed, the residues of the main crop – tobacco - could not be consumed by animals. Moreover, the space allocated to fodder cultivation was very limited (3% of the cultivated surface in the village, see map b in Supplementary materials part VI) and the deficits in the nitrogen balance observed for fodder cropping systems illustrates the priority given to other crops.

Petlad's territorial metabolism hence seems to be diametrically opposed to the one described for pre-industrial Austria (Krausmann, 2004) or for first half of the 20th century Savoie in France (Bonaudo et al., 2017). In these examples, crop-livestock integration, involving often labour-intensive practices, ensured the reproducibility of a system producing and exporting low levels of nitrogen. In Petlad, the nitrogen flows within the territory were negligible in comparison to the nitrogen imported: the volumes produced, particularly of tobacco, were large, but the input levels were such that most of the imported nitrogen flowed into the atmosphere and the aquifers. Indeed, the nitrogen cycle has been seriously altered in India and this has major consequences for the environment (Singh and Singh, 2008; Velmuragan et al., 2008).

The prevailing metabolism in Petlad is far closer to that of contemporary Europe, described in different works mentioned above, but it does show two differences. The nitrogen surpluses, which were even higher in Petlad than in these studies, are mainly linked to the input of synthetic fertiliser while in Europe, they mainly come from the import of concentrates for animal feed whose nitrogen is then found in the manure spread on the fields. The second difference is linked to the structure of the fabric of farms in Petlad, which is extremely dense and very heterogeneous in terms of access to resources. The following section examines the links between these two specificities.

4.2. Inefficiency and pollution linked to socio-economic conditions

Several research studies are concerned with the drivers behind the specialization and input-intensification of agriculture and the lock-ins that hinder its evolution towards a more sustainable agriculture. Agricultural policies, e.g. the CAP in Europe, market globalization and global macroeconomic conditions are thus often identified as important factors (Ryschawy et al., 2013; Allison et al., 2004). Other authors insist on the lack of available information on more sustainable practices, the logistical constraints to their implementation and the difficulties of coordination between value chain operators (Meynard et al., 2018; Magrini et al., 2019; Mamine and Farès, 2020). In Petlad, agricultural policies and, in particular, the subsidies granted to the fertiliser industry combine to provide a plausible explanation of the low level of crop-livestock integration. These subsidies are one of the pillars of the policies supporting the green revolution in India and they represent the second main item in the national budget allocated to agriculture (Gulati et al., 2018). The comparison between the selling price of urea and the amount of the subsidy per kilo of urea (Dorin, 2021, updated from Dorin and Jullien, 2004) suggests that it results in a threefold decrease in the price of urea for farmers, who are hence encouraged to use them in large quantities. Therefore, the reduction of the subsidies and the resulting increase in the cost of synthetic nitrogen fertilisers appear as a potential lever to strengthen crop-livestock integration and limit the environmental impact of agriculture in Petlad.

The results obtained in this study suggest, however, that a reduction in fertilisers subsidies alone is unlikely to be sufficient. Nitrogen flows are also shaped by the diversity of farms and unequal access to resources at the local scale, which helps to define the varying interest shown in livestock and crop activities by the different social groups. The PS1 to PS4 production systems that have access to large areas of land are certainly highly productive, but they show some of the poorest nitrogen efficiency levels at the farm scale. While such farms are numerically fewer in the village, they are the largest contributors to the nitrogen surplus. PS5 to PS9, which have less or no land, use nitrogen more efficiently (except PS6), and generate lower surpluses. Their contribution to the village's crop production is low (19, 15 and 6% for cereals, tobacco and fruits or vegetables), but their livestock activities allow them to produce about one quarter of the village's milk.

Our economic assessment suggests that behind the different impact of farm types on the environment, there are important differences in remuneration. The income for PS5 to PS9 remains close or even below the poverty threshold. PS1 to PS4 earn far higher incomes and a large landowner who gives out land for sharecropping can earn up to 37 times more than a landless agricultural labourer. Thus, while the tobacco produced by PS1 and PS3 generates employment for families who have little or no land, their situation remains precarious. They are very poorly paid, and such employment does not allow them to escape poverty. Therefore, the largest environmental impact of these production systems cannot be justified by arguments of social equity and fair economic development.

The characteristics of Petlad's territorial metabolism emerges more clearly once social and biophysical diversity dimensions are combined. Most owners with access to relatively large areas of land (PS1 and PS3) carry out irrigated cultivation based on cheap labour supplied by day labourers or sharecroppers, and hence obtain high incomes. Their high contribution to the nitrogen surplus in the territory is linked to the land they control, as well as the larger share of crop rotation dedicated to tobacco cultivation, on which large amounts of synthetic fertilisers are used. No livestock is found on the largest farms (PS1), as it is too labour intensive, which also limits the possibility of substituting imported fertilizers by internal flows of manure. Small landowners (PS5), largely supported by family labour and combining crops—with a higher presence of cereals, receiving less fertilizer than tobacco—and livestock, use nitrogen more efficiently, and their contribution to the nitrogen surplus is lower. Their income, however, remains average, which leads them to also work as agricultural labourers on other farms. The few landowners who raise large milk cattle herds (PS2 and PS4), making use of a permanent salaried staff, earn a high income and they use nitrogen more efficiently than PS1. Nonetheless, due to their use of concentrates, they contribute 20% of the nitrogen imports into the village. Following the aims of the white revolution (Atkins, 1988), sharecroppers and day labourers raise female buffalos in order to supplement their income (PS7 and PS8). Their low wages and income as labourers or sharecroppers makes income from livestock essential for them. Therefore, as they have no access to land and hence limited access to fodder, they purchase significant quantities of concentrates, thus also contributing to the import of nitrogen into the territory. The current role of the pastoralists (PS9) in today's territorial metabolism is not very different from that of the day labourer livestock keepers (PS8), but their total income is generally higher thanks to non-farming activities. While they were historically central to Petlad's territorial metabolism, they only play a minor role today.

Thus, crop-livestock integration is low in Petlad because, in addition to the low price of synthetic fertilizers, farmers at both ends of the social scale, given their access to resources, either have little interest in integrating these two activities or do not have the means to do so. These results show similarities with a study of the dynamics of crop-livestock systems in the Mediterranean (Alary et al., 2019), which indicates a tendency to specialise in irrigated crops or milk cattle on farms that have access to large areas of land, and the persistence of crop-livestock interactions in smaller farms and non-irrigated regions, which are more fragile economically. Their analysis shows "an overwhelming antagonism between social vulnerability and ecological efficiency" (Alary et al., 2019).

4.3. The need to take social diversity into account in research on the environmental impact of agriculture

There are two types of approaches – we used both in Petlad – accounting for diversity in assessing the environmental impacts of agriculture.

The first consists in considering what we call the “technical diversity”. Like our study in Petlad, such approach assesses the environmental impacts of different types of farms, and analyse the results in terms of underlying bio-technical processes. It is extremely useful, both to understand the environmental impacts of agriculture and to consider ways of reducing the negative impacts. Such an approach allows identifying the room for manoeuver that, for example, enable an increase in the efficiency of nitrogen use in specific types of farms, or even at the scale of territories or landscapes. Several authors nonetheless underscore its limits and the need to include the social dimension in the analysis (Scoones and Toulmin, 1998; Ramisch, 2005; Poccard-Chapuis et al., 2014).

Rooted in the social sciences, the second approach to the diversity of farms focuses on “social diversity”, makes social relations central to the analysis, and sees diversity through the lens of inequality and power relationships in societies (Fabinyi et al., 2014). It is a means of showing how social relationships shape the environmental impacts of agriculture. For example, the study of the manoral regime in pre-industrial Austria showed that landlords produced large surpluses while maintaining agroecological sustainability through flows of matter (Gizicki-Neundlinger and Güldner, 2017). On the contrary, taxation and the very limited access peasants had to land, for grazing in particular, and thus to livestock activity, did not allow them to ensure the flow of nitrogen nutrients required for the sustainability of their cultivation, thus compromising their subsistence.

We can draw a parallel between the historical situation in Austria, which the authors describe as ”the sustainability costs of inequality” (Gizicki-Neundlinger and Güldner, 2017), and the one we have revealed in Petlad, even if it is reversed, where large landowners who cultivate tobacco make a high contribution to nitrogen surpluses and hence do not maintain agroecological sustainability. Nonetheless, like the landlords in Austrian case, the large landowners earn a large income from both their large landholdings and the fact they make use of a cheap hired workforce. At the other end of the social scale, some of the landless agricultural labourers who seek to complement their income with livestock, are forced to stop this activity, as collecting natural fodder in this highly cultivated space requires too much time in comparison to the time available for them before and after their day of paid work. From the perspective of using research results to design projects and policies that could help increase the sustainability of agriculture, the inclusion of this social diversity is therefore very useful: while there are indeed numerous good agronomic, ecological and fossil energy-saving reasons to transform practices and reinforce crop-livestock integration in Petlad, it is unlikely that there will be any change as long as the socio-economic conditions, particularly the current features of social diversity, do not evolve. As highlighted in the management of coastal resources (Fabinyi et al., 2010), taking social diversity into account in Indian agriculture is likely to increase the efficiency of policies seeking to increase the effectiveness of nitrogen use.

The proposal to take social diversity into account concurs with certain critiques of both socio-ecological metabolism (Gizicki-Neundlinger and Güldner, 2017) and socio-ecological systems (Fabinyi et al., 2014; Stojanovic et al., 2016) approaches. These authors emphasise that by seeking to model reality along the lines of a coherent system, these approaches tend to homogenise social differences and exclude an analysis of inequalities, power relations and conflicts. The results of the research carried out in Petlad also question the vision of diversity present in works on crop-livestock interactions: in a large number of them, as Fabinyi et al. (2014) note with regard to research on socio-ecological systems, diversity is viewed as a positive feature (González-García et al., 2012; Dumont et al., 2013; Lemaire et al., 2014; Moraine et al. 2017). The study conducted in Petlad shows that while the diversity of farms effectively translates into a flow of matter between landless livestock keepers and farmers who can recycle these nutrients, it is difficult to qualify it as beneficial in this case, as there is such a high level of social inequality. Thus, while large diversity makes interactions and complementarities possible, in no way it guarantees them nor ensures that they will be socially equitable. Similarly, it seems particularly complex to implement the suggestions made by Moraine et al. (2017) or Alary et al. (2019), for participative research or projects based on co-management or collective action taking the diversity of farms into account, in the existing social conditions in Petlad. This concurs with another critique of socio-ecological systems approaches, underlining that by highlighting organised social groups and institutions, these approaches “tend to prioritize consensus and collective action over contestation” (Fabinyi et al., 2014).

More than the limits of approaches to the technical diversity of farms, socio-ecological systems, or the socio-ecological metabolism, the lesson we can draw from this research is that it is necessary to take social diversity into account in the analysis of the environmental impacts of agriculture and in the search of solutions to improve these impacts. The need for interdisciplinarity in a study of crop-livestock relations, underscored by scholars working in the bio-technical sciences and farming system research (Devendra, 2001; Tanaka et al., 2008; González-García et al., 2012), is hence reinforced: to include social diversity in the analysis, it is necessary to draw upon the social sciences, particularly critical approaches that distinguish themselves “from a system ontology” (Stojanovic et al., 2016). We should avoid “reinventing the wheel” by properly including contributions from different fields of the social sciences that emerged in response to similar debates that took place in the past, for example, on the inclusion of inequalities and hierarchies in anthropology (Fabinyi et al., 2014). The question of linking frameworks from the bio-technical sciences and the social sciences nonetheless remains a challenge (Stojanovic et al., 2016) to which comparative agriculture provides answers in the agricultural field (Cochet, 2015a). In the light of the study conducted in Petlad, two constitutive features of comparative agriculture seem to be crucial to an understanding of social diversity: (i) the long fieldwork, with observation and interview methods that are similar to ethnography, which allow for a finer understanding of social relations than the surveys that are often used in the bio-technical sciences; (ii) the study of agrarian changes over the long term of six decades, which highlights the process by which farms are differentiated, and allows us to grasp their current diversity and relations.

5. Conclusion

Crop-livestock integration, which is recognised today as a key lever to improve the environmental impacts of agriculture, remains limited in Petlad. In this area of alluvial plain, which is intensely cultivated today and has a very high animal density, crop-livestock interactions, represent minor nitrogen flows in comparison to the flow of inputs in the form of synthetic fertilizer and feed concentrates. The output flows, in the form of tobacco, cereals and milk, are also low and most of the nitrogen input is lost into the hydrosphere and the atmosphere, where it contributes to pollution.

This study shows, that considering the existing socio-economic conditions in Petlad, particularly in terms of social diversity, allows to shed a new light on this environmentally harmful situation. Indeed, most of the owners who have large landholdings focus on very profitable tobacco production and tend to abandon livestock, which they no longer need either technically or economically. Their farms, that make use of large amounts of synthetic fertiliser, generate high nitrogen surpluses. The households who have access to small areas of land are motivated to raise milk animals, in order to supplement their lowest incomes, which they earn from crops: small farms raising one or two female buffalo show a higher level of crop-livestock integration, use nitrogen more efficiently, and are minor contributors to the village's nitrogen surplus. Finally, the landless agricultural labourers for whom livestock is vital, as they earn so little working as labourers for landowners, show a very efficient use of nitrogen, but they dedicate a large amount of time gathering natural fodder.

However relevant it is from the environmental viewpoint, stronger crop-livestock integration is unlikely to happen in Petlad unless the socio-economic conditions change. This result advocates for characterizing the social diversity when analysing the environmental impacts of agriculture and considering solutions to those environmental impacts. Echoing the suggestions that emerge from the critical analysis of socio-ecological systems or socio-ecological metabolism approaches discussed in this article, comparative agriculture combined with territorial metabolism seems capable of fulfilling some of these needs.

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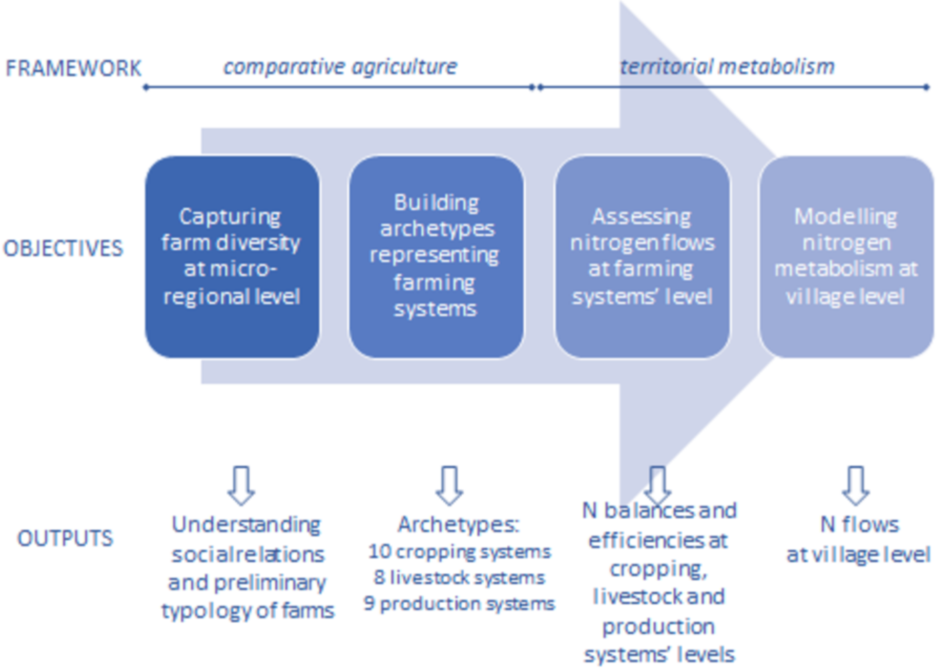
FRAMEWORK
comparative agriculture
territorial metabolism
OBJECTIVES
Capturing farm diversity at micro-regional level
Building archetypes representing farming systems
Assessing nitrogen flows at farming systems' level
Modelling nitrogen metabolism at village level
OUTPUTS
Understanding social relations and preliminary typology of farms
Archetypes:
10 cropping systems
8 livestock systems
9 production systems
N balances and efficiencies at cropping, livestock and production systems' levels
N flows at village level