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

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14 Highlights

15 • Despite its importance, the integration of social diversity in environmental assessment
16 remains challenging due to the lack of adequate frameworks

17 • We combined *comparative agriculture* and *territorial metabolism* to study nitrogen flows at
18 village level in Petlad, India

19 • N surpluses were large, mostly lost to the environment, and crop-livestock interactions
20 remained limited in spite of great potential

21 • Large socio-economic contrasts, with diverging objectives amongst farmers' categories,
22 hamper developing synergies between systems

23 • The framework proposed here showed potential to improve research on the environmental
24 impacts of agriculture

25

26 ABSTRACT

27 CONTEXT

28 Addressing the environmental impact of agriculture requires a comprehensive analysis of the system
29 at stake, and accounting for the social diversity (i.e. social groups involved in farming and
30 relationships between them) is particularly important for designing efficient policies aimed at
31 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

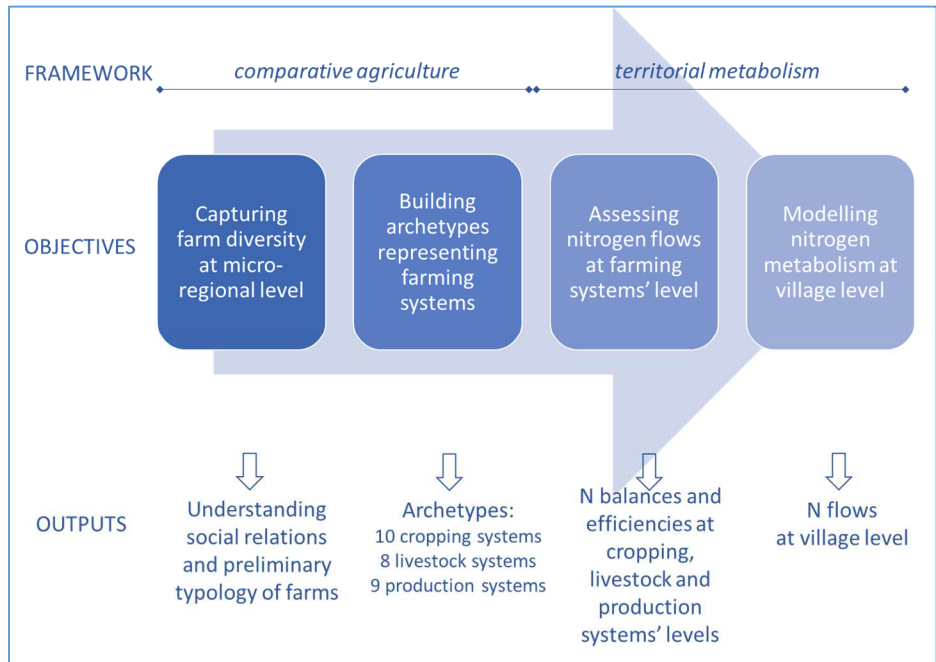Concurring with certain critiques of socio-ecological systems approaches, this result advocates for a better consideration of social diversity in the analysis of the environmental impacts of agriculture and in the design of interventions.

67

68   GRAPHICAL ABSTRACT

69

70

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

72   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 developed a conceptual framework at the interface between the bio-technical and social sciences. This approach allows not only to grasp

107 the diversity of farms and their functional interactions at the scale of a territory, but also to situate
108 this diversity in the environmental, historical and social conditions under which they were developed
109 (Cochet, 2015a), and thus address what we call "social diversity". The latter refers to the diversity of
110 farmers who are part of different social groups, and to the social relations that bind them around
111 land, labour exchanges and the resulting levels of remuneration, flows of matter and produce or
112 debt. Comparative agriculture has often been used to understand the relationships between farming
113 societies and their environment (e.g. Torquebiau et al., 2010; Leauthaud et al., 2013; Lacoste et al.,
114 2016), but environmental assessments based on this approach are still scarce (e.g. Moreau et al.,
115 2012).

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

128 India is a particularly interesting country to study crop-livestock interaction, as historically, the
129 integration of the two activities played a key role (Aubron et al., 2019). The green (for crops) and
130 white (for milk) revolutions of the 1970s (Dorin and Landy, 2009) encouraged more specialized
131 production systems, but the potential for integrating these two dynamics is, *a priori*, vast (Erenstein
132 and Thorpe, 2010). The stakes are high, as agricultural intensification has major environmental
133 consequences, particularly in terms of nitrogen pollution (Agrawal et al., 1999; Buvaneshwari et al.,
134 2017). Besides, rural societies in India are marked by strong contrasts in access to land
135 (Pouchepadass, 2006; Rawal, 2008) that place the issue of social diversity at the heart of its
136 agricultural development.

137 In this context, we aim at demonstrating the interest of combining the conceptual frameworks of
138 comparative agriculture with that of *territorial metabolism*, a systemic and multi-criteria assessment
139 method allowing qualitative and quantitative analyses of the transfer, storage and transformation of

140 matter within a territory (Barles, 2010; Bonaudo et al., 2016). We applied these combined

141 frameworks to model and analyse nitrogen flows at the scale of a village (360 households, 218 ha of

142 agricultural land) while considering the local diversity of farming systems. In particular, we looked at

143 the crop-livestock integration as a possible way to reduce nitrogen losses from agriculture, and

144 studied how social diversity impacts this integration. The choice of nitrogen was driven by the fact

145 that it is a powerful "marker" of the impact of human activity, agriculture in particular (Billen et al.,

146 2014): losses can occur during the different phases of the "nitrogen cascade" and can affect every

147 compartment of the environment (Galloway et al., 2003).

148 The study focused on a small region in the northwest of India, Petlad block, in Anand district, Gujarat

149 state. Like most alluvial zones in the Indian subcontinent, Petlad underwent a green revolution from

150 the 70s onwards, which translated into the extension of irrigated crops, particularly tobacco, to the

151 majority of the block's surface. In addition, dairy farming is prominent in Petlad, as it is located in the

152 collection zone of the Amul milk cooperative which inspired the white revolution in India and went

153 on to be a model for the implementation of other milk cooperatives in the rest of the country. Today

154 the animal density – cattle and buffalos – is among the highest in the world (Gilbert et al., 2018).

155

2. Methods

156

157 *2.1. Capturing farm diversity at the micro-regional level*

158 The comparative agriculture framework combines three interlocked scales of analysis, using specific

159 concepts for each: the "agrarian system" (Mazoyer and Roudart, 2006) at the village, region or

160 country level; the "production system" (PS) at the farm level; and the "cropping system" (CS) or

161 "livestock farming system" (LFS) at the plot or herd level (Cochet, 2012; see Supplementary materials

162 part I for detailed definitions).

163 Disparities between farmers in access to resources structure the choices of production and practices

164 and play a key-role in agricultural development processes (Dufumier, 2007). Capturing the diversity

165 of farms is thus an essential step of the research in comparative agriculture. At the regional level, this

166 is done through the combination of: (i) the characterization of ecosystem resources, which at least

167 partly define what can be produced, how, when and where; (ii) the reconstitution of the agrarian

168 history and the farm differentiation process over the last five decades (Cochet and Devienne, 2006;

169 Lacoste et al., 2018). Both analyses were achieved in Petlad through a two-month fieldwork and led

170 to a first typology of farms (figure 1).

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

FIELDWORK STEps

❶ Petlad block, 2 months landscape observations and interviews with older farmers (n=25)

❷ Petlad block, 3 months interviews with farmers (n=60) on cropping and livestock farming practices

❸ Village, 4 months interviews with farmers (n=49) on manure management and fertilization practices; measurements (water, manure, crops)

❹ Village, 5 months village mapping, interviews with farmers (n=42), census and cadastral data collection and assignement to farming systems

OUTPUTS

Understanding of social relations and preliminary typology of farms

Archetypes:
10 cropping systems
8 livestock systems
9 production systems

N balances and efficiencies at CS, LS and PS' levels

N flows at village level

171
172 **Fig. 1.** Research process in Petlad: frameworks, objectives, fieldwork steps and outputs
173

174 *2.2. Building archetypes to represent and assess farming systems*

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

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

188 of variables set beforehand collected through surveys within a reasonable period of time (Lacoste et
189 al., 2018).

190 The economic assessment included in this paper was based on the structure and the functioning of
191 farming systems as modelled in the archetypes, supplemented by data on prices, equipment lifetime
192 and use of hired labour, collected through the same interviews (figure 1, fieldwork step 2). More
193 details on the methods and indicators used for this economic assessment are available in Cochet
194 (2015a et 2015b) and other results for Petlad in Aubron et al. (2015).

195 *2.3. Assessing nitrogen balances and efficiencies at farming systems' level*

196 The nitrogen flows considered at cropping, livestock farming and production systems' level are
197 shown in figure 2. They arise from the material flows included in the archetypes, be they inputs, i.e.
198 flows entering into the systems, outputs, i.e. flows outing the systems, or internal flows, i.e. flows
199 circulating between the different components of the system in the case of production systems. This
200 knowledge was complemented during step 3 of the fieldwork by focuses on manure production,
201 storage, spreading and sales and on the way it varies between production systems in Petlad. We
202 converted these material flows into nitrogen flows using different sources of data (Supplementary
203 materials part II).
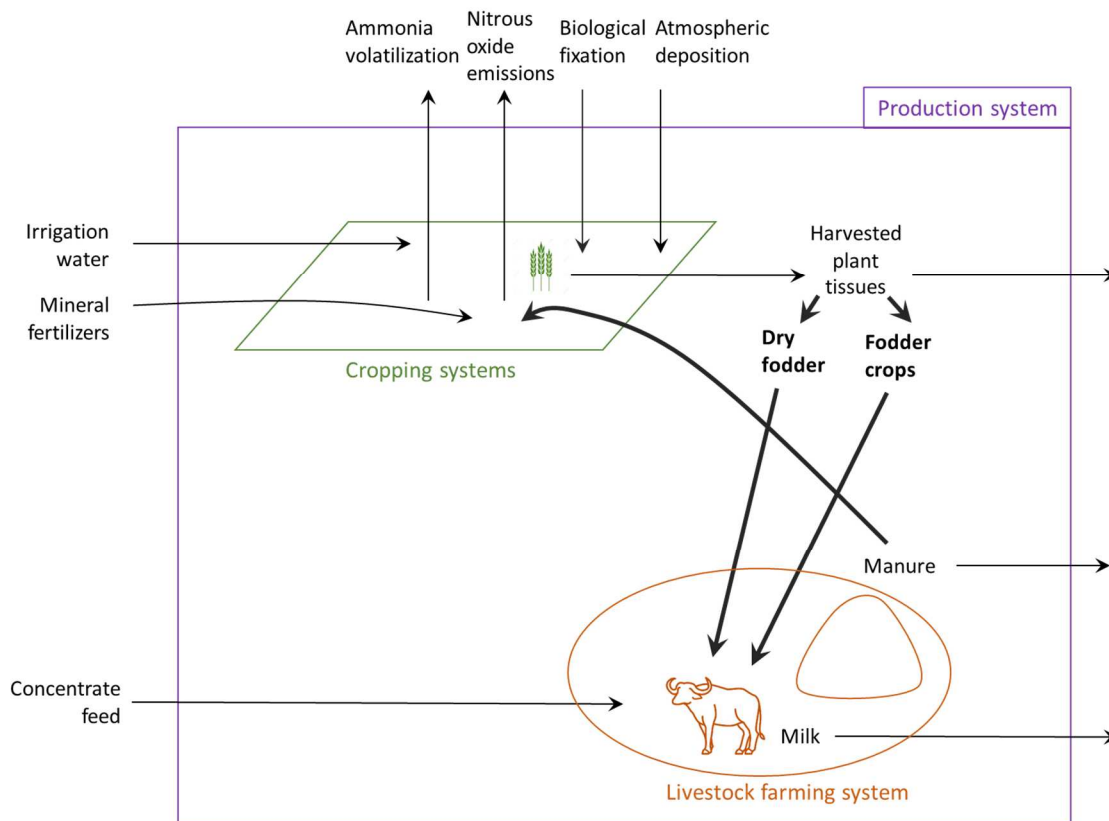
204
205 **Fig. 2.** Nitrogen flows at the cropping, livestock farming and production system scales (example of
206 Production System 5: small diversified farms). Production system internal flows are **in bold**

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

209 $N\ balance = N\ inputs - N\ outputs$ (Equation 1)

210 $N\ efficiency = \frac{N\ collected\ outputs}{N\ inputs}$ (Equation 2)

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

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

232 *2.4. Modelling nitrogen metabolism at village level*

233 The assessment of nitrogen territorial metabolism at village scale was carried out in a village located
234 in Petlad block, composed of 360 houses according to the 2011 population census. The choice of this
235 geographical entity – the village – was guided by the search of a compromise: this village represented
236 almost the whole diversity of farming systems identified in Petlad block, while considering a number
237 of farms which was not too high (a few hundreds to be compared to the several tens of thousands of
238 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.

272   We then converted these material flows into nitrogen flows and used them for assessing: (i) the

273   contribution of each category of inputs, internal flows and outputs to nitrogen flows at village level;

274   and (ii) the contribution of each production system to nitrogen flows at village level.

275   **3. Results**

276   Results are divided into two main sections. The first provides historical trajectories that are key to

277   understand today's production systems and presents their main features and economic results. The

278   second section assesses the environmental implications of this development path considering

279   nitrogen flows at both farming system and village level.

280   *3.1. Petlad's agricultural development: green and white revolutions and the persistence of*

281   *inequalities*

282   The reconstitution of Petlad's agrarian history carried out in this study showed that, in 1950, Petlad's

283   agriculture was characterised by fairly high crop-livestock integration from a technical point of view.

284   At that time, in this alluvial plain with a semi-arid climate, crops were mainly rainfed (millet,

285   sometimes associated with legumes, rice in the lower zones), with a single crop season during the

286   monsoon (*kharif*). Well irrigation, used to grow tobacco and vegetables, only involved 15 % of the

287   cultivated surface (Shah and Shah, 1950). Ruminant livestock farming (sheep, cattle, buffalos) played

288   an essential role in the fertility management of the cultivated land: animals were fed on uncultivated

289   grazing areas, on cultivated plots during the fallow period and on crop residues. Excreta were used as

290   amendment and for the renewal of the soil fertility by nutrient transfer. Draught animals were also

291   essential for some cultivation operations (tillage), drawing water from the wells, and transportation.

292   In terms of social organisation, there were strong contrasts. Land was largely concentrated in the

293   hands of owners mainly belonging to the Patel caste, who owned up to 20 ha per household, and was

294   worked by landless labourers from the Solanki, Parmar, Chauhan, Thakor and Vagri castes, who

295   rarely owned animals. Two pastoral communities (Rabhari and Bharvar) completed this picture. The

296   latter did not own cultivated land either, but they had access rights to grazing areas for their herds of

297   ruminants and hence played a role in providing the farmers with draught animals and participated in

298   the fertility management of cultivated land.

299   In Petlad, from the 1960s onwards, the green revolution took the form of an expansion of irrigated

300   surfaces (figure 3) and an increase in the cropping intensity, like in the other alluvial zones in India

301   that can be easily irrigated by wells and bore wells fitted with motor pumps. Today, the cultivated

302   area represents 90% of the district's territory, and it is entirely irrigated. Tobacco, a very profitable

303   winter (*rabi*) 7-month crop, gradually gained importance in the crop rotation. It is often rotated with

304   a summer crop (millet) or a monsoon crop (rice or millet), and is sometimes part of an annual

305   rotation including three crop cycles. Since the 1990s, banana and chilli cultivation has increased in

306   farms that had the means to purchase the expensive equipment and inputs that these crops require.

307   In terms of land, the successive agrarian reforms adopted in India (Appu, 1997) had only a limited

308   impact in Petlad: some families who had little or no land were granted plots (often located in zones

309   earlier reserved for grazing, figure 3), but a large number remained landless and continued to work

310   as agricultural labourers. They are particularly present in tobacco cultivation, which is very labour

311   intensive. Some of these landless families have gained access to land *via* sharecropping contracts,

312   where the owner provides the inputs, and the sharecropper provides all the labour and receives 20%

313   of the harvest. Although landowners in Petlad were little affected by the agrarian reforms, the size of

314   their properties has diminished as a result of successive divisions due to inheritance. Few still own up

315   to ten hectares, but today, a 1 to 2 ha farm is considered a "large farm" (table 1).
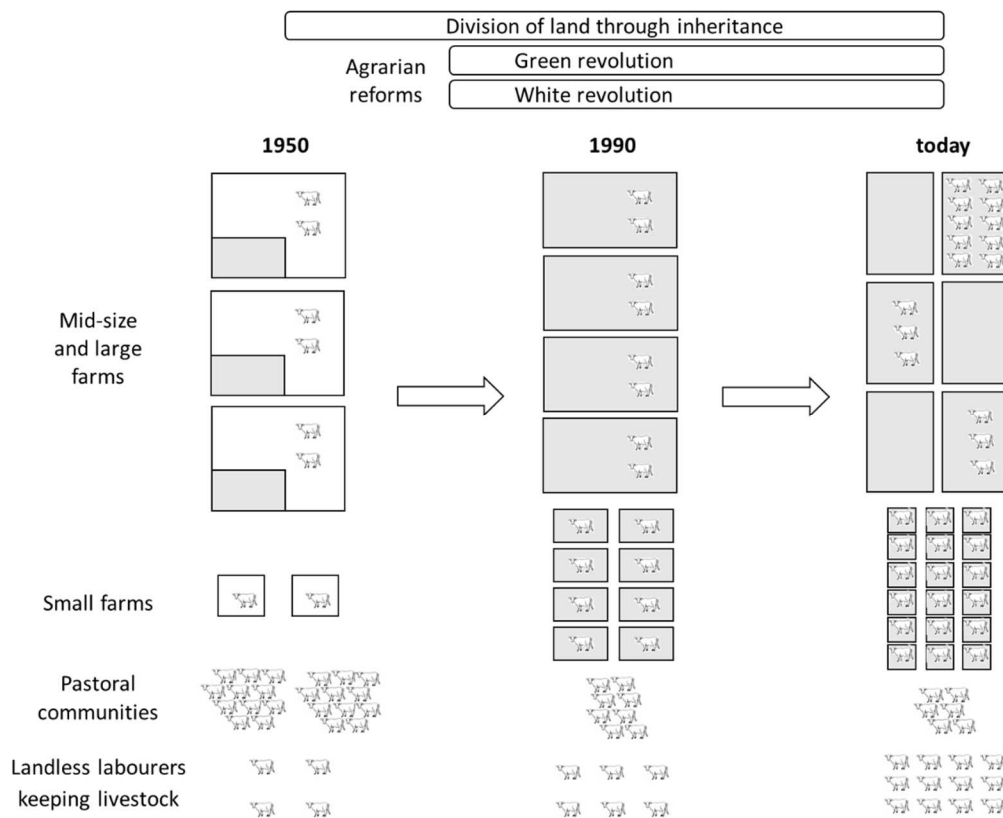
316

317   **Fig. 3.** Diagram showing agricultural change in Petlad. The rectangles represent the cultivated area by

318   different production systems, and are grey when they are irrigated; cows represent the ruminant

319   herds.

320   As the use of synthetic fertilisers, motor pumps and then tractors increased, livestock lost its

321   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.

354　**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%	-	-	-

355　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-
356　annual rotation.
357　co=cow; bu=female buffalo
358　Fn=natural fodder; Fd=dry fodder (straw); Ffc=fodder crops; C=concentrate feed.
359　* 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).

360   *3.2. Environmental implications of this development path in terms of nitrogen flows*

361   *3.2.1. Nitrogen balances at the farming system scale*

362   Table 2 shows N balances and efficiencies for each cropping system, livestock farming system and

363   production system. For more details on inputs and outputs, see Supplementary materials part V.

364   **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

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

369   Among cropping systems, fodder cultivation showed the smaller N balance surpluses, with even

370   negative N balances for Napier grass and maize/maize/sorghum rotation. Rice cultivation preceded

371   by a fallow period (fallow/fallow/rice) and chilli cultivation also presented relatively small surpluses,
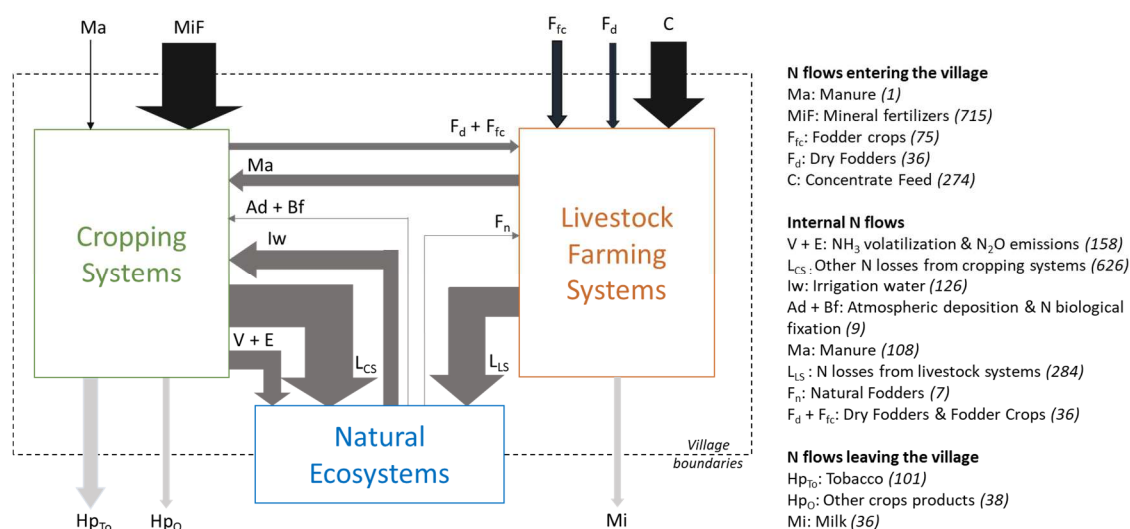
372 particularly when compared to cropping systems that include tobacco. For the latter the balance
373 surpluses were all above 600 kgN/ha/yr as a consequence of the large N inputs (between 762 and
374 1398 kgN/ha/yr) and small N outputs (between 269 and 560 kgN/ha/yr). The tobacco/millet/rice
375 rotation shows the largest surplus of 880 kgN/ha/yr. Mineral fertilisation was the main input of N in
376 all the cropping systems (37 to 75% of inputs), with the exception of the fallow/fallow/rice system,
377 where irrigation was the main N input (44%). Organic manure represented only 11 to 40% of the
378 input. The N efficiencies were good for fodder crops and very poor for other crops (between 0.09 and
379 0.21).

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

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

390 *3.2.2. Nitrogen flows at the village scale*

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

403

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;

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

425   **4. Discussion**

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

430   *4.1. High nitrogen surpluses and an under-exploitation of the crop-livestock integration potential*

431   Whether at the scale of cropping systems, livestock farming systems or production systems, nitrogen
432   balances in Petlad were mainly high surpluses compared to literature values. The nitrogen balances
433   estimated in long-term socio-ecological research for the pre-industrial period in Europe, which
434   represents a relevant reference to analyse the sustainability of agricultural systems (Garcia-Ruiz et
435   al., 2012), did not rise above 10 kgN/ha/yr, and were sometimes negative (Garcia Ruiz et al., 2012;
436   Gizicki-Neundlinger and Güldner, 2017). The balance obtained from FAO cultivation data for the
437   contemporary period (2009) shows a surplus of 10 kg/ha/yr for Africa (Billen et al., 2014). The annual
438   surplus of 642 kgN/ha/yr for cultivation obtained in the studied village is twenty-two times higher
439   than the French average in 2005 (Peyraud et al., 2012), nearly eight times higher than in the intensive
440   pig and dairy farming region in France (Le Gall et al., 2005), two and a half times higher than the
441   value obtained from the FAO data for China, the region that shows the highest surplus in Billen et
442   al.'s (2014) study, and nearly three times higher than the maximum value obtained in pig farms in
443   Italy (Bassanino et al., 2007). While accounting for losses towards the hydrosphere and the
444   atmosphere, the latter study indicates a farm-gate balance surplus of 486 kgN/ha/yr (Bassanino et
445   al., 2007), i.e. half of the village total surplus value obtained in this study (926 kgN/ha/yr). Such very
446   large nitrogen losses into the ecosystem are likely to generate pollution. Indeed, water
447   contamination by nitrates was confirmed by groundwater analyses carried out during step 3 of the
448   field work in Petlad (11 of the 16 samples taken are over the NO_3 potability limit of 50 mg/L), even
449   though part of this contamination could be due to human waste. This is consistent with water quality
450   degradation observed in other regions of India that were also involved in the green revolution
451   (Agrawal et al., 1999; Singh and Singh, 2004; Buvaneshwari et al., 2017).

452   Looking more closely, cropping practices seem to be the most problematic, because crops contribute
453   far more than livestock farming to nitrogen loss towards the ecosystem (Figure 4). The nitrogen use

454 efficiency in Petlad is also far better in livestock farming systems than in cropping systems, except for

455 fodder cultivation systems. In addition, comparing efficiencies with references found in the literature

456 suggests a larger gap in performance for cropping systems than in livestock farming systems. In

457 Austrian agriculture during the pre-industrial period, two studies estimated that the nitrogen loss

458 linked to the storage and spreading of manure varied respectively between 40 and 60% (Krausmann,

459 2004) and 27 and 60% (Güldner et al., 2016). In African crop-livestock systems, Rufino et al. (2006)

460 quoted a study carried out in Kenya, where up to 40% of the nitrogen contained in excreta was not

461 recovered due to collection practices, and estimated that 23 to 70% of the nitrogen recovered was

462 then lost during the manure storage process. The nitrogen flows at the scale of large regions

463 described by Billen et al. (2014), based on FAO data and works by Sheldrick et al. (2003) and Oenema

464 et al. (2003), revealed that animal excreta not recovered by man, and the nitrogen lost during the

465 storage or spreading of manure, represented 70% of the nitrogen excreted by animals in India, and

466 67% in Europe. With 78% of the nitrogen excreted in the village lost through uncollected excreta or

467 during the manure collection, storage or spreading processes, Petlad's livestock farming systems

468 show fairly low performance for these criteria.

469 In the case of crops, the values obtained can be compared with those provided by Austrian studies

470 which are to our knowledge among the most detailed on this subject with an historical perspective in

471 the literature. While the balances calculated for two large Austrian farms for the pre-industrial period

472 revealed a nitrogen use efficiency of about 30% for crop cultivation, it was far better (54 and 77%) for

473 peasant farms (Gizicki-Neundlinger and Güldner, 2017). In other studies, still in Austria (Krausmann,

474 2004), the nitrogen use efficiency for crop cultivation was above 63%, both in the pre-industrial and

475 the contemporary period. Finally, in the regional comparison based on FAO data, the efficiency for

476 crop cultivation was ≥ 40% in all the regions studied except for three, including India and China

477 (Billen et al., 2014). According to the same study, the global world efficiency of nitrogen use in crop

478 cultivation was 43%. Thus, with an efficiency of 9 to 21%, Petlad's non-fodder cropping systems seem

479 to be highly inefficient from the perspective of nitrogen use. This poor efficiency in cultivation has

480 been also observed in other works in India (NAAS, 2005; Singh and Singh, 2008; Velmurugan et al.,

481 2008), but the values obtained in Petlad were even lower.

482 This inefficiency is linked to a very high use of imported inputs, representing 79% of the nitrogen

483 input related to agriculture in the village. Such a dependency on external inputs has been found in

484 livestock farms in Italy (Bassanino et al., 2007), but it was much lower for agricultural systems studied

485 in different regions of Austria (Krausmann, 2004): while imported nitrogen was absent in pre-

486 industrial times, in contemporary times it represented 57% of the nitrogen input in the lowlands,

487 34% in the uplands and only 8% in the alpine zone of Austria. Crop-livestock integration, which makes

488   it possible to substitute imported nitrogen with internal flows in the territory (Dumont et al., 2013),
489   was largely under-utilised in Petlad: although nitrogen input from manure spreading was almost
490   sufficient to cover the crop needs, farmers applied two to four times more nitrogen in the form of
491   synthetic fertilisers, generating considerable surpluses. As well as this, the large use of concentrates
492   for animal feed can also be explained by the low level of crop-livestock interaction in the territory:
493   although rice and millet straw contributed to animal feed, the residues of the main crop – tobacco -
494   could not be consumed by animals. Moreover, the space allocated to fodder cultivation was very
495   limited (3% of the cultivated surface in the village, see map b in Supplementary materials part VI) and
496   the deficits in the nitrogen balance observed for fodder cropping systems illustrates the priority given
497   to other crops.

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

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

514   *4.2. Inefficiency and pollution linked to socio-economic conditions*

515   Several research studies are concerned with the drivers behind the specialization and input-
516   intensification of agriculture and the lock-ins that hinder its evolution towards a more sustainable
517   agriculture. Agricultural policies, e.g. the CAP in Europe, market globalization and global
518   macroeconomic conditions are thus often identified as important factors (Ryschawy et al., 2013;
519   Allison et al., 2004). Other authors insist on the lack of available information on more sustainable
520   practices, the logistical constraints to their implementation and the difficulties of coordination

521   between value chain operators (Meynard et al., 2018; Magrini et al., 2019; Mamine and Farès, 2020).

522   In Petlad, agricultural policies and, in particular, the subsidies granted to the fertiliser industry

523   combine to provide a plausible explanation of the low level of crop-livestock integration. These

524   subsidies are one of the pillars of the policies supporting the green revolution in India and they

525   represent the second main item in the national budget allocated to agriculture (Gulati et al., 2018).

526   The comparison between the selling price of urea and the amount of the subsidy per kilo of urea

527   (Dorin, 2021, updated from Dorin and Jullien, 2004) suggests that it results in a threefold decrease in

528   the price of urea for farmers, who are hence encouraged to use them in large quantities. Therefore,

529   the reduction of the subsidies and the resulting increase in the cost of synthetic nitrogen fertilisers

530   appear as a potential lever to strengthen crop-livestock integration and limit the environmental

531   impact of agriculture in Petlad.

532   The results obtained in this study suggest, however, that a reduction in fertilisers subsidies alone is

533   unlikely to be sufficient. Nitrogen flows are also shaped by the diversity of farms and unequal access

534   to resources at the local scale, which helps to define the varying interest shown in livestock and crop

535   activities by the different social groups. The PS1 to PS4 production systems that have access to large

536   areas of land are certainly highly productive, but they show some of the poorest nitrogen efficiency

537   levels at the farm scale. While such farms are numerically fewer in the village, they are the largest

538   contributors to the nitrogen surplus. PS5 to PS9, which have less or no land, use nitrogen more

539   efficiently (except PS6), and generate lower surpluses. Their contribution to the village's crop

540   production is low (19, 15 and 6% for cereals, tobacco and fruits or vegetables), but their livestock

541   activities allow them to produce about one quarter of the village's milk.

542   Our economic assessment suggests that behind the different impact of farm types on the

543   environment, there are important differences in remuneration. The income for PS5 to PS9 remains

544   close or even below the poverty threshold. PS1 to PS4 earn far higher incomes and a large landowner

545   who gives out land for sharecropping can earn up to 37 times more than a landless agricultural

546   labourer. Thus, while the tobacco produced by PS1 and PS3 generates employment for families who

547   have little or no land, their situation remains precarious. They are very poorly paid, and such

548   employment does not allow them to escape poverty. Therefore, the largest environmental impact of

549   these production systems cannot be justified by arguments of social equity and fair economic

550   development.

551   The characteristics of Petlad's territorial metabolism emerges more clearly once social and

552   biophysical diversity dimensions are combined. Most owners with access to relatively large areas of

553   land (PS1 and PS3) carry out irrigated cultivation based on cheap labour supplied by day labourers or

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

574 Thus, crop-livestock integration is low in Petlad because, in addition to the low price of synthetic
575 fertilizers, farmers at both ends of the social scale, given their access to resources, either have little
576 interest in integrating these two activities or do not have the means to do so. These results show
577 similarities with a study of the dynamics of crop-livestock systems in the Mediterranean (Alary et al.,
578 2019), which indicates a tendency to specialise in irrigated crops or milk cattle on farms that have
579 access to large areas of land, and the persistence of crop-livestock interactions in smaller farms and
580 non-irrigated regions, which are more fragile economically. Their analysis shows "an overwhelming
581 antagonism between social vulnerability and ecological efficiency" (Alary et al., 2019).

582 *4.3. The need to take social diversity into account in research on the environmental impact of*
583 *agriculture*

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

586   The first consists in considering what we call the "technical diversity". Like our study in Petlad, such

587   approach assesses the environmental impacts of different types of farms, and analyse the results in

588   terms of underlying bio-technical processes. It is extremely useful, both to understand the

589   environmental impacts of agriculture and to consider ways of reducing the negative impacts. Such an

590   approach allows identifying the room for manoeuver that, for example, enable an increase in the

591   efficiency of nitrogen use in specific types of farms, or even at the scale of territories or landscapes.

592   Several authors nonetheless underscore its limits and the need to include the social dimension in the

593   analysis (Scoones and Toulmin, 1998; Ramisch, 2005; Poccard-Chapuis et al., 2014).

594   Rooted in the social sciences, the second approach to the diversity of farms focuses on "social

595   diversity", makes social relations central to the analysis, and sees diversity through the lens of

596   inequality and power relationships in societies (Fabinyi et al., 2014). It is a means of showing how

597   social relationships shape the environmental impacts of agriculture. For example, the study of the

598   manoral regime in pre-industrial Austria showed that landlords produced large surpluses while

599   maintaining agroecological sustainability through flows of matter (Gizicki-Neundlinger and Güldner,

600   2017). On the contrary, taxation and the very limited access peasants had to land, for grazing in

601   particular, and thus to livestock activity, did not allow them to ensure the flow of nitrogen nutrients

602   required for the sustainability of their cultivation, thus compromising their subsistence.

603   We can draw a parallel between the historical situation in Austria, which the authors describe as "the

604   sustainability costs of inequality" (Gizicki-Neundlinger and Güldner, 2017), and the one we have

605   revealed in Petlad, even if it is reversed, where large landowners who cultivate tobacco make a high

606   contribution to nitrogen surpluses and hence do not maintain agroecological sustainability.

607   Nonetheless, like the landlords in Austrian case, the large landowners earn a large income from both

608   their large landholdings and the fact they make use of a cheap hired workforce. At the other end of

609   the social scale, some of the landless agricultural labourers who seek to complement their income

610   with livestock, are forced to stop this activity, as collecting natural fodder in this highly cultivated

611   space requires too much time in comparison to the time available for them before and after their day

612   of paid work. From the perspective of using research results to design projects and policies that could

613   help increase the sustainability of agriculture, the inclusion of this social diversity is therefore very

614   useful: while there are indeed numerous good agronomic, ecological and fossil energy-saving reasons

615   to transform practices and reinforce crop-livestock integration in Petlad, it is unlikely that there will

616   be any change as long as the socio-economic conditions, particularly the current features of social

617   diversity, do not evolve. As highlighted in the management of coastal resources (Fabinyi et al., 2010),

618   taking social diversity into account in Indian agriculture is likely to increase the efficiency of policies

619   seeking to increase the effectiveness of nitrogen use.

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

639 More than the limits of approaches to the technical diversity of farms, socio-ecological systems, or
640 the socio-ecological metabolism, the lesson we can draw from this research is that it is necessary to
641 take social diversity into account in the analysis of the environmental impacts of agriculture and in
642 the search of solutions to improve these impacts. The need for interdisciplinarity in a study of crop-
643 livestock relations, underscored by scholars working in the bio-technical sciences and farming system
644 research (Devendra, 2001; Tanaka et al., 2008; González-García et al., 2012), is hence reinforced: to
645 include social diversity in the analysis, it is necessary to draw upon the social sciences, particularly
646 critical approaches that distinguish themselves "from a system ontology" (Stojanovic et al., 2016).
647 We should avoid "reinventing the wheel" by properly including contributions from different fields of
648 the social sciences that emerged in response to similar debates that took place in the past, for
649 example, on the inclusion of inequalities and hierarchies in anthropology (Fabinyi et al., 2014). The
650 question of linking frameworks from the bio-technical sciences and the social sciences nonetheless
651 remains a challenge (Stojanovic et al., 2016) to which comparative agriculture provides answers in
652 the agricultural field (Cochet, 2015a). In the light of the study conducted in Petlad, two constitutive
653 features of comparative agriculture seem to be crucial to an understanding of social diversity: (i) the

654 long fieldwork, with observation and interview methods that are similar to ethnography, which allow

655 for a finer understanding of social relations than the surveys that are often used in the bio-technical

656 sciences; (ii) the study of agrarian changes over the long term of six decades, which highlights the

657 process by which farms are differentiated, and allows us to grasp their current diversity and

658 relations.

659 **5. Conclusion**

660 Crop-livestock integration, which is recognised today as a key lever to improve the environmental

661 impacts of agriculture, remains limited in Petlad. In this area of alluvial plain, which is intensely

662 cultivated today and has a very high animal density, crop-livestock interactions, represent minor

663 nitrogen flows in comparison to the flow of inputs in the form of synthetic fertilizer and feed

664 concentrates. The output flows, in the form of tobacco, cereals and milk, are also low and most of

665 the nitrogen input is lost into the hydrosphere and the atmosphere, where it contributes to pollution.

666 This study shows, that considering the existing socio-economic conditions in Petlad, particularly in

667 terms of social diversity, allows to shed a new light on this environmentally harmful situation.

668 Indeed, most of the owners who have large landholdings focus on very profitable tobacco production

669 and tend to abandon livestock, which they no longer need either technically or economically. Their

670 farms, that make use of large amounts of synthetic fertiliser, generate high nitrogen surpluses. The

671 households who have access to small areas of land are motivated to raise milk animals, in order to

672 supplement their lowest incomes, which they earn from crops: small farms raising one or two female

673 buffalo show a higher level of crop-livestock integration, use nitrogen more efficiently, and are minor

674 contributors to the village's nitrogen surplus. Finally, the landless agricultural labourers for whom

675 livestock is vital, as they earn so little working as labourers for landowners, show a very efficient use

676 of nitrogen, but they dedicate a large amount of time gathering natural fodder.

677 However relevant it is from the environmental viewpoint, stronger crop-livestock integration is

678 unlikely to happen in Petlad unless the socio-economic conditions change. This result advocates for

679 characterizing the social diversity when analysing the environmental impacts of agriculture and

680 considering solutions to those environmental impacts. Echoing the suggestions that emerge from the

681 critical analysis of socio-ecological systems or socio-ecological metabolism approaches discussed in

682 this article, comparative agriculture combined with territorial metabolism seems capable of fulfilling

683 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