Environ Dev Sustain (2010) 12:669–689
DOI 10.1007/s10668-009-9218-z

Crop–livestock interactions along agro-ecological gradients: a meso-level analysis in the Indo-Gangetic Plains, India

Olaf Erenstein · **William Thorpe**

Received: 26 June 2009 / Accepted: 14 October 2009 / Published online: 29 October 2009

Abstract Although conceptually simple and often idealized, disentangling crop–livestock interactions typically proves more complex in practice. Part of the complexity arises from their changing nature along agricultural intensification gradients. Such interactions increase in scope when extensive systems intensify, but decline in importance as already intermediate systems intensify further. This changing nature of crop–livestock interactions in relation to the system's developmental stage implies that these exchanges can both contribute but also undermine system sustainability. We examine crop–livestock interactions in the Indo-Gangetic Plains as an empirical case, drawing from village surveys to explore and illustrate these relations and implications along the agro-ecological gradient of this vast and important eco-region. Such an understanding is increasingly needed as adapting crop residue management practices is recognized as the key to address sustainability concerns in the prevailing rice–wheat systems and as a stepping stone towards conservation agriculture. The agricultural R&D community needs to incorporate this understanding more proactively into its R&D agenda if it is to succeed in sustaining productivity gains, improving rural livelihoods equitably, and securing environmental sustainability.

Keywords Crop residue management · Rice–wheat systems · Livestock feeding · Crop–livestock interactions · Intensification gradient · Indo-Gangetic Plains

Readers should send their comments on this paper to BhaskarNath@aol.com within 3 months of publication of this issue.

O. Erenstein (✉)
International Maize and Wheat Improvement Centre (CIMMYT), NASC, Pusa, New Delhi 110012, India
e-mail: o.erenstein@cgiar.org

W. Thorpe
International Livestock Research Institute (ILRI), NASC, Pusa, New Delhi 110012, India

Present Address:
W. Thorpe
2 Stratfield Close, Cambridge CB4 3NA, UK

1 Introduction

The Green Revolution transformed South Asia's agriculture and led to the emergence of rice–wheat systems in the Indo-Gangetic Plains (IGP). These intensive systems cover some 13.5 million ha and became the region's granary supporting millions of livelihoods and underpinning national and regional food security. India thereby moved from a state of deficiency in these staples to a position of secure self-reliance. However, since the 1990s there are increasing concerns over the sustainability of rice–wheat systems. Ominous indicators include stagnating productivity gains and increasing signs of natural resource overexploitation, including falling ground water tables and soil degradation. These are generally attributed to the prevailing natural resource management practices in the current rice–wheat production systems (Pingali and Shah 2001).

The Rice–Wheat Consortium (RWC) for the IGP (www.rwc.cgiar.org) was established in 1994 to address these sustainability concerns (Seth et al. 2003), and it has become a strong advocate of conservation agriculture-based technologies (Hobbs et al. 2008). Conservation agriculture revolves around minimal disturbance of the soil, retention of crop residue mulch on the soil surface and a rational use of crop rotations. These principles, along with profitability at the farm level, are increasingly recognized as essential for sustainable agriculture. To date, most significant progress with conservation agriculture-based technologies in the rice–wheat systems has been made by reducing tillage for wheat, particularly through zero tillage in NW India (Erenstein and Laxmi 2008). Crop residue management—hereafter referred to as straw management in view of the prevailing cereals in the IGP—also has to be addressed to ensure adequate retention of soil cover. The use of zero tillage wheat without necessarily maintaining some soil cover in the IGP has so far had limited perceptible negative consequences (Erenstein and Laxmi 2008), a consequence of its seasonal use, with plots still being tilled for the subsequent rice crop (Erenstein et al. 2008). However, with the year-round—or double no-till—rice–wheat system, straw retention becomes imperative. The retention of straw as mulch as advocated under conservation agriculture likely implies trade-offs, particularly where these have alternate uses or scarcity value (Erenstein 2003). These trade-offs are expected to vary within the IGP: behind the apparent homogeneity of vast irrigated plains—often resulting in generalizations based on the NW situation, which is better documented—are some marked agro-ecological variations resulting in both straw scarcities and surpluses (Erenstein et al. 2007b).

Mixed crop–livestock (CL) farms sit at the core of the livelihood strategies of millions of predominantly resource-poor families in the IGP. These farms reflect the complementarities between CL production, although the prevailing crops and livestock species vary spatially along an agro-ecological gradient (Erenstein et al. 2007b). Furthermore, the agro-ecological diversity implies that the role, type and extent of CL interactions are likely to vary considerably and that their influence on technological change cannot be generalized. Yet, until recently, there has been little systematic research to assess the benefits of these interactions, or to evaluate the potential for improvement. A review from South Asia (Devendra et al. 2000) reported a paucity of research that incorporates livestock interactively with cropping and a woeful neglect of social, economic and policy issues. Biophysical commodity-based crop *or* livestock research dominated, a systems perspective was lacking, and many of the developed technologies were not adopted. The need for a systems perspective in agricultural R&D and the varying role of CL interactions in agricultural systems has been eloquently illustrated in Pakistan (Byerlee and Husain 1992). More recently, broad classifications of CL systems in South Asia and their component technologies have been documented (e.g. Parthasarathy Rao and Birthal 2008), although there is little documentation of CL interactions in the IGP. Scale poses a particular challenge to the analysis of CL interactions and livelihoods in a vast and diverse eco-region (Dalgaard et al. 2003). As well as understanding the complex micro-level system interactions, there is a need to link these to the wider landscape (Scoones 2009). The divide between the macro- and micro-level is particularly persistent in the IGP whereas its diversity makes it imperative to contextualize findings for any given study. Indeed, without the larger agro-ecological context, the interpretation of locale-specific studies remains problematic and undermines their contribution.

Improving our understanding of CL interactions and their contributions to rural livelihoods along the IGP's agro-ecological gradient will better position the R&D community to be more effective in addressing the major challenges of improving rural livelihoods equitably while ensuring environmental sustainability in this important eco-region. This is in line with the external review of the Rice–Wheat Consortium (Seth et al. 2003), which emphasized the need to assess interventions from a more holistic system perspective. Agro-ecological gradients often are associated with intensification gradients, and thereby can help to interpret the factors that brought the system to its current state. This understanding will also help to deduce the likely future development scenarios and implications for research, extension and policy change.

The present study aims to fill some of these knowledge gaps by analysing CL interactions in relation to the IGP's agro-ecological gradient. In the next section, a conceptual framework links CL interactions to agricultural intensification gradients. The subsequent section introduces the study area, the associated agro-ecological gradient and the village surveys that were used to characterize CL interactions. Finally, the results are presented and discussed, with emphasis on straw management—the critical nexus between conservation agriculture and ruminant feeding.

2 Conceptual framework

Integrated CL systems are often perceived positively (e.g. Devendra 2007). They are seen as sustainable and beneficial for the environment and for pro-poor development, capitalizing on CL interactions that allow for complementarities, circular resource flows (e.g. nutrient cycles) and reduce the reliance on external inputs. However, measuring these implications presents numerous challenges, and there are problems to establish how integrated a given agricultural system really is. For instance, Sumberg (2003) distinguishes CL interactions in terms of exchanges of biomass, manure, power and financial resources and argues that CL integration needs to be assessed in terms of the physical dimensions of space and time and the organizational dimensions of management and ownership. A related important issue is that the costs/constraints and benefits/opportunities associated with CL interaction differ along these dimensions. CL interactions are not cost free and will only remain of interest to farmers when the benefits associated with them outweigh the costs. The local agro-ecology and system evolution will influence these incentives and thus farmers' interest in CL interactions.

A schematic representation of CL interactions is provided in Fig. 1. Interactions are perceived as the overlap between the crop and livestock sub-systems. Most obvious are the direct physical exchanges, which generally revolve around the use of crop biomass as animal feed (e.g. straw, other crop by-products, forage crops, feed crops), nutrient flows (e.g. use of farm yard manure-FYM) and power supply (e.g. use of animal traction). Less

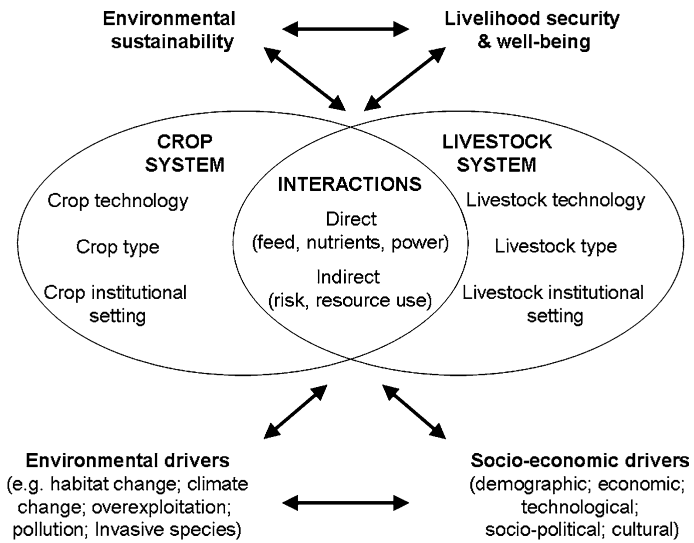

Fig. 1 A schematic representation of crop–livestock interactions

obvious are the indirect interactions, which include complementarities in income and resource use (e.g. labour, cash) and the associated risk reduction. These interactions are shaped by characteristics of the sub-systems, with each being a function of technology use, the type of enterprise and the institutional setting. The sub-systems and their interactions have implications for both livelihoods and the environment (Erenstein et al. 2007b). In turn, the sub-systems are influenced by a number of environmental and socio-economic drivers (Millennium Ecosystem Assessment 2005). One would thus expect systems and their sub-systems to evolve based on the associated drivers and feedback loops. Correspondingly, one would expect the dimensions of CL interactions to change along an agricultural system intensification gradient.

Table 1 presents a conceptualization of agricultural systems along an intensification gradient. The gradient thereby relates to the intensity of agricultural land and technology use, a reflection of population density, market opportunity and/or resource endowments. On one extreme, one can envisage extensive subsistence systems where the crop and livestock sub-systems largely exist in parallel with limited CL interactions. On the other extreme, one can envisage intensive commercial crop and livestock production systems in which interactions again play a relatively limited role as the systems have increasingly specialized. CL interactions play the most prominent role in-between these two extremes. As extensive systems start to intensify, there is an increasing degree of CL integration, with an increasing role for straw as feed source, FYM for fertility management, animal power for tillage and sub-system complementarities. Associated with the intensification gradients are the system orientation and integration in input–output markets and the factor prices, which variously induce capital-, labour- and/or land-saving innovation.

Table 1 implicitly presents three system typologies. In practice, existing systems may be variously positioned along this gradient. Indeed, one would not expect all of the individual system attributes to evolve simultaneously and harmoniously along the gradient. For instance, diverging technology options and institutional settings may imply that within a specific locality the crop and livestock systems are variously positioned along the

Table 1 Conceptualization of agricultural systems along an intensification gradient

Indicator	Intensification gradient		
	Extensive	Intermediate	Intensive
Crop nutrient source	Fallow	Manure	Chemical fertilizer
Livestock feed source	Rangeland	Crop residues	Feed crops, concentrates
Agricultural power source	Manual	Animal traction	Motorized
Agricultural finance source	Natural assets/stocks	Informal credit/loan	Formal credit/loan
System orientation	Subsistence, barter exchange	Semi-commercial	Commercial, monetized market
Crop + livestock system evolution	Parallelization	Integration	Specialization
Nominal cost gradients			
Capital	High	←	Low
Labour	Low	→	High
Land	Low	→	High
Induced innovation	Capital saving	↔	Land and/or labour saving

intensification gradient. These diverging transitions are likely to imply sub-optimal outcomes in terms of environment and livelihoods.

The foregoing has two important implications. First, integrated CL production systems are often idealized, particularly from an agro-ecological point of view. However, the intensification gradient suggests that CL interactions may first facilitate system intensification of initially extensive systems, but are likely to become less important as systems with intermediate intensification levels intensify further. Second, system evolution and how it influences CL interactions have important implications for agricultural R&D.

3 Materials and methods

3.1 Study area

The study area encompasses the Indo-Gangetic Plains (IGP) in India, comprising five contiguous states across northern India along the Himalayan range: Punjab, Haryana, Uttar Pradesh (UP), Bihar and West Bengal (WB). The IGP can be divided broadly into north-western (NW) and eastern plains. The NW—the Trans-Gangetic Plains (TGP) comprising Punjab and Haryana—is the Green Revolution heartland. It is mainly semiarid and would be water-scarce if not for its irrigation infrastructure. Winter wheat has traditionally been, and continues to be, the mainstay of food security, whereas monsoon rice only expanded rapidly in recent decades. In contrast, the eastern plains (WB) suffer from flooding, and rain-fed lowland rice is the traditional staple. It was only in recent decades that wheat was introduced and picked up as a cool-season crop in eastern India, north of the Tropic of Cancer. The prevailing large ruminants provide another important contrast: cattle in the east and buffalo in the NW (Table 2). In broad terms, therefore, the eastern plains are characterized by rice–cattle farming systems, while the NW are based on wheat–buffalo systems. The states of UP and Bihar form the transition zone in-between (Erenstein et al. 2007b).

Table 2 Characteristics of IGP sub-regions

	TGP	UP	Bihar	WB	Mean (s.d.)
Secondary data (state level)					
Average farm size (2001, ha)	3.0	0.8	0.6	0.8	0.9
Rice–wheat system area share (2004, % cultivated area)	44	24	22	5	25
Irrigated area (2001, % cultivated area)	90	73	49	44	67
Tractor density (2002, tractors km^{-2})	8.2	2.8	1.1	0.4	3.1
Livestock density (2003, cow equivalents km^{-2})	199	201	203	255	210
Change in livestock (1972–2003, % growth p.a.)	0.9	0.3	0.4	1.6	0.6
Herd composition (2003, % heads)					
Buffalo	69	39	21	3	29
Cattle	20	30	40	45	36
Small stock	10	28	39	52	35
Average herd size (2003, cow equivalents per rural household)	3.6	2.4	1.5	2.0	2.2
Rural population density (2001, km^{-2})	328	546	788	651	568
Rural population below poverty line (2000, %)	7	31	44	32	32
Village survey data					
Male wage rate (Rs/day, $n = 70$)	87[d]	58[c]	49[b]	39[a]	57 (± 21)
Rental price irrigated land ('000 Rs/ha, $n = 68$)	27[b]	15[a]	11[a]	14[a]	17 (±10)
Interest rate moneylenders (% p.a., $n = 46$)	23[a]	38[b]	58[c]	98[d]	51 (±33)

Notes State level indicators derived from various secondary data sources as cited in Erenstein et al. (2007b). Village survey data from Erenstein et al. (2007b). Data preceding different letters differ significantly—Duncan multiple range test (significance level: 0.10), within row comparison. Average exchange rate for 2005: US$1 = Rs44.1

The prevalence of buffalo in the NW is relatively recent: in the early 1970s, buffalo and cattle numbers were grossly at par, but subsequently there was a marked growth in buffalo whereas cattle and small ruminants declined. In contrast, cattle numbers increased in WB over the period, which in addition to a marked growth in small ruminants, resulted in the highest aggregate livestock growth rates and highest livestock density in the IGP (Table 2). The widespread substitution of buffalo for cattle in the upstream sub-regions in part reflects the preference for higher-fat buffalo milk, but also seems to be associated with two CL interaction-related modifiers. First, tractors increased nearly 15-fold over three decades in India (triennium ending [TE] 1974 to TE2006—http://faostat.fao.org), but mechanization was markedly concentrated in the NW IGP. As mechanization increasingly substituted for animal traction, the relative attractiveness of keeping cattle vis-à-vis buffalo decreased. Indeed, the eroding role of draft bullocks in combination with socio-cultural restrictions of culling cattle and the increasing availability of artificial insemination drastically reduce the value of male cattle offspring and inherently limits the accumulation of herd capital. In contrast, male buffalo can be sold for meat (primarily for export in view of the dietary preferences). Second, the advent of irrigation and the consequent increase in cropping intensity have tilted the balance in favour of stall-feeding that favours buffalo (and crossbreds) over local cattle. Buffalo also are relatively more effective users of straw and high fibre feeds (McDowell 1988).

Associated with the gradient of CL systems are a number of west–east gradients in resource endowments and prices (Table 2). The aggregate asset base is markedly more favourable in the NW, with larger farms and livestock herds and more irrigation and mechanization. The NW is also more reliant on rice–wheat cropping and fodder cultivation, more market oriented and has a more intensive use of external inputs and non-family labour sources. The east is particularly densely populated, has more diverse cropping patterns, and small ruminants are more prominent (Erenstein et al. 2007b). Relative factor prices contributed to technological choice—the relatively low cost of capital and the relatively high cost of labour facilitating the NW's more pronounced mechanization. The gradients in resource endowments and technology use contribute to a stark gradient in rural poverty (Table 2; Erenstein et al. 2009). Rural development indicators in the NW now compare well with those of middle income countries—yet large tracts of the eastern plains remain marred in dire poverty. The size of the IGP also means that each sub-region assumes national prominence in India: the TGP is the granary; UP is the most populous state; Bihar is one of the poorest states; and WB is the most densely populated state. Therefore, although the IGP is a contiguous plain area, there is a marked agro-ecological gradient resulting in significant regional variations.

In the present paper, we follow Dalgaard et al.'s (2003) interpretation of agro-ecology as "the interactions between plants, animals, humans and the environment within agricultural systems". The IGP's agro-ecological gradient thus reflects the interplay of biophysical and socio-economic factors whereas its agricultural systems have variously evolved over time in response to the diverging opportunities and constraints. A case in point is the NW with the emergence of irrigated rice–wheat systems and the substitution of buffalo for cattle. The current agro-ecological gradient is thereby a reflection of variations in both the biophysical and socio-economic environment and their interactions over time. Compared to the earlier intensification gradient (Table 1), we would expect the NW to be positioned at the intensive end of the intensification spectrum whereas the eastern plains would be intermediate.

3.2 Data and methods

The main data source for the present paper was a village-level survey of 72 communities from April to June 2005 in the Indian IGP. The communities were randomly selected using a stratified cluster approach. At the first level, the Indian IGP was grouped into four sub-regions: the TGP (Punjab and Haryana) and the Gangetic plains of UP, Bihar and WB. At the second level, three representative districts were purposively selected, one from each of the three main agro-ecological sub-zones within the four sub-regions (Table 3). At the final cluster level, six villages were randomly selected around a central point, typically the district headquarters. The selection of the six villages was done by taking two villages along three different directions, one village typically relatively close (generally within 5 km) and the second further away (generally more than 15 km). There are thus 12 survey clusters of 6 villages each, which where relevant are referred to by the corresponding district name.

Within each survey, village key informants and a self-selected group of villagers were interviewed using a semi-structured survey instrument. In each village survey, the team comprised at least one expert from the national agricultural research and extension system familiar with the district and one core team member. The survey process typically included a briefing of the village leaders and key informants leading into a larger group meeting with villagers (mainly landed, with an average of 6–20 participants) and a separate smaller group meeting with landless (2–10 participants). The group meetings endeavoured to include a representative group of village households that covered the diverse spectra of gender, social and wealth categories—albeit that we were less successful in involving women directly (Erenstein et al. 2007b).

Table 3 Characteristics of surveyed districts (secondary data)

IGP sub-region	Surveyed district	Agro-climatic sub-zone	Rainfall (mm p.a.)	Irrigated area (% village area)	Rural population density (km^{-2})	Population below poverty line (%)	Rural female literacy rate (%)
TGP	Patiala	Central	880	90	328	7	55
	Kurukshetra	Eastern	850	100	399	5	56
	Hisar	Arid western	490	82	286	9	45
UP	Meerut	Western	860	97	597	13	48
	Kanpur	Central	910	73	482	43	54
	Faizabad	Eastern	1,160	81	772	36	39
Bihar	Bhojpur	South	1,150	75	806	47	39
	Samastipur	Northwest	1,200	55	1,126	63	30
	Begusarai	Northeast	1,120	61	1,169	55	34
WB	Malda	Barind	1,490	37	817	48	38
	Nadia	Central—alluvial	1,470	64	923	25	55
	W. Medinipur	Central—laterite & red-soil	1,600	42	613	24	63

District level indicators derived from various secondary data sources as cited in Erenstein et al. (2007a)

TGP trans-gangetic plains, includes Punjab [Patiala] and Haryana [Kurukshetra, Hisar], *UP* Uttar Pradesh, *WB* West Bengal

The 12 surveyed districts lie along an upstream to downstream gradient from Punjab in the NW to WB in the east (Table 3). The survey instrument compiled a number of village-level indicators to characterize and assess rural livelihoods in terms of assets, processes and activities and the linkages between crop and livestock systems. Indicators included aggregate numbers of village assets, prevailing prices, occurrence of practices (reported hereafter as share of villages reporting) and the intensity of their use (reported as share of village households). Many village indicators provide an indicative order of magnitude, which compared reasonably with available secondary data. Indicators of direct CL interactions were compiled and quantified, whereas indirect interactions were more qualitative in nature. The emphasis here is straw management and livestock feeding practices in view of the potential trade-offs vis-à-vis conservation agriculture. For each sub-region, the comprehensive study results have been compiled: TGP—Erenstein et al. (2007c); UP—Singh et al. (2007); Bihar—Thorpe et al. (2007) and WB—Varma et al. (2007). A comprehensive regional analysis and synthesis is provided by Erenstein et al. (2007b).

4 Results

4.1 Straw management

Crop production is the main activity in all the 72 surveyed communities, with wheat-based cropping systems prevailing in the northern plains and rice-based in the east. The production of these staples is relatively intensive (using fertilizer, improved varieties, irrigation) and market oriented. Straw constitutes an important by-product widely used as animal feed, albeit with marked regional variation (Table 4). Wheat straw is the preferred

Table 4 Straw management indicators by sub-region (village survey data)

	TGP	UP	Bihar	WB	Mean (SD)	*p*
Straw management and transaction practices (% of villages reporting)						
Ex situ feed use	100	100	100	100	100 (0)	NS
In situ grazing	11[a]	39[b]	44[bc]	67[c]	40 (49)	0.01
Non-feed uses	72[bc]	44[a]	67[ab]	94[c]	69 (46)	0.01
In situ burning	87[b]	33[a]	11[a]	11[a]	33 (48)	0.00
Sales	94	89	100	100	96 (20)	NS
In-kind payment ($n = 71$)	61[c]	29[b]	33[b]	0[a]	31 (47)	0.00
Given away	50[b]	39[b]	0[a]	0[a]	22 (42)	0.00
Straw collection for ex situ feed by crop (% of households)						
Wheat ($n = 68$)	95[b]	100[b]	100[b]	4[a]	78 (40)	0.00
Rice ($n = 66$)	28[a]	69[b]	76[b]	99[c]	70 (42)	0.00
Maize ($n = 26$)	0	31	46	25	38 (47)	NS
Other crops ($n = 71$)	30[b]	29[b]	19[ab]	0	19 (39)	0.08
Duration of straw storage by crop (months)						
Wheat ($n = 57$)	12[c]	12[c]	9[b]	4[a]	10 (3)	0.00
Rice ($n = 54$)	5[a]	4[a]	5[a]	12[b]	7 (4)	0.00
Categorization of households as deficit or surplus in straw by crop (% of households)						
Net seller						
Wheat ($n = 67$)	16[b]	8[ab]	7[a]	0[a]	8 (14)	0.02
Rice ($n = 66$)	9	7	4	21	10 (24)	0.15
Net buyer						
Wheat	24[b]	29[b]	34[b]	0[a]	22 (29)	0.00
Rice	0[a]	2[a]	21[b]	25[b]	12 (24)	0.00
Straw prices by crop (Rs/kg)						
Wheat						
Average ($n = 54$)	1.4[a]	1.2[a]	1.7[b]	–	1.4 (0.5)	0.00
Peak ($n = 51$)	1.9[a]	1.5[a]	2.4[b]	–	1.9 (0.7)	0.00
Trough ($n = 51$)	1.2[a]	1.0[a]	1.4[b]	–	1.2 (0.4)	0.01
Rice						
Average ($n = 35$)	0.2[a]	0.1[a]	0.8[b]	0.8[b]	0.7 (0.6)	0.03
Peak ($n = 24$)	0.3	–	1.4	1.2	1.2 (1.1)	NS
Trough ($n = 24$)	0.2	–	0.6	0.6	0.6 (0.3)	NS

Notes $n = 72$ unless otherwise indicated. Data preceding different letters differ significantly—Duncan multiple range test (significance level: 0.10), within row comparison

NS non-significant

feed with near-universal use in the northern plains, whereas its use as feed is marginal in WB. Rice straw shows a marked opposite gradient. In the TGP, only straw from aromatic long-grain rice varieties are used as animal feed, whereas WB's preference for rice straw extends to Bangladesh. Two factors largely explain these differential uses. The first factor is tradition: wheat is the traditional staple in the NW but a relatively recent arrival in the east. Conversely, rice is the traditional staple in the east with the Green Revolution inducing its arrival in the NW. Directly linked to the prevailing traditional staple is its straw use as livestock feed. A second factor is that wheat straw has benefited from the mechanical threshing, which chops it into more palatable small pieces, a technology that yet has to make inroads into WB.

Most straw is collected and fed to livestock ex situ (stall-feeding). Except for the NW, cereals are primarily harvested manually and threshed at a central place. Wheat is generally threshed mechanically and the chopped straw subsequently stored and used, with storage duration declining proceeding downstream (Table 4). Rice is threshed in various ways (e.g., manually, trampling by oxen or tractor, mechanic thresher), but generally keeps the straw relatively intact. Its use as livestock feed is typically seasonal and storage limited to 4–5 months, except for WB where it is year-round (Table 4). Prior to feeding, rice straw is chaffed, typically with a mechanical chaff-cutter except in WB where labour-intensive manual chaffing prevails.

The use of combine harvesters was largely limited to the TGP, where they are used to harvest wheat and particularly (non-aromatic) rice (Beri et al. 2003; Sidhu et al. 1998). Straw collection in combine harvested fields is problematic and represents a potential trade-off vis-à-vis manual harvesting, the latter being labour and time intensive but allowing for maximum straw recovery. To alleviate this trade-off, a wheat straw reaper was developed locally in the mid-1980s and has become increasingly popular in the TGP. It collects and chaffs the loose straw and standing stubbles, recovering at least half (Beri et al. 2003). The straw is more likely to include impurities, leading some farmers to keep threshed wheat straw for their own use and selling off the combined one. The limited use of rice straw in the NW implies that the straw trade-offs for combining rice tend to be more limited. Another important factor is the timeliness of wheat establishment; combining (rice) generally has favourable implications for reducing the turn-round time between rice and wheat.

In situ stubble-grazing complements straw collection for ex situ use from the same fields. Stubble grazing shows a marked increase towards the east and varies for wheat and rice (Table 4). This mirrors the respective straw preference, but is also associated with irrigation constraints and cropping patterns. The rice–wheat cropping pattern implies a more ample turn-around time after wheat, when few crops remain in the field thereby facilitating grazing and reducing supervision costs. The limited stubble grazing reported in the TGP was confined to the irrigation-limited wheat–cotton belt (the Hisar cluster). Straw is also used for non-feed uses, primarily as fuel and construction material (e.g., thatching, ropes), with such uses generally increasing towards the east (Table 4). The reported non-feed uses in the TGP needs to be qualified as, generally, the quantities involved were relatively small except for rice straw for industrial processing (cardboard factories, paper mills).

In the downstream plains, limited rice or wheat straw remains in the field at the time of land preparation, and therefore, in situ burning is uncommon. This contrasts with the NW (Table 4), where the combine harvesting results in incomplete straw recovery, and particularly, the rice straw has limited value. Many Punjab farmers go to the extent of cutting the rice stubble with a tractor-drawn shredder after combining to hasten drying and realize a more effective burning (Sidhu et al. 1998). By contrast wheat straw is intensively collected and only the leftovers burned in the field. These practices are a reflection of farmers' perceived need to have 'clean' fields prior to initiating their mechanized land preparation and to vacate the field quickly (Beri et al. 2003). The seasonal burning of rice straw in the NW creates severe air pollution and health hazards (Gustafsson et al. 2009). The advent of zero tillage in the NW has, so far, not markedly reduced the in situ burning, because first-generation drills had trouble handing loose straw. Zero tillage implements are being further adapted so as to maintain straw as mulch without burning or incorporation (Erenstein et al. 2008; Erenstein and Laxmi 2008).

Straw sales are common, but straw was also used as in-kind payment—often interlinked with the labour market, particularly in the NW—and sometimes also given away—with gifts confined to the west and often restricted to rice (Table 4). The gradients in non-monetized straw transactions and gifts are associated with the larger farm sizes in the NW and the relative resource scarcity in the east. Nearly one-third of the community households are engaged in the wheat straw market, with 8% being net sellers and 22% net buyers. However, wheat straw transactions were confined to the northern sub-regions (Table 4). Wheat straw prices were seasonal and highest in Bihar (Table 4). Straw thereby provides a significant contribution to the income derived from wheat production, although its value seems relatively low compared to their importance for livestock production. In contrast, rice straw transactions are mainly restricted to the east, where prices are relatively higher and seasonal (Table 4). This also explains why rice straw was sometimes simply given away in the upstream plains. Overall, wheat straw typically has a markedly higher value than rice straw, whereas rice straw prices were more distinctly affected by varieties (e.g., preference for long-grain rice straw) and cropping seasons (e.g., preference for monsoon/aman rice over winter/boro rice). Still, straw-quality factors did not reportedly play a major role in determining straw prices whereas varietal choice mainly reflected expected grain yield.

4.2 Livestock feed inputs and availability

Livestock ownership in the surveyed communities is widespread, with buffalo predominant in the NW and local cattle and small ruminants in the east. Livestock complements the rice- and wheat-based cropping systems, with straw providing the predominant feed. Large ruminants are fed a cereal straw-based basal diet throughout the year. The use of wheat straw prevails in the NW, increasingly complemented and substituted by rice straw proceeding east. Where available, other crop residues are also used. The basal diet is supplemented with green fodder, grazing, collected grasses/forage, non-straw crop by-products and compound feed (Table 5).

Table 5 Comparative input use indicators for livestock and crop production by sub-region (village survey data)

	TGP	UP	Bihar	WB	Mean (SD)	*p*
Use of non-straw feed sources (% of households)						
Non-straw crop by-products ($n = 72$)	94	78	79	74	81 (35, 72)	NS
Compound feed ($n = 72$)	31^{ab}	16^{a}	39^{b}	13^{a}	25 (35)	0.08
Grazing ($n = 69$)	9^{a}	31^{b}	44^{b}	84^{c}	42 (46)	0.00
Collected grasses/forage ($n = 67$)	27^{a}	50^{b}	48^{ab}	84^{c}	53 (41)	0.00
Planted (green) forage ($n = 70$)	75^{c}	62^{bc}	44^{b}	1^{a}	45 (46)	0.00
Input use for crop production (% of farm households)						
Tractors ($n = 69$)	89^{b}	90^{b}	88^{b}	66^{a}	84 (27)	0.02
Draft animals ($n = 59$)	31^{ab}	37^{bc}	10^{a}	60^{c}	36 (39)	0.00
Chemical fertilizer ($n = 72$)	97	100	100	89	97 (16)	0.13
Farmyard manure ($n = 69$)	84^{bc}	88^{c}	64^{ab}	59^{a}	74 (38)	0.06

Notes Data preceding different letters differ significantly—Duncan multiple range test (significance level: 0.10), within row comparison

The expressed preference for wheat and/or rice straw reflects the diametrically opposed farmer opinions in WB and the TGP. In WB, wheat straw is generally not perceived to have any feed use, whereas in the TGP farmers tend to have the same opinion of rice straw. TGP farmers generally believe long-term feeding with rice straw to be detrimental due to (amongst others) perceived silica content and to reduce milk yield. Differences in agro-ecology, crop varieties and livestock species contributed to these diverging views. Pearce et al. (1988) have earlier reported a wide range of in vitro digestibility for both wheat straw (21–58%) and rice straw (30–62%), in part reflecting varietal and seasonal effects. They flag that straw intake and digestibility in ruminants are also influenced by feeding conditions and by animal characteristics. There still is a paucity of comparable studies in which animals were only fed wheat or rice straw—diets often variously supplemented with nitrogen, minerals and energy. Assessments of whole straws is also hampered by differences between the plants' morphological fractions, whereas different harvesting, threshing and feeding practices affect these relative fractions and thus the nutritive value of the straw (Pearce et al. 1988). Wheat shows more marked variations in the in vitro digestibility of its morphological fractions compared to rice, with particularly low digestibility for the stem internodes (Pearce et al. 1988). The widespread mechanical threshing of wheat in the northern plains thereby facilitated its straw use as feed, further aided by the buffalos' more effective straw use (McDowell 1988). Long-term experiments in the region found wheat and rice straws to have good palatability, nutritive value and bailing and densification properties, with similar results for cattle and buffaloes (Yadav et al. 1994). These regional studies also report crude protein content of wheat straw to be somewhat better than for rice straw, although both being far below that of green fodders. More recently, mean in vitro digestibility was estimated at 39% (range 34–45) for rice straw and 46% (42–51) for wheat straw using near infrared reflectance spectroscopy and drawing on monthly samples from fodder markets across the IGP (Blummel and Teufel Personal communication).

The use of green fodder shows a marked decline proceeding east (Table 5), mirroring the decline in cultivated fodder area from 10% of the seasonally cultivated area in the NW to negligible levels in WB (Erenstein et al. 2007b). Except for WB, most households had a chaff-cutter, which was used for chopping the green fodder and straw not already chopped during harvesting/threshing. The use of nutrient-dense crop by-products is common. These are fed as straights or as homemade mixes and include oilseed cakes, cereal bran, pulses/oilseed residues and grounded grains from the own farm or bought. It is relatively uncommon to use compound feed. These feeds are primarily used to increase the yields of lactating animals, and their use is reported as either stable or increasing, although current feed rates appear to be low. Their reported prices varied by locality but were generally lower than the prevailing milk price, suggesting that their increased use would be profitable. In the same way, there were limited reports of purchasing mineral mixtures, despite known links between poor reproductive performance and mineral deficiencies.

With practically no grazing land in the NW, livestock is generally stall-fed in or near the household compound throughout the year. Proceeding east, bovines are primarily stall-fed on straw but increasingly complemented by grazing (particularly where fallow or barren lands are available) and collected grasses/forage (e.g., from barren land, field boundaries and roadsides). These fodder sources are also important for small ruminants, their use being aided by the relatively low labour opportunity cost in the east. As a result, there is a marked increase in both grazing and collected forage proceeding east (Table 5).

Overall fodder availability seemed more problematic in the east, compounded by limited irrigation, population pressure and seasonality. For landed households, forage is mainly home-produced and availability more manageable, particularly in the NW.

Purchases are important to alleviate shortfalls in home-produced forage. Marginalized and landless households face a more dire forage scarcity as they often lack the resources for purchases and thereby often depend on a combination of grazing and collection of grasses, tree leaves and straw from the farming community. The livestock pressure on straw was markedly higher in WB, associated with the highest livestock density, smallest farm size and relatively low cropping intensity (Erenstein et al. 2007b).

Current feed management reflects farmers' responses to the prevailing opportunities and constraints. Bovines are generally an integral part of the livelihood strategies of landed households, but they were not perceived as primary income earners. Instead, bovines are converters of readily available straw into milk—both for household consumption and as a means of regular cash—and accumulating the dairy herd growth, but not from meat production because of the sacred status of cattle in Hindu theology and dietary preferences (Babcock Institute 2006; Erenstein et al. 2007b). The landless households concentrated mainly on small ruminants in the east with their fast flock growth as an important means of capital accumulation and source of cash.

4.3 Livestock input to crop production

Traditionally, male bovines were the main source of power/traction in agriculture and rural transport. But with tractorization, the relative importance of livestock for traction has declined. Although 84% of farm households use tractors for crop production in the surveyed communities, more than one-third (also) use draft animals. WB stands out with more widespread use of draft animals and having markedly lower levels of mechanization (Table 5), and a greater reliance on 2-wheel tractors (power-tillers) vis-à-vis the 4-wheel tractors that prevail in the other sub-regions. This is associated with the small average farm size in WB, in addition to a socio-political climate that has not been supportive of mechanization in view of its perceived labour-saving nature. Tractor use was markedly similar in the three other sub-regions, despite significant variations in the asset base and poverty. Somewhat surprisingly, relatively poor Bihar had the lowest reported use of draft animals. This appears associated with whether tractors and draft animals are complements or substitutes and the relative trade-offs between utility and cost. For instance, the maintenance cost of draft animals is relatively high in densely populated Bihar where tractors and draft animals are primarily substitutes, with farmers using one or the other. In contrast, in some of the relatively 'better-off' surveyed communities, tractors and draft animals are primarily complements. For instance, in the Meerut cluster, in the sugarcane belt of W UP, farmers used tractors primarily for tillage and used draft animals—male buffalo and bullocks—for hauling cane to the mill and inter-row cultivation. The maintenance cost of draft animals in this area was kept in check by the widespread availability of sugarcane tops.

Farmyard manure (FYM) is the traditional way of replenishing soil fertility, but widespread access to subsidized chemical fertilizer has provided an imperfect substitute. Although chemical fertilizer use is near-universal in the surveyed villages, FYM use is still widespread (Table 5). FYM quantities actually applied to crops are small due to limited availability: except for WB with markedly higher livestock densities, the surveyed villages generally averaged 1–2 cow equivalents per cultivated hectare (Erenstein et al. 2007b). Still, FYM use was reportedly highest in the NW, and lowest in WB. The stall-feeding of large ruminants in the NW facilitates dung recovery, whereas in WB grazing is more widespread. Furthermore, although FYM use is reportedly widespread in the NW, fields generally only receive it once in every 3–4 years, and application focuses on the rainy season and fodder crops (Sidhu et al. 1998). Further restricting the availability of FYM is the use of about half the annually collected dung as household fuel (Erenstein et al. 2007b). The relative dung use is seasonal, with fuel use prevailing in the dry season and FYM in the rainy season.

4.4 Indirect crop–livestock interactions

Combining crop and livestock production implies a more diverse livelihood portfolio and reduction in risk, as their income co-variance is likely to be low. The two enterprises also have different resource use patterns (particularly labour and cash flow), which imply complementarities and potential resource savings at the household level by allowing more efficient resource use. Farm income also becomes more regular. Crop sales are highly seasonal and often realized once or twice a year, whereas proceeds from the sale of milk, meat, young stock, etc., can be more regular and more flexible. Financial interactions between the two enterprises were reportedly important: financial proceeds from livestock are used to meet crop expenses and vice versa. Livestock also provide an investment and accumulation opportunity, which serves as an insurance and financing function and displays status (Moll 2005). These functions can be particularly important where the institutional setting is underdeveloped and/or poverty prevails (e.g. Rangnekar 2006). Conversely, alternative risk-reducing mechanisms (e.g., assured irrigation or the TGP's assured cereal markets) may reduce the importance of livestock's insurance function and thus further dilute CL interactions.

The group meetings highlighted the importance of the crop and livestock enterprises in terms of contributing to household income and consumption (staple, milk, fuel) and internal services (use of crop by-products, manure, traction) and their complementarities in terms of labour use and more regular income. Somewhat surprising was that their contributions were generally related to the individual crop and livestock enterprises, and not so much attributed to interactions. Perhaps, the two enterprises are so obviously interdependent in these mixed CL systems that this is not expressed overtly.

The group meetings also highlighted some disadvantages of CL systems. One interesting view was the perception that the livestock enterprise 'trapped' the young generation by its year-round labour demands, preventing their mobility to pursue other livelihood venues. More frequent were reports about damages to crops by free-roaming animals (including stray male cattle). Because of their religious status, cattle slaughter is prohibited in India except in two states both far from the IGP (Kerala and Nagaland). There is some anecdotal evidence of exports of cattle through the IGP to neighbouring countries like Bangladesh where slaughter is allowed, but these are unofficial, sensitive and largely undocumented (Hussain 2009). Blue bulls ('nilgai', *Boselaphus tragocamelus*) are the wildlife counterparts of stray cattle in northern India. The local belief that they are cows and hence sacred, has protected the biggest Asian antelope against hunting and made it into a crop menace, causing large-scale damages especially along the Gangetic belt despite the high human population densities (http://en.wikipedia.org/wiki/Nilgai).

5 Discussion

5.1 Re-assessing crop–livestock interactions in the IGP

The current study confirmed CL complementarities in the vast IGP where only a few households are specialized in either crop or livestock production and mixed CL systems are the rule. The mixed systems exhibited high levels of integration in terms of the physical dimensions of space and time and the organizational dimensions of management and ownership identified by Sumberg (2003). The bovine livestock is highly integrated with the major staple crops, albeit with distinct management for the two enterprises particularly in the NW. Indeed, crop production is relatively intensified and relied on external input use to produce a marketable surplus. In contrast, dairying seemed largely a by-product of crop production, with intensification lagging and with the 'harvesting' of milk and sales of surplus milk (Erenstein et al. 2007b).

The present study thereby questions the extent to which this integration is based on mutually beneficial CL interactions. Clearly, livestock production relies on straw, grasses, weeds and other agricultural wastes for feed purposes. However, the beneficial return flows from livestock are more limited. Animal traction has largely been replaced by tractors. The soil fertility function of FYM has been, to a large extent, superseded by chemical fertilizers, and in any case is limited by competing household fuel demands and availability constraints. Over time and space, the intensification and commercialization of the agricultural systems have thereby weakened CL interactions and increasingly decoupled the crop and livestock sub-sectors in line with our conceptualized intensification gradient (Table 1). But whereas crop production in the IGP and particularly in the NW has increasingly shifted to the intensive end of the spectrum, livestock production (dairying) seems to be stuck at the intermediate level. This strongly suggests that stimuli for livestock intensification have so far been less pronounced.

Land is relatively scarce throughout the IGP, but particularly marked in the east with its small farm sizes and high rural population density. Land scarcity normally would induce intensification, but in the east this was held back by the high poverty incidence, the high cost of capital and the restrictive institutional setting. In contrast, intensification in the NW took off first with land saving technology during the Green Revolution aided by lower capital costs and the supportive institutional setting. Subsequently, increasing seasonal labour scarcity has induced mechanization. Compared to the other sub-regions, CL interactions currently indeed play a more prominent role in WB, particularly the Medinipur and Malda clusters. The institutional setting and high capital scarcity have kept these systems at intermediate intensification levels despite high population densities—with a concomitant role for CL interactions. In the other WB (Nadia) cluster, CL interactions have declined with the intensification and commercialization of crop systems induced by its proximity to Calcutta. Somewhat surprising was the relatively pronounced CL interactions in the Meerut cluster in W UP, despite its high intensification level and proximity to Delhi. This was primarily linked to the cultivation of sugarcane—with its additional forage supply and animal traction needs.

Although mixed CL systems prevailed, there were reports of resource-poor rural households managing and raising livestock for the resource-rich on a share basis (i.e. informal contracts whereby livestock products including offspring were shared between owner and manager, Erenstein et al. 2007c). The poorest households are typically landless—without access to any self-cultivated land—but still are keeping livestock. Feed/straw markets and exchange mechanisms (e.g. in-kind straw payments for harvesting labour) allowed them to access feed. Storage helps mitigate seasonality in supply (straw) and use (manure). One would assume that the physical characteristics of straw and manure and their relatively low economic value would limit the exchange of these commodities over large distances. However, they can still be both substantial and far-flung—with seasonal hauling and storage of straw along major transport axis to deficit areas like urban centres commonplace in the IGP and in South India (Blummel and Parthasarathy Rao 2006). Similarly, the drying and shaping of manure into “dung cakes/sticks” has facilitated exchanges and trading. The IGP’s increasingly high land use intensity also seems a major contributor to the reduced extent and importance of seasonal migration of livestock herds between the plains and the hills (Singh and Grewal 1990).

In the pre-Green Revolution era of the early twentieth century, the IGP’s agricultural systems were prevailingly at the intermediate intensification level (Table 1). Crop and livestock production were more integrated, with more pronounced mutual interdependency. The Green Revolution resulted in the marked intensification of staple crop production, whereas livestock largely remained at the intermediate level. Had the whole agricultural system intensified, one would have expected increasing farm specialization and a declining role for CL interactions. As it was, only the dependency of crop production on livestock production showed a marked decline, with livestock production remaining dependent on crop by-products. This unilateral unbinding of CL interactions had a number of consequences, not least in terms of shaping current CL systems and undermining overall system sustainability. This unravelling was most drastic in the Green Revolution heartland. Still, even at the relatively intermediate livestock intensification levels—compared to crop intensification—there is a gradient along the IGP, particularly reflected by the greater reliance on planted (green) forage crops in the NW to supplement the basal diet of cereal straw. In part, this is associated with the more marked advent of irrigation in the NW, which enabled the cultivation of irrigated forage crops, aided by the larger farm sizes, higher productivity levels and more favourable institutional setting.

One may posit that the end point of progress and modernization is a business agriculture, driven by entrepreneurship and vibrant markets and linked to a burgeoning urban economy (Scoones 2009). This also is in line with our conceptual framework, which suggests that CL integration becomes increasingly incongruent with agricultural intensification once an intermediate intensification level has been achieved (Table 1). What future then for the CL systems in the IGP? The predominantly small-scale integrated CL farms are likely to remain so in the medium term—lacking the means or opportunities for a drastic realignment of their livelihoods (Erenstein et al. 2007b). The few large land holdings, however, seem to move towards crop specialization having the means to invest in mechanization and thereby circumvent labour bottle necks, particularly in the NW. Further specialization into commercial dairy is likely for those that have a potentially big enough milk enterprise and secured market access, which is more likely in the peri-urban interface (Birthal et al. 2006). Such specialized dairy would also imply an increasing spatial separation between livestock production and feed production and further reliance on, and development of, straw and fodder markets.

5.2 Methodological issues

Although easy to conceptualize, measuring and disentangling CL interactions again proved more complex in practice. The less tangible indirect interactions remain particularly problematic. Group discussions and participatory methods can help elicit insights to qualitative dimensions, but quantification and generalization would remain challenging. Follow-up household surveys could contribute, for instance through the inclusion of quantifiable and robust proxies and/or large enough sample sizes. The purpose of the village surveys that underpin the present study was primarily to provide a broad brush understanding of the main issues related to CL interactions and livelihoods along an agro-ecological gradient (Erenstein et al. 2007b). It was conceived as a scoping study that did not intend to provide a comprehensive assessment of the crop and livestock sub-sectors of

India's IGP, but instead emphasized the linkages and exchanges at the farm and village level between the two sub-sectors. As the paper shows, village surveys can be a valuable method for the quick assessment of systems and their interactions. Still, not all indicators are equally suitable: group responses tend to provide orders of magnitude that are typically more valuable in relative rather than absolute terms, which may suffice for a scoping study along an agro-ecological gradient and can help fine-tune and target quantification in subsequent research.

A particular strength of the present approach is to use these village surveys as a meso-level characterization tool and thereby link micro-level contextual realities along the IGP's agro-ecological gradient. All too often the interpretation and thus contribution of locale-specific studies is thwarted by the inability to link the finding to the wider context. The present study reiterates and illustrates the importance of the context—be it in terms of hypothesized intensification gradients or empirical data along the IGP's agro-ecological gradient. The context is particularly important for interpreting CL interactions as it can lead to diametrically opposed conclusions. Proceeding from an extensive base, agricultural intensification implies *increasing* CL integration. However, as in the case of the IGP, proceeding from an intermediate base further intensification likely induces specialization and thus *reduces* integration. In addition, the intensification process—associated with population density, market opportunity and/or resource endowments—can be problematic to capture empirically. This helps explain why linkages between land use intensity and CL integration across various studies may appear relatively weak and complex (Sumberg 2003). Linking agro-ecological gradients with intensification gradients opens a particularly promising avenue to associate spatial system dimensions to the underlying dynamics. It thereby offers scope to interpret observed spatial and historic variations and help scale out interventions and reflect on future system trajectories.

The village surveys help address questions of scale and the ability to synthesize across studies. Our focus here was on the sub-regional level, but village surveys can also provide useful insights at lower aggregation levels, as illustrated in the underlying sub-regional reports. The main contribution of the sub-regional reports is that they reiterate and illustrate the importance of local context, which otherwise tends to be lost in the sub-regional averages. They thereby help interpret the diversity of CL interactions within the sub-regions and highlight the importance of proximity to urban agglomerations. Perhaps less successful was our ability to capture market access gradients around the central point in each cluster. We originally hypothesized—and still expect—that market access directly influences intensification incentives and thus CL interactions. But the limited number of villages per site (6) and the rather arbitrary use of proximity to the cluster's central point, did not provide additional insight. To more adequately capture market access gradients one would need to inter alia ramp up the number of data points, extend the spatial scale and provide more robust market access proxies (e.g. Erenstein 2006).

5.3 Research and development implications

Rural livelihoods in the IGP are being undermined by the environmental implications of current CL interactions. Particularly problematic is the continuous mining of soil fertility and organic matter. The extractive biomass flows from the fields to the livestock sheds are largely one-way—leading to depletion of the soil organic matter stock. Soil fertility is further undermined by unbalanced fertilizer use. Dung and agricultural biomass use as household fuel is a major source of indoor air pollution and poses considerable health concerns (Dasgupta et al. 2006). Addressing these slow and relatively invisible degradation processes remains a major challenge for the R&D community—particularly daunting in the east in view of the prevailing poverty and resource scarcity. The IGP's high population density and still positive population growth exert considerable and increasing pressure on the already intensively used natural resource base.

Conservation agriculture can help rebuild soil health, albeit that the application of its underlying principles in the IGP still poses considerable challenges (Erenstein 2009). The prevailing crop management practices are largely incompatible with mulch retention despite significant biomass production. Straw use is near-universal and rigorous—albeit with spatial and seasonal variations—making it valuable and markets and institutional arrangements have developed accordingly. The present paper thus illustrates varying trade-offs for farmers, the situation in the east being particularly challenging. More promising perhaps are the opportunities offered by seasonal variations. The NW combines intensive straw collection from the main winter crop with widespread in situ straw burning of the main monsoon crop (Erenstein et al. 2007c; Gupta et al. 2004). This seasonal burning suggests considerable biomass surplus in the NW and poses the challenge of smoothing straw use over the two seasons/crops. An additional challenge is to provide farmers with viable options to establish crops in the presence of such surplus straw (Erenstein and Laxmi 2008).

Faced with the ground reality a piecemeal approach to conservation agriculture in the IGP seems advisable, aiming for the year-round retention of some straw as mulch and soil cover—the retention of all straw being unrealistic. There are a number of component technologies that merit further attention in the R&D community particularly as they could alleviate straw retention-feed trade-offs. Partial harvesting and retention of straw seems promising—particularly if the basal stubble is retained in the field which anyway is less digestible and thus less valuable as livestock feed. Agronomic practices and varietal variation can influence feed quality and quantity (Blummel and Parthasarathy Rao 2006; McDowell 1988; Pearce et al. 1988). Dual-purpose wheat also offers promise, either in terms of field grazing (Holman et al. 2009) or as a green fodder cut (Bisht et al. 2008).

Technological change needs to be complemented with institutional change. The root cause of land degradation in the IGP is not agricultural intensification per se, but rather the policy environment and associated incentives that have encouraged injudicious resource use. Subsidies (for nitrogen fertilizers; for irrigation development and power; for machineries) have led to unbalances and inefficiencies, whereas market support for wheat and rice has reduced diversification incentives (e.g. substituting legumes—Lauren et al. 2001). These incentives enabled the rapid crop intensification and emergence of rice–wheat systems, but also facilitated the unilateral unbinding of CL interactions. Reducing the distortions will help make these intensive crop production systems more sustainable. Perhaps the most pressing complementary institutional change would be to address the limited incentives for livestock intensification. Our study findings suggest that this is a major cause for the unilateral unbinding of CL interactions. Thus, counter intuitively perhaps, this implies that livestock intensification will reduce the straw retention-feed trade-offs, with potentially favourable effects on both system sustainability and poverty alleviation.

Progress in addressing these challenges in the IGP is likely to be slow—not aided by the reluctance to make politically unpopular adjustments. The R&D community will require guile and persistence. Still, where stakeholders see remunerative opportunities change can be swift. More in-depth research is needed to understand the implications of technological and institutional change along the IGP's agro-ecological gradient. There is also a need to more rigorously quantify some of the CL interactions and implications for livelihoods and the environment. The management of crop biomass remains of particular interest and the research should take into account the multiple straw functions (including fuel) and the various stakeholders (including the landless) and livestock species along the agro-ecological gradient.

The research can build on the increasing recognition of straw management (Bijay-Singh et al. 2008; Gupta et al. 2004). Indeed, this area has long been relatively neglected by the R&D community, but current straw management practices are increasingly recognized as part of the problem and thus need to change to make the systems more sustainable. However, there is the caveat that the situation in the relatively intensive NW is markedly better documented—whereas our study shows the need to consider agro-ecological and intensification gradients when analysing CL interactions. Future studies could enhance their utility by contextualizing their findings in relation to these gradients. Promising too would be a more in-depth contrast of the IGP's wheat–buffalo systems in the NW, the rice–cattle systems in the Bengal plains and the intermediate mixed systems.

An important contribution of a focus on CL interactions is that it encourages agro-ecosystem thinking and inter-disciplinarity. Traditionally, much research on straw feeding was done by focusing on laboratory measurements of feed quality and using additives (Pearce et al. 1988; Schiere et al. 2000). Such research typically neglected farmers' perceptions or their agro-ecosystems and, not unsurprisingly, led to disappointing results in terms of transfer and uptake of feeding technologies. System analysis provides methodologies and concepts that bridge the gap between formal commodity research and field application (Schiere et al. 2000). A final strength of the present study was its ability to bridge disciplinary divides. All too often there is a "disconnect" between crop and livestock scientists and/or social and biophysical scientists—let alone between scientists and their clients. Research on CL interaction served as a good starting point to start bridging these divides and to strengthen the client orientation and productivity of the agricultural R&D community.

6 Conclusion

The roles of CL interactions are intricately linked to a system's developmental stage. This implies that these exchanges can both contribute to but also undermine system sustainability and that they should be understood and contextualized. Our empirical analysis in the IGP illustrates not only some of the complexities but also the scope of meso-level analysis based on village surveys. This is a useful tool to help link micro-level contextual realities across a vast and important eco-region and to unravel the variations along agro-ecological gradients. If calls for conservation agriculture in the IGP are to succeed, understanding and addressing the variations in straw management practices is imperative, with the situation in the east particularly challenging. Yet, an important realization is that conservation agriculture and livestock intensification are not antagonistic, such that increasing the incentives for livestock intensification will reduce the straw retention-feed trade-offs. The agricultural R&D community needs to incorporate a better understanding of CL interactions more proactively into its R&D agenda if it is to succeed in sustaining productivity gains, improving rural livelihoods equitably and securing environmental sustainability.

Acknowledgments The paper draws from detailed sub-regional studies (Erenstein et al. 2007c; Singh et al. 2007; Thorpe et al. 2007; Varma et al. 2007) and a synthesis (Erenstein et al. 2007b). The original studies were jointly funded by USAID, ILRI, CIMMYT and the CGIAR Systemwide Livestock Programme

(SLP). The views expressed here are those of the authors and do not necessarily reflect the views of the donors or the authors' institution. The study benefited from the assistance of numerous individuals and institutions that have been acknowledged in the corresponding reports to the extent possible. The current paper benefitted from reviewer comments. The usual disclaimer applies.

References

Babcock Institute. (2006). *The dairy sector of India: A country study*. Babcock institute discussion paper No. 2006-2. Madison, USA: The Babcock Institute for International Dairy Research and Development, University of Wisconsin–Madison.

Beri, V., Sidhu, B. S., Gupta, A. P., Tiwari, R. C., Pareek, R. P., Rupela, O. P., et al. (2003). *Organic resources of a part of Indo-gangetic plain and their utilization. NATP*. Ludhiana: Dept of soils, PAU.

Bijay-Singh, Shan., Johnson-Beebout, Y. H., Yadvinder-Singh, S. E., & Buresh, R. J. (2008). Crop residue management for lowland rice-based cropping systems in Asia. *Advances in Agronomy, 98*, 117–199.

Birthal, P. S., Taneja, V. K., & Thorpe, W. (2006). *Smallholder livestock production in India: Opportunities and challenges*. Nairobi, Kenya: NCAP/ICAR/ILRI.

Bisht, J., Kant, L., & Srivastva, A. (2008). Cutting management of dual purpose wheat cultivars: A new approach for increasing fodder availability. *Cereal Research Communications, 36*(1), 177–187.

Blummel, M., & Parthasarathy Rao, P. (2006). Economic value of sorghum stover traded as fodder for urban and peri-urban dairy production in Hyderabad, India. *International Sorghum and Millets Newsletter, 47*, 97–100.

Byerlee, D., & Husain, T. (1992). *Farming systems of Pakistan: Diagnosing priorities for agricultural research*. Islamabad, Pakistan: Vanguard.

Dalgaard, T., Hutchings, N. J., & Porter, J. R. (2003). Agroecology, scaling and interdisciplinarity. *Agriculture, Ecosystems & Environment, 100*(1), 39–51.

Dasgupta, S., Huq, M., Khaliquzzaman, M., Pandey, K., & Wheeler, D. (2006). Indoor air quality for poor families: New evidence from Bangladesh. *Indoor Air, 16*(6), 426–444.

Devendra, C. (2007). Small farm systems to feed hungry Asia. *Outlook on Agriculture, 36*, 7–20.

Devendra, C., Thomas, D., Jabbar, M. A., & Zerbini, E. (2000). *Improvement of livestock production in crop-animal systems in agro-ecological zones of South Asia*. Nairobi, Kenya: ILRI.

Erenstein, O. (2003). Smallholder conservation farming in the tropics and sub-tropics: A guide to the development and dissemination of mulching with crop residues and cover crops. *Agriculture, Ecosystems & Environment, 100*(1), 17–37.

Erenstein, O. (2006). Intensification or extensification? Factors affecting technology use in peri-urban lowlands along an agro-ecological gradient in West Africa. *Agricultural Systems, 90*(1–3), 132–158.

Erenstein, O. (2009). Adoption and impact of conservation agriculture based resource conserving technologies in South Asia. In WCCA (Ed.), *Proceedings 4th World Congress on Conservation Agriculture, February 4–7 2009, New Delhi, India* (pp. 439–444). WCCA: New Delhi.

Erenstein, O., Farooq, U., Malik, R. K., & Sharif, M. (2008). On-farm impacts of zero tillage wheat in South Asia's rice–wheat systems. *Field Crops Research, 105*(3), 240–252.

Erenstein, O., Hellin, J., & Chandna, P. (2007a). *Livelihoods, poverty and targeting in the Indo-Gangetic plains: A spatial mapping approach*. New Delhi: CIMMYT-RWC.

Erenstein, O., Hellin, J., & Chandna, P. (2009). Poverty mapping based on livelihood assets: A meso-level application in the Indo-Gangetic Plains, India. *Applied Geography*. doi:10.1016/j.apgeog.2009.05.001.

Erenstein, O., & Laxmi, V. (2008). Zero tillage impacts in India's rice–wheat systems: A review. *Soil and Tillage Research, 100*(1–2), 1–14.

Erenstein, O., Thorpe, W., Singh, J., & Varma, A. (2007b). *Crop-livestock interactions and livelihoods in the Indo-Gangetic Plains, India: A regional synthesis*. Mexico, DF: CIMMYT.

Erenstein, O., Thorpe, W., Singh, J., & Varma, A. (2007c). *Crop-livestock interactions and livelihoods in the trans-gangetic plains, India. Research report 10*. Nairobi: ILRI.

Gupta, P. K., Sahai, S., Singh, N., Dixit, C. K., Singh, D. P., Sharma, C., et al. (2004). Residue burning in rice–wheat cropping system: Causes and implications. *Current Science, 87*, 1713–1717.

Gustafsson, O., Krusa, M., Zencak, Z., Sheesley, R. J., Granat, L., Engstrom, E., et al. (2009). Brown clouds over South Asia: Biomass or fossil fuel combustion? *Science, 323*(5913), 495–498.

Hobbs, P. R., Sayre, K., & Gupta, R. (2008). The role of conservation agriculture in sustainable agriculture. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences, 363*(1491), 543–555.

Holman, J. D., Thompson, C. R., Hale, R. L., & Schlegel, A. J. (2009). Grazing effects on yield and quality of hard red and hard white winter wheat. *Agronomy Journal, 101*(4), 775–788.

Hussain, D. (2009). Border rustling. *Himal SouthAsian, 22*(2), 56–59.
Lauren, J. G., Shrestha, R., Sattar, M. A., & Yadav, R. L. (2001). Legumes and diversification of the rice–wheat cropping system. *Journal of Crop Production, 3*(2), 67–102.
McDowell, R. E. (1988). Importance of crop residues for feeding livestock in smallholder farming systems. In J. D. Reed, B. S. Capper, & P. J. H. Neate (Eds.), *Plant breeding and the nutritive value of crop residues*. Addis Ababa: ILCA.
Millennium Ecosystem Assessment. (2005). *Ecosystems and human well-being: Synthesis*. Washington, DC: Island Press.
Moll, H. A. J. (2005). Costs and benefits of livestock systems and the role of market and nonmarket relationships. *Agricultural Economics, 32*, 181–193.
Parthasarathy Rao, P., & Birthal, P. S. (2008). *Livestock in mixed farming systems in South Asia*. New Delhi & Patancheru, India: NCAP/ICRISAT.
Pearce, G. R., Lee, J. A., Simpson, R. J., & Doyle, P. T. (1988). Sources of variation in the nutritive value of wheat and rice straws. In J. D. Reed, B. S. Capper, & P. J. H. Neate (Eds.), *Plant breeding and the nutritive value of crop residues*. Addis Ababa: ILCA.
Pingali, P. L., & Shah, M. (2001). Policy re-directions for sustainable resource use: The rice–wheat cropping system of the Indo-Gangetic plains. *Journal of Crop Production, 3*(2), 103–118.
Rangnekar, D. V. (2006). *Livestock in the livelihoods of the underprivileged communities in India: A review*. Nairobi, Kenya: ILRI.
Schiere, H., Singh, K., & De Boer, A. J. (2000). Farming systems research applied in a project on feeding of crop residues in India. *Experimental Agriculture, 36*(1), 51–62.
Scoones, I. (2009). Livelihoods perspectives and rural development. *Journal of Peasant Studies, 36*(1), 171–196.
Seth, A., Fischer, K., Anderson, J., & Jha, D. (2003). *The rice–wheat consortium: An institutional innovation in international agricultural research on the rice–wheat cropping systems of the Indo-Gangetic plains (IGP)*. New Delhi: The Review Panel Report. RWC.
Sidhu, B. S., Rupela, O. P., Beri, V., & Joshi, P. K. (1998). Sustainability implications of burning rice- and wheat-straw in Punjab. *Economic & Political Weekly, 33*, 163–168.
Singh, J., Erenstein, O., Thorpe, W., & Varma, A. (2007). *Crop–livestock interactions and livelihoods in the Gangetic plains of Uttar Pradesh, India. Research report 11*. Nairobi: ILRI.
Singh, J., & Grewal, S. S. (1990). *Socio-economic profile of migrant Gujjars in Punjab*. PAU, Ludhiana: Department of Economics & Sociology.
Sumberg, J. (2003). Toward a dis-aggregated view of crop-livestock integration in Western Africa. *Land use policy, 20*(3), 253–264.
Thorpe, W., Erenstein, O., Singh, J., & Varma, A. (2007). *Crop-livestock interactions and livelihoods in the Gangetic plains of Bihar, India. Research report 12*. Nairobi: ILRI.
Varma, A., Erenstein, O., Thorpe, W., & Singh, J. (2007). *Crop-livestock interactions and livelihoods in the Gangetic plains of West Bengal, India. Research report 13*. Nairobi: ILRI.
Yadav, K. K., Lohan, O. P., Rathee, C. S., & Berwal, R. S. (1994). Effect of replacement of wheat straw with paddy straw feeding on milk yield and composition in buffaloes. *Indian Journal of Dairy Science, 47*(9), 796–798.