Chapter 15
Nonlinear Groundwater and Agricultural Land Use Change in Rajasthan, India

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Abstract Since the 1950s, the rapid expansion of groundwater irrigation globally has led to dramatic shifts in land use. Nowhere is this more true than in India where, since the 1960s, groundwater irrigation has expanded to 34.5 million hectares, 70 % of the country's total. Yet we do not know the character of this landscape nor the degree to which changes in land use are the result of multiple ecological and social drivers. Therefore, this article asks: (1) what is the relationship between groundwater decline and agricultural land use change in India, and what does it mean for the future of agricultural intensification; and (2) in what ways do social institutions produce and adapt to this change, while leading to yet further shifts in land use? This chapter draws on government statistics and from household surveys and interviews from a case study in the semiarid state of Rajasthan, India, to examine these questions.

Findings suggest that the relationship between the expansion of groundwater-irrigated area and land use change is nonlinear, in that the expansion of irrigated area initially led to the expansion of market-oriented crops but rapid groundwater decline is demanding a return to local cropping varieties, particularly among the most marginal producers. This return is being facilitated through the creation of new adaptive social institutions, such as tube well irrigation partnerships, under conditions of dynamic ecological change, including synergistic groundwater and land use change. The conclusion offers suggestions toward a second Green Revolution in agriculture via the strengthening of local social institutions.

Keywords Adaptation • Groundwater • India • Irrigation • Second Green Revolution • Social institutions

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15.1 Introduction

More than 300 million hectares (ha) of agricultural land are irrigated globally (Shah 2005). Historically supplied by surface water, this pattern continues into the present with more than 66 % being surface water dependent (Shah 2005). But this is changing. In the United States, for example, between 1950 and 2000 groundwater withdrawals, as a percentage of total water use for irrigation, increased from 23 to 42 % (Hutson et al. 2005). In India, groundwater-based irrigated area rose from 7.4 million hectares in 1962 to 34.5 in 2003 (Narayanamoorthy 2006), currently accounting for 70 % of total irrigated area (World Bank 2005). The rise in groundwater-based irrigation in India therefore a significant and rapid land use transformation, therefore.

Although irrigated area has expanded significantly, intensification has also occurred through the adoption of further Green Revolution technologies, such as chemical fertilizers and high-yielding seed varieties (HYVs). The extensification and intensification of agriculture, made possible through the spread of groundwater irrigation systems, has resulted in vastly increased agricultural yields and in increased capital accumulation among farmers. Taken together, these shifts support an increasingly globalized production regime. Wheat exports in India, for example, rose from 632,468 million tons (mt) in 1995 to 2,007,947 in 2004 (FAO 2008). It has also exacerbated disparities between classes and castes of farmers (Jeffrey 2001; Birkenholtz 2008a). So too, the rapid increase in groundwater-irrigated area in India is dependent not only on the availability of groundwater and the spread of new groundwater-lifting technologies but also on farmers' abilities to create adaptive social institutions to access them, while mediating ecological and global political-economic change.

However, demand for groundwater in India is expected to exceed supply by 2020, which may lead to new forms of conflict or cooperation as resource scarcity increases (World Bank 2005). Consequently, the future viability of groundwater-led intensified agriculture is of significant concern. It is not clear, however, whether groundwater decline will result in a linear decline in either groundwater-irrigated area or in HYVs, or what this means for land use change and farmers' abilities to adapt to these dynamic political-economic and ecological shifts. The questions become: What is the relationship between groundwater decline and agricultural land use change in India, and what does it mean for the future of agricultural intensification?; and second, in what ways do social institutions produce and adapt to this change, while leading to yet further shifts in land use?

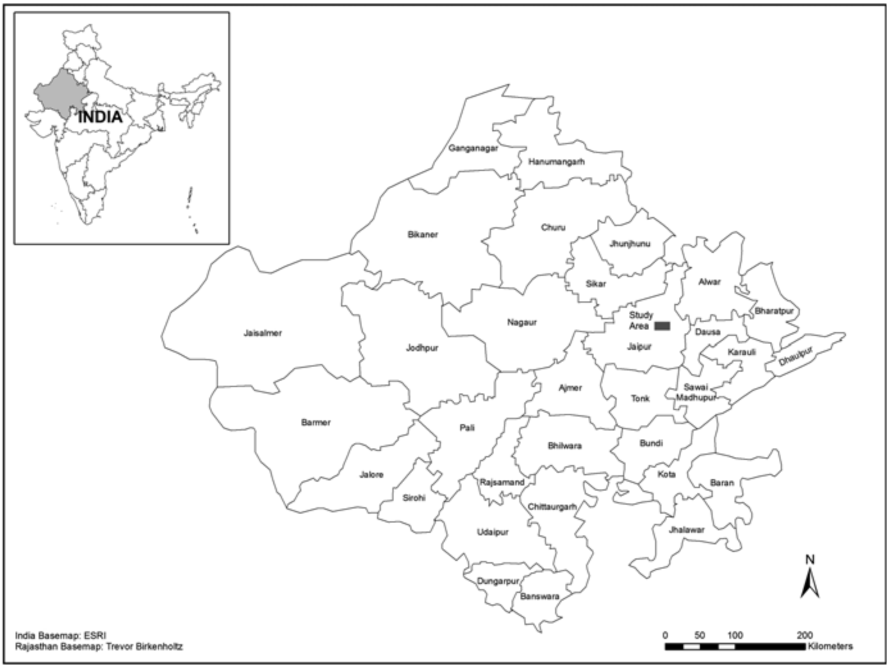
In human–environment research, increasing attention is focused on the degree to which land use transformations are the product of multiple social and ecological processes (Mertz et al. 2005; Chowdhury and Turner 2006; Caldas et al. 2007). Hazell et al., for example, identified a number of drivers of global agricultural change that are informative in thinking about land use change specifically (Hazell and Wood 2008): these include global-scale drivers such as globalization of markets, OECD agricultural support and privatization of agricultural science;

country-scale drivers such as agricultural supports, energy policy, and water scarcity; and local-scale drivers such as local natural resource availability, property rights regimes, and non-farm employment opportunities (Hazell and Wood 2008, p. 502). To these local-scale drivers I would add local social institutional change or adaptation that may result from but also feed back into these multi-scalar drivers. Adaptation in this sense is the shifting practices that farmers (i.e., land managers) employ to meet ecological or social challenges to continue or expand production. For example, farmers may apply gypsum to the soil to reduce its alkalinity, or they may form partnerships for tube well irrigation systems, which are too expensive (and/or risky) to adopt on their own, to intensify production.

Much related work to date, however, examines the political and ecological drivers of changing cultivation and fallow practices under globalization pressures around deforestation (Vasquez-Leon and Liverman 2004; Zimmerer 2006; Lawrence et al. 2008), particularly in the Amazon (Walker and Homma 1996; Caldas et al. 2007; Hecht and Saatchi 2007), rather than the conversion of dry-land agriculture or grazing areas to irrigated agriculture (but see Wadley et al. 2006). Work in India, for example, has shown that increases in groundwater use via tube well adoption led to radical increases in winter cropping and decreases in fallow grazing area (Robbins 2001). Yet looking at the shifts in agricultural area does not detail the actual and shifting character of the agricultural landscape. There is a need to link the positive, but nonlinear, social and ecological feedbacks that result from agricultural intensification (Peters et al. 2007). And, although some rightly point to the need to examine the effects of land use change on hydrological processes (DeFries and Eshleman 2004), few have attempted to examine the positive feedbacks between land use and hydrological processes and social decision making (Alauddin and Quiggin 2008; Gaur et al. 2008). Therefore, the relationship between groundwater decline, agricultural land use change, and social decision making in India is in need of explication.

This chapter examines these relationships through a case study from the semiarid northwestern Indian state of Rajasthan, where 71 % of irrigated agriculture and 80 % of the state's drinking water needs rely on groundwater (Directorate of Economics and Statistics 2003; World Bank 2005). In Rajasthan, as with much of India, groundwater withdrawal and tube well construction are not regulated. This lack of regulation, along with State efforts to expand rural electrification and to provide low-interest loans to farmers for agricultural intensification since the late 1960s, has been a dramatic driver of country-scale agricultural change (Birkenholtz 2008a). This scenario has resulted in rapid technological diffusion of 1.4 million agricultural tube wells across the state, with a 33 % increase between 1991 and 2001 alone (GORGB 2003). Groundwater irrigated area also increased dramatically, by 52 %, to more than four million hectares between 1994 and 2001.

Given the state's (and India's) heavy reliance on this water source, understanding the relationship between social, groundwater, and land use change is very important. Moreover, it informs our theoretical understanding of land use change under multiple and shifting driving forces. This research, carried out in Rajasthan's Jaipur District (Fig. 15.1), suggests that the relationship between the expansion of



India Basemap: ESRI
Rajasthan Basemap: Trevor Birkenholtz

Fig. 15.1 Study area in Jaipur District, Rajasthan, India

groundwater-irrigated area and land use change is nonlinear in that the expansion of irrigated area initially led to the expansion of market-oriented crops but that rapid groundwater decline is demanding a return to local cropping varieties, particularly among the most marginal producers. This return is being facilitated through the creation of new adaptive social institutions, under conditions of dynamic political-economic and ecological change, including synergistic groundwater and land use change. These ecological constraints are felt by farmers differentially and may undermine some farmers' abilities to adapt to broader political, economic and ecological shifts (such as climate change) in the future.

15.2 Study Area and Methods

15.2.1 Study Area: Jaipur District, Rajasthan

Jaipur District is a semiarid region of moderately productive, yet spatially uneven, agricultural land, with nitrogen-poor alluvial soils and reasonable groundwater recharge (Singhania and Somani 1992). The area is entirely reliant on groundwater for domestic and irrigation needs. There is no surface water and no government water supply. Summer temperatures commonly reach 44 °C. Average annual rainfall is typically between 500 and 600 mm, occurring mostly between July and September, but can be highly variable; for example, rainfall in 2002 was 207 mm. There are two cropping seasons: the *khariph* (summer) crop, which is cultivated from July to October (i.e., during the rainy season), and the *rabi* (winter) crop, which is cultivated between October and March. The main *khariph* crops are millet, peanuts, sesame, legumes, spices, vegetables (for those who can grow them), and fodder crops; the main *rabi* crops are wheat, barley, fodder crops, and a limited number of vegetables. The *rabi* crop is fully dependent on (mostly flood) irrigation whereas the *khariph* crop relies on monsoon rains. Those with the capability irrigate the *khariph* as well. The *rabi* crop, therefore, can only be produced by those households with access to irrigation.

The social environment of the study area is highly stratified, composed of low- and high-caste Hindus and small, medium, and large landholders. There is a significant and interdependent relationship between caste and landholdings, with χ^2 (4, $n = 151) = 17.556$, $p = .001$, where marginal castes own the least amount of land. Access to resources, including groundwater and irrigation, is mediated through these relationships, which impacts land use. Farmers have formed partnerships for the construction, use, and maintenance of tube wells for irrigation. The size of these partnerships is stratified by landholdings (class), which is also related to caste (see previous). Farmers form these partnerships, not because one tube well can irrigate more area than some farmers own, but because of the high cost of the tube well and electrical connections and the high rates of tube well failure as groundwater declines (Birkenholtz 2009). Agriculture is the main occupation, with high levels of off-farm employment, particularly among the most marginal households (Tables 15.1 and 15.2).

15.2.2 Methods

Research for the present study was carried out between 2002 and 2007. First, it draws on district-level statistical data published by the Department of Economics and Statistics of the State of Rajasthan. It analyzes cropping pattern change over the period between 1993–1994 and 2001–2002, the longest period for which comparable district-wide data were available. Second, in 2005 a household survey, utilizing an every-third-household selection technique, was conducted of 151 farmers in six villages of Bassi Tehsil, about 60 km east of Rajasthan's capitol city, Jaipur. The surveys detailed basic household production information (including cropping and income), groundwater use, and irrigation, along with more open-ended questions regarding the groundwater situation. Third, the surveys were followed up with repeated in-depth interviews with 78 farmers and with government engineers and tube well-drilling firms in 2005 and 2007. These interviews provide detailed accounts of adaptive cultivation strategies under dynamically changing conditions of groundwater quality and quantity.

Table 15.1 Percentage change in area and production of principal crops in Jaipur District, Rajasthan, between 1993–1994 and 2001–2002

Crop	Area change	Production change	Subsistence (S) or commercial (C)	Irrigation requirement
Linseed	−96.55	−90.91	C	High
Rape/mustard	−60.12	−66.97	C	High
Red chili	−36.82	−36.61	C	High
Total oilseed	−38.97	−25.75	C	High
Maize	−6.42	132.91	S/C	High
Pulses	−1.04	−6.41	S	None
Barley	6.69	71.17	S	High
Total food grain	10.17	42.61	C	–
Wheat	12.30	56.23	S/C	High
Pearl millet	13.73	37.15	S	Low
Sorghum	23.39	−60.97	S	Low
Total condiments and spices	32.10	−41.02	C	–
Sesame	48.96	27.14	C	Low
Groundnut	52.93	171.94	C	Low
Total vegetables	53.58	11.01	C	High

Table data arranged by "area change" from most negative to most positive

Table 15.2 Income and land use indicators from survey ($n = 151$)

Land category (hectares, ha)					
	0.25–0.5	0.51–1.0	1.10–2.5	2.51–3.9	4.00–7.5
No. households	6	28	81	24	12
Tube well partners	7.1	3.11	2.96	2.68	2.15
Average income[a]	46,591	82,176	104,457	137,477	205,766
Average crop income	9,425	14,212	40,716	74,636	127,600
Average crop income/ha	27,013	20,759	28,935	24,695	24,451
Average	1.33	0.96	1.91	2.33	2.00
Crops					
Average number of summer crops	1.16	1.57	2.17	2.54	3.00
Average percent irrigated, winter	94	63	83	80	69
Average percent irrigated, summer	67	63	74	76	62
Average total hectares	2.15	19.11	116.08	72.66	65.82
Total irrigated area, winter	2.03	12.28	93.75	57.47	45.44
Total irrigated area, summer	1.39	12.05	85.32	54.43	41.27

[a] Average income in rupees; at time of research, 45 rupees = $1

15.3 Groundwater Decline, Agricultural Land Use Change, and the Future of Intensification

Between 1994 and 2002, total net irrigated area in Jaipur District rose by more than 9 % from 302,428 to 330,569 ha. Groundwater irrigation became more prominent over this period with an increase in net tube well irrigated by 11 % to 329,000 ha. However, the composition and productivity of groundwater-irrigated areas changed dramatically. Table 15.1 illustrates the change in area and productivity of subsistence and commercial crops in the district. Irrigation-intensive oilseeds have declined significantly in both categories. Commercial spices have increased in area but have declined in production. Overall, there is an area and productivity increase in low irrigation-demanding mixed subsistence and commercial crops such as pearl millet, sorghum, sesame, and groundnut. And finally, the production of wheat, barley, and maize, which have high irrigation requirements, has gained in productivity with relatively little change in the amount of land devoted to them.

These district-level patterns, although more precise that most measures of land use, say little of the processes producing them. One possibility is a change in market prices, encouraging farmers to switch production to more lucrative crops, but commodity prices overall during this period have moved downward (Barker and Molle 2005; FAO 2006). Therefore, this does not explain the decline in oilseed production or the rise in sorghum, sesame, or groundnuts. The change in land use over the period could also be caused by a lack of available inputs, such as seeds, fertilizer, or pesticides. According to farmers and local government officials, however, this is not the issue either.

This significant transformation in land use is actually the result of rapid groundwater decline. Rapid utilization of groundwater for irrigation throughout the 1990s has resulted in falling water tables of as much as 60 m throughout the study area (GORGB 2003). There is also a yearly groundwater overdraft of 410 million m^3. This considerable groundwater decline in the area has led to increases in concentrations of naturally occurring minerals, such as sodium and calcium, and to the creation of saline water and sodic soils (Jacks et al. 2005). This change has encouraged a return to local crop varieties that are more tolerant to these soil and water conditions. Quoting one farmer:

> Formerly we could grow tomatoes, okra, chili peppers and eggplant, but now we do not like to because we cannot produce much of it due to the salty water. So now we grow mostly sesame, groundnuts, fodder crops and some lentils [which require less irrigation].

Groundwater salinity is not constant spatially or temporally. One hundred percent of 151 farmers surveyed indicated that they had at least seasonal groundwater salinity and/or hardness (*talia*). Following another farmer:

> The groundwater becomes more saline throughout the summer. It did not used to be like this; it [the salinity of the water and the calcification/sodic soil] happened with the irrigation.

Therefore, to answer the first question—*what is the relationship between groundwater decline and agricultural land use change and what does it mean for the future of agricultural intensification*—is that groundwater decline and, in particular, the changing character of groundwater, is undermining the continued production of water-demanding, mostly market (e.g., oilseeds, spices, vegetables), varieties, which without future adaptive management action (such as investment into less water demanding varieties and irrigation efficiency-enhancing technologies) will likely undermine continued intensification. Looking to the household, however, the role of social institutions in producing and adapting to this change becomes apparent. It also illustrates the ways that these regional land use shifts emerge from the disaggregated decisions of individual farmers (and farmer partnerships).

15.4 Social Institutions and Shifting Land Use

Stratifying the survey into five landholding categories, the relationship between the number of tube well irrigation partners, income, and cropping variety becomes apparent. Of the sample, 83 % of all tubewells were owned in partnerships and 76.6 % of the sample coordinated irrigation timing with their partners or neighbors. This practice allows the smallest farmers to irrigate large proportions of their land, 94 % in the winter and 67 % in the summer (see Table 15.2), and to maintain high income to crop area ratios relative to larger landholding classes. Partnerships for the construction and use of tube wells initially underwrote the expansion of groundwater-irrigated area and the cultivation of water-demanding crops, but the size of the partnership impacts the variety of crops and the quality of irrigation.

There is an inverse relationship between the number of irrigation partners and cropping variety in both winter and summer (see Table 15.2). Smaller landholders have larger numbers of partners, which reduces the availability of irrigation per partner. This arrangement also produces a higher spatial concentration of wells, which places heavier demands on groundwater, further exacerbating localized groundwater drawdown and mineralization (as well as mutual interference between wells in close proximity). These factors limit the variety of crops that can be grown to low irrigation-demanding crops, such as fodder crops and crops for subsistence use.

Indeed, in land category one, 67 % of the sample produced sorghum and 83 % produced wheat during the winter for home consumption. In the summer, 33 % produced both pearl millet and sorghum for home consumption. Only one farmer in this category produced the primary winter crops of sorghum and wheat and two farmers produced groundnut and pearl millet in the summer for the market. None of the farmers produced vegetables, which are primarily market crops. These crops are also very water demanding and are sensitive to irrigation timing. Farmers are adapting to this change by returning to local crop varieties (see previous farmer quote). Thus, tube well adoption, rather than leading to further capitalization and to market integration, has had the opposite effect of disengagement from the market and an increase in subsistence cultivation as a consequence of groundwater quality constraints.

Small farmers adapt to these conditions, therefore, by returning to local, more resilient cropping varieties such as pearl millet, sorghum, sesame, and groundnut. They are also abandoning monocultural cropping in favor of intercropping. Figures 15.2 and 15.3 illustrate the intercultivation of pearl millet, sorghum, sesame, and watermelon in the same field. Two years earlier, this field was divided into HYV millet and spices. Intercropping, along with prevalent home use, also makes it difficult to obtain accurate data for planted area or crop production (hence their absence from this study). Moreover, typical LULC classifications are too coarse to register this shift, even though the social and ecological impacts are quite diverse. These patterns of production and adaptation strategies are in contrast to those of larger farmers.

In land category four, 50 % produced sorghum, 100 % produced wheat, 50 % produced barley, and 17 % produced alfalfa for home consumption in the winter. In the summer, 88 % produced pearl millet and 38 % produced sorghum, in addition to six other crops, for home consumption. But in the winter, 95 % produced wheat, 4 % produced pearl millet, gram, and chickpeas, 67 % produced sorghum and barley, and 8 % produced sesame for the market. Finally, 25 % of the farmers in this category produce lucrative but water-demanding vegetables (during the winter), indicating their greater access to groundwater of acceptable quality. Thus, for these larger farmers, who have 2.68 tube well partners on average, tube well adoption allows them to integrate with the market and to expand their cropping variety. Table 15.2 shows the average number of crops being grown during the winter and

Fig. 15.2 Image of study area indicating multicropping

Fig. 15.3 Detailed image of study area indicating multicropping

summer seasons for each of the five land categories. Clearly, larger farmers produce a more diverse variety of crops, but this is not solely the result of larger landholdings. It is the result of fewer irrigation partners, which provides them a more reliable supply of irrigation, enabling them to increase their cropping variety and integrate more fully (and selectively) into commodity markets.

Larger farmers are also able to grow more varieties because their beneficial economic position enables them to engage in further adaptive strategies, such as the addition of gypsum to the soil. Adding gypsum to soil, then flushing it with irrigation (or carefully timed precipitation), can reduce alkalinity and sodicity (Ramesam and Barua 1973; Fullen and Catt 2004). Of 151 farmers, 100% indicated that they had at some time added gypsum to their soil to "loosen" it up, but this is a very expensive adaptation. One (large) farmer in the survey, with 6.33 ha, adds $275 worth of gypsum yearly to the soil. This adaptation allows some farmers to grow lucrative, but less salt tolerant, varieties such as vegetables.

Therefore, the answer to the second question—*what ways do social institutions produce and adapt to this change*, *while leading to yet further shifts in land use?*—is that tube well irrigation partnerships initially led to the expansion of irrigation-demanding, market-oriented crops. But the spread of groundwater irrigation resulted in groundwater drawdown, diminishing the quality and availability of groundwater for irrigation, particularly among the smallest producers, who have to form larger partnerships. Therefore, the cause and consequences of ecological feedbacks are socially stratified, which has also resulted in socially differentiated adaptation. Small producers have returned to intercropping local varieties that are less water demanding and more subsistence oriented. Larger farmers generally have better access to high-quality groundwater, but have also turned to mitigation techniques, such as adding gypsum as a soil beneficiation practice. These divergences in adaptive ability have led to yet further differentiation, which is visible in the landscape via its impacts on land use diversity, in income disparities, and in degree of market integration.

15.5 Discussion: Groundwater Decline, Social Institutions, and Land Use

The rapid diffusion of groundwater irrigation throughout the study area since the Green Revolution initially led to the expansion of water-demanding and market-oriented crop production, a significant transformation in land use. Because of the success of this process of state-supported, but farmer-led, agricultural intensification and local institutional adaptation, however, significant groundwater decline has also occurred, undermining the original ecological conditions under which this revolution occurred. This contretemps is leading to yet another significant shift in land use and to further local adaptations, a shift that is not caught by typical coarse categories of land use classification.

Returning to the typology of drivers of change in agriculture set out by (Hazell and Wood 2008), the authors point to global-, country-, and local-scale drivers. Although global-scale political economic drivers, such as OECD agricultural subsidies that make it difficult for farmers in less developed countries (LDC) to compete on global markets, are important, particularly in driving the initial rise in agricultural intensification in the study area, the most significant drivers of changing land use in this chapter are more localized, at least for the time being. Of course the future potential of global climate change (GCC) to increase climate variability and to produce more extreme events, particularly in the tropics, is an issue (IPCC 2007). So too, future trends in global agricultural policy could cause shifts as well.

Therefore, at different moments in the economic and ecological process, the drivers of land use change are divergent. Initially, the innovation and diffusion of Green Revolution technologies faced few ecological hurdles. The barriers were rural electrification and sufficient capital investment and adaptation (i.e., tube well adoption via collective investment), which the state and local farmers addressed, respectively. But currently, local-scale social and ecological change is driving these shifts in land use. Hazell and Wood (2008) point out that “water shortages within river basins and aquifers will curtail irrigated agriculture in many countries if not addressed soon” (p. 502). The present research suggests, however, that groundwater decline does not curtail irrigated agriculture in a simple linear fashion. Instead, this is a dynamic process wherein the groundwater-irrigated area is still expanding but the character of the crops and the adaptive diversification strategies of the farmers are changing, both producing and mediating these ecological shifts.

Rapid groundwater decline, however, has begun, and without further country-scale technical intervention, such as the expansion of efficiency-enhancing drip irrigation systems, irrigated area and market crop production will continue to decline. Rather than promoting the spread of these technologies with state investment, as with the Green Revolution, the state is proposing a series of state- and local-level institutional reforms, including the privatization of water resources, the liberalization of markets, and new nondemocratic forms of decentralized governance, which will undermine local institutions (Birkenholtz 2008a, b). These proposed interventions are being influenced by a current political-economic climate that promotes neoliberal, market-led approaches to property institutions and natural resource management.

These series of proposed interventions represent another particular economic and ecological moment, which are unlikely to produce the conditions necessary for farmers to continue to evolve local adaptive management strategies. It is clear that farmers need to develop land use strategies to help them mitigate unpredictable economic and ecological conditions (Hanson et al. 2007). But the ecological conditions described here, along with the currently proposed state interventions, reduce farmer flexibility and the dynamism in decision making that is needed to mediate the unpredictability of globalized markets and nonlinear ecologies.

15.6 Conclusions

The case study presented here illustrates that the global expansion of groundwater-irrigated area is the result of positive feedbacks between social and ecological drivers. These drivers, however, vary nonlinearly from moment to moment within political, economic, and ecological processes, rendering land use a complex process. Although there continues to be vast potential for further groundwater irrigation globally (Faurès et al. 2007), local groundwater decline and social adaptive potential are highly uneven. This caveat will continue to impact land use and social well-being, including food security. However, the continued expansion of irrigated area and crop production need not face future limits, currently imposed proximately by groundwater decline but ultimately by political and economic will.

Clear scope exists to enhance the efficiency of groundwater irrigation systems. Research in Southern India has recognized, for example, up to 60 % efficiency gains with drip irrigation (Narayanamoorthy and Deshpande 2005). Thus, there is potential and need for a second Green Revolution in India and throughout the Global South (Postel et al. 2001; Wollenweber et al. 2005). The potential for this second Green Revolution is dependent on strengthening local social institutions and adaptive capacity with focused public and private support.

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