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Achieving sustainable irrigation requires effective management of salts, soil salinity, and shallow groundwater

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ABSTRACT

Salinity and waterlogging have impacted agricultural production in arid areas for more than 2000 years. The causes of the problems are well known, as are the methods and investments required to manage salt-affected soils and shallow water tables. Yet the problems persist in many regions where farmers apply excessive irrigation water, and where farmers and irrigation departments fail to invest in adequate drainage solutions. Long ago, Professor E.W. Hilgard described the inevitability of salinity problems in arid areas and the measures required to prevent or overcome those problems. Hilgard warned of impending salinization in California's Central Valley, based partly on his understanding of salinity and waterlogging problems in India. More recently, Jan van Schilfgaarde, Jim Oster, and others also have described the inevitable environmental impacts of irrigation. These authors suggest that irrigation likely can be sustained, but the cost of reducing the environmental impacts to an acceptable level might be substantial in some areas. We review the perspectives of these authors, and others, with an outlook toward a future in which the goal of achieving sustainable irrigation coincides with the goal of intensifying agriculture more generally, to provide food and fiber for an expanding global population. We propose five activities that might be implemented in a comprehensive program to achieve successful management of salinity and waterlogging. We also introduce the notion of implementing a deposit or bond payment for the salt contained in irrigation water deliveries. Farmers would be reimbursed in accordance with their salt management and disposal practices.

1. Motivation

The global population likely will increase to 9 or 10 billion between 2015 and 2050. The increase in population, along with rising incomes, will lead to greater demands for crop and livestock products. Faced with the challenge of increasing food production by 50% or more by 2050, many analysts are promoting the notion of sustainable intensification of agriculture, which generally involves higher rates of key inputs per hectare, in pursuit of higher yields, while minimizing potential impacts on the environment and natural resources (Tilman et al., 2011; Tscharntke et al., 2012; Garnett et al., 2013; Godfray and Garnet, 2014).

The call for sustainable intensification comes amidst the emerging understanding that the rates of increase in crop yields in key production regions have fallen substantially from the growth rates observed during the 1960s through the 1990s (Ray et al., 2012; Iizumi et al., 2013). Current growth rates in the yields of maize, rice, wheat, and soybeans are insufficient to meet projected food demands in 2050 (Ray et al., 2013). The causes of declining growth rates include increasing pressure from salinity and waterlogging (Humphreys et al., 2010), depletion of soil nutrients and organic matter (Chianu et al., 2012; Srinivasarao et al., 2013), climate change (Chen et al., 2010; Lal, 2011; Lin and Huybers, 2012; Lobell, 2012; Rao et al., 2014), and inappropriate crop management practices (Fan et al., 2012).

Water scarcity and the rising cost of obtaining groundwater as water tables fall, due to excessive pumping, also have contributed to declining rates of growth in crop yields (Ambast et al., 2006; Humphreys et al., 2010). In rice–wheat production areas of the upper portion of the Indo-Gangetic Plain, groundwater levels have declined by 5–15 m since the 1980s, while tubewell density has increased to 15 km^{-2}. Wheat yields are still increasing in the region, but rice yields appear to have stabilized (Ambast et al., 2006).

Much of the needed increase in crop yields between now and 2050 will come from innovations in plant genetics and agricultural

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technology. Substantial research is underway in several countries in the fields of plant genomics, physiology, and agronomy (Sinclair et al., 2004). Successful outcomes of this research, when applied in agriculture, will be necessary, but not sufficient, in producing the amounts of food and fiber required in 2050 (Wollenweber et al., 2005). Needed also are notable improvements in agronomic practices on small and large farms in all producing regions. Such improvements are needed to offset some of the declines in crop yields observed in recent years, and also to boost crop yields beyond the average levels achieved in key production areas, such as northern China, south and southeast Asia, and sub-Saharan Africa (George, 2014).

The necessary improvements in agronomic practices must be implemented in ways that are helpful in achieving sustainable irrigation in both humid and arid regions. The challenge likely will be more substantial in arid and semi-arid regions, where large production areas are impacted by soil salinity, inadequate subsurface drainage, and waterlogging. In many areas, saline and sodic soils must be reclaimed before higher yields can be achieved and sustained. Reclamation can be achieved using chemical soil amendments or by implementing plant-based strategies, such as phytoremediation (Qadir and Oster, 2004; Qadir et al., 2007). Improving the distribution uniformity of irrigation and providing adequate subsurface drainage also will be important components of successful efforts to achieve sustainable irrigation (Wichelns and Oster, 1990; Oster and Wichelns, 2003; Wichelns and Oster, 2006).

In this paper, we review the current state of knowledge regarding sustainable irrigation, with particular emphasis on arid and semi-arid areas, in the context of the global challenge of ensuring food and nutritional security by 2050. Many scholars and practitioners, including Jim Oster and his research partners in several countries, have studied soil salinity and sodicity, irrigation uniformity, subsurface drainage, and crop production practices for many years. They have contributed a large volume of literature regarding the scientific, policy, and management aspects of the efforts needed to achieve sustainable irrigation. We review a small portion of that literature and we describe several examples of irrigation and drainage problems that might be solved, in part, by adopting some of the recommendations put forth by Jim Oster and his colleagues.

1.1. The challenge is not a new one

Farmers in arid and semi-arid areas have faced the challenge of achieving sustainable irrigation for more than 2000 years. The demise of ancient civilizations due partly to crop failures caused by the accumulation of salts in agricultural soils is well known (Jacobsen and Adams, 1958; Letey, 2000; Zhou et al., 2012; Zhao et al., 2013). So too are the long-standing problems of salinity and waterlogging in key production regions of the world (Hillel, 1991; Hillel and Vlek, 2005; Rengasamy, 2006; Proust, 2008; Qadir et al., 2009; Singh, 2009).

In the second half of the 19th century, Professor E.W. Hilgard of California, while visiting with engineers from India, learned of vast areas of formerly productive farmland that had succumbed to waterlogging and salinity within a few years after farmers began to irrigate. The farmers received water deliveries from large surface irrigation schemes, built to supplement or replace groundwater pumping. Professor Hilgard understood the cause of the problem quite well. Both seepage from the elevated delivery canals and the excessive application of irrigation water by farmers "relieved from the laborious processes of well irrigation" caused shallow groundwater to rise very near the soil surface, thus allowing salts to accumulate in the root zone (Hilgard, 1886). The remedy was straightforward, although costly:

1. lower the elevated canals to reduce seepage and force the farmers to lift water for irrigation, and;
2. construct a regional drainage system to carry the saline subsoil water into rivers and the sea, "thus relieving the land more or less permanently of that scourge (Hilgard, 1886)."

Professor Hilgard understood the similarity between agronomic conditions in India and California's Central Valley, where he saw great potential for agriculture to thrive, if it was managed appropriately (Hilgard, 1893). Thus, he wrote passionately about the potential threat of waterlogging and salinity in California, urging farmers and public officials to build regional drainage systems and to use irrigation water "sparingly" to prevent the otherwise inevitable, future harm that could occur in California agriculture. In his words,

"It is hardly necessary to go further into the details [of the problems occurring in India] to enforce the lesson and warning they convey to our irrigating communities. The evils now besetting the irrigation districts of northwest India are already becoming painfully apparent; and to expect them not to increase unless the proper remedies are applied is to hope that natural laws will be waived in favor of California. The natural conditions under which the irrigation canals of India have brought about the scourge, are exactly reproduced in the great valley of California; and what has happened in India will assuredly happen there also (Hilgard, 1886)."

Hilgard recommended a three-part strategy for achieving sustainable irrigation, management, published in the *Bulletin of the University of California* College of Agriculture (Hilgard, 1886):

1. "Drainage correlative with irrigation." Hilgard emphasized the need to develop drainage solutions concurrent with irrigation schemes. He understood the potential harm that can arise when drainage systems are not installed in a timely manner.
2. Region-based solutions. Hilgard wrote that "single individuals however, can do but little in the matter; the action to be taken must, of necessity, be that of whole communities." Given that excessive irrigation causes a shallow water table to rise beyond the borders of individual farms, a regional drainage system is required.
3. "Sparing use of water to restrict the rise of alkali." Hilgard warned that if irrigation was expanded without management strategies that used water sparingly to "restrict the rise of alkali" [as used by Hilgard, the term 'alkali' is synonymous with salinity], then waterlogging and salinity would plague California agriculture.

Hilgard's prescription for achieving sustainable irrigation is as valid in the 21st century as it was in the 19th. The salinity and drainage problems in California and elsewhere arise and persist largely for the same reasons Hilgard described in 1886: excessive irrigation, inadequate drainage, and lack of a regional management program. Most farmers everywhere lack sufficient incentives to optimize their irrigation deliveries and manage deep percolation in ways that minimize off-farm impacts. Community involvement in the form of establishing regulations, providing incentives, and generating funds for infrastructure development is essential to prevent regional degradation of land and water resources.

Lacking regional, comprehensive efforts, salinity and drainage problems persist in many key production regions, such as the southwestern United States, much of Australia, Iran, and large portions of the Indo-Gangetic Plain in India and Pakistan (Ritzema et al., 2008; Singh, 2009; Singh et al., 2010; Emadodin et al., 2012; Wichelns and Oster, 2014). To achieve sustainable irrigation in these and other areas, farmers must implement the right mix of agronomic practices, in conjunction with wise water use and careful management of shallow water tables, while working together