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1 Acknowledgments

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2 Executive summary

For the Eastern Gangetic Plains of India, Nepal, and Bangladesh soil health is an area of concern, with soil pH and associated toxicities, trace element deficiencies (Zn, Cu, B), low organic C levels, and soil structural problems all identified as key issues. This SRA focused on the following questions:

1. In areas where N fertiliser use has increased, are soils acidifying, and how rapidly is this acidification process likely to proceed?
2. Is Zn deficiency widespread, and will application of Zn fertiliser increase rice yields?
3. Is the organic matter increase observed under conservation agriculture (CA) practice resulting in an improvement in soil structure?

Evaluation of acidification risk. Soil samples (surface and subsoil) were collected from typical farmer's cereal cropping fields and the soil pH and pH buffer capacity were measured. Soils across the sampling region were dominantly slightly acidic; the median pH was 5.75, with individual country values all being similar (West Bengal 5.81, Nepal 5.82, Bangladesh 5.69). Evaluation of buffer capacity showed that all soils evaluated were poorly buffered and thus readily susceptible to acidification. To estimate the rate of acidification as a result of cropping practice, acid inputs were calculated for two cropping scenarios, one reflecting current farmer's practice, the second considering a higher level of production where fertilizer rates and grain and residue removal are increased. APSIM modelling was used to evaluate optimum rates of N fertilization and the potential yield. In most situations, yield continued to increase as fertilizer application was increased to around 1.5 times the current recommended rates. Using this approach, the time taken for the soil to acidify to pH 4.5 (a level at which crop growth would be markedly reduced by Al toxicity) was estimated for the current practice scenario to be less than 10 years for the majority of sites evaluated. Under the higher productivity scenario, this time dropped to less than five years for most sites. However, this analysis did not consider the input of alkalinity that occurs as a result of using groundwater for irrigation. This input of alkalinity was estimated to be sufficient to balance acid inputs at low levels of productivity, but insufficient to address the acid input as productivity increases.

Acidification is driven by two main factors, removal of produce and use of N fertilizer. Removal of grain is clearly unavoidable and is likely to increase considerably as the productivity of the system is increased. N fertilization is currently the greatest driver of acidification, and this will increase disproportionately to the other factors as the system intensifies. Increased use of DAP will markedly increase acidification, as will increased nitrate leaching. A key need for the future is optimal management of N fertilizer to ensure that the financial return to the farmer is maximized, and to ensure that adverse environmental impact such pollution of water bodies and nitrous oxide emission is minimized.

Zinc nutrition in rice. Strip trials were undertaken in farmers' fields to determine if there was any benefit in fertilisation with Zn (and in some cases, B also). We assessed plant performance through visual assessment of plant growth, measurement of yield, and through analysis of plant tissue samples from the Zn-fertilised and unfertilised areas. Generally, the addition of Zn (and B) fertilisers increased yield, although this was not observed at all sites. Grain Zn concentration was not markedly increased. This finding confirms the importance of Zn for the nutrition of crops, and confirms the need for agricultural extension projects to identify responsive areas, and to ensure that adequate fertilisers are applied to crops in order to maximise productivity.

Soil structural benefits of conservation agriculture. Dual ring infiltrometer measurements were made at several sites where conventional tillage and zero tillage had been implemented. Soil samples from the same locations were collected and aggregate stability evaluated by wet sieving. Neither infiltration rate nor aggregate stability was improved by the implementation of zero tillage.

3 Introduction

The External Supplemental Review of the Sustainable and Resilient Farming Systems Intensification (SRFSI) project (CSE/2011/077) identified soil health as an area of concern, with soil pH and associated toxicities, trace element deficiencies (Zn, Cu, B), low organic carbon levels, and soil structural problems identified as key issues. The review identified the following opportunities and needs for further soil health research:

- Investigate use of lime and/or trace elements to address soil pH barriers to economically viable crop and forage production
- Investigate opportunities to enhance soil organic carbon levels through better management of soil mulching
- Give greater emphasis to the development of site-specific soil nutrient management particularly for rabi crops
- Investigate the opportunities for an increased emphasis on the production of biologically fixed N through the greater use of legumes and pulses.

In several instances, these recommendations were based on limited data. This SRA provides additional information to allow the validity of these future research needs to be determined.

The SRA focuses on the following questions:

4. In areas where N fertiliser use has increased, are soils acidifying, and how rapidly is this acidification process likely to proceed?
5. Is Zn (B) deficiency widespread, and will application of Zn fertiliser increase rice yields?
6. Is the organic matter increase observed under conservation agriculture (CA) practice resulting in an improvement in soil structure?
7. What insights into system sustainability can be gained from simple partial nutrient budgets?
8. Can APSIM modelling extend our understanding of the benefits of CA in a broader range of environments, and under different climate scenarios.

Eastern Gangetic Plains – Soil Acidification

Soil acidity is not a difficult problem to understand. As soils become acidic, the soil minerals dissolve releasing aluminium, and this is highly phyto-toxic so crop productivity decreases. Nor is soil acidity a difficult problem to solve; you simply apply lime (where the subsoil is acid, this presents a much greater challenge due to the difficulty in moving lime to depth, as do no-till systems where lime incorporation is an issue). Of course, the devil lies in the detail. Aluminium toxicity has no specific symptoms, the Al ions damage the root system, so crops suffer from poor phosphorus and micronutrient supply, are more prone to drought stress, more susceptible to soil borne disease, and suffer from about a dozen other problems. Legumes are impacted to a greater extent than cereals because the process of nodulation is particularly sensitive to Al. The lack of clear foliar symptoms means that soil acidity can develop without farmers, farm advisors, or scientists realizing what is going on. This is what happened in many areas of Australia, soil pH decreased as a result of poor management practices, the productivity of the land dropped as a result of the soil acidity problem, and now the cost of remediation through lime application is prohibitive given the low productivity of the degraded land. The Australian numbers are sobering. In Australia, 50% of agricultural land is impacted by acidification, the annual cost in foregone production is $1.5 billion, and it is only economically viable to apply lime to 4% of the affected area. This economic constraint is well reflected on our lime use; we apply somewhere in the range of 2 M tonne of lime to agricultural land per year, but it is estimated that to get surface soil pH back up to 5.5 would require 66 M tonnes of lime – the problem is so great it will never be addressed.

With increased N fertiliser use in the Eastern Gangetic Plains, there is the risk that soils are acidifying without the national research organizations realizing the potential impact. There is very little published data on soil acidification in India, and there is a real risk that the problem is being overlooked. As an illustration, in a major review paper “Soil Degradation in India: Challenges and Potential Solutions”, Bhattacharyya et al (2015) state in the opening sentence of the abstract “Soil degradation in India is estimated to be occurring on 147 million hectares (Mha) of land, including 94 Mha from water erosion, 16 Mha from acidification, 14 Mha from flooding, 9 Mha from wind erosion, 6 Mha from salinity, and 7 Mha from a combination of factors.”. The authors then go on to make no mention of the process of acidification in the paper. Indeed, the paper contains only one small paragraph on acid soils, where the application of lime is recommended. In a very long paper, but the second most important soil degradation mechanism in India gets a single paragraph. Researchers from Cornell (Duxbury 2001) did some work on soil acidity on the Gangetic Plains, reporting acid soils in West Bengal, Bangladesh, and the Terai of Nepal, where cropping is intensive and monsoonal precipitation is high. Their work showed yield increases of up to 30% were achieved by lime application, but noted that lime is not used in any of these areas. The SRFSI project found that 15 to 20% of sites in the Coochbehar, Rangpur and Sunsari areas required lime application, while another 30 to 45% of sites should be monitored for pH. In the Madhubani district, at least four nodes (87%) required lime application as a matter of urgency.

The potential acidification problem

Agricultural land management causes acidification by several mechanisms. The most important two are through the removal of alkalinity in the harvested material, and through the application of ammonium-nitrogen fertiliser. Removal of harvested material is unavoidable, but in this context it is important to remember that yields have been considerably increased, and intensification of the system (better agronomy, better cultivars, an additional crop per year, more fertiliser application) further accelerates the rate of acidification. Ammonium fertiliser generates protons as it is nitrified ($NH_4^+ + 2O_2 \leftrightarrow NO_3^- + 2H^+ + H_2O$), if the nitrate is taken up by plants, a proton is consumed partly offsetting the proton release during nitrification. The overall generation of acidity varies depending on the fertilizer source, mono-ammonium phosphate (MAP) and ammonium sulfate are the most acidifying, di-ammonium phosphate is intermediate, and urea is non-acidifying, provided all of the N is taken up by the crop. If nitrate is leached (i.e. there is no balancing consumption of protons through plant uptake), then the rate of acidification is greater. Use of calcium nitrate, or calcium ammonium nitrate (CAN) will result in soil pH increasing.

The Gangetic Plains is an area of existing high productivity, and current relatively heavy N fertiliser use (Figure 3.1). Indeed, the expectation is that N fertiliser use will increase, particularly in the Eastern Gangetic Plains. Furthermore, N fertiliser use is relatively inefficient – remembering that leaching of nitrate increases the extent of acidification.

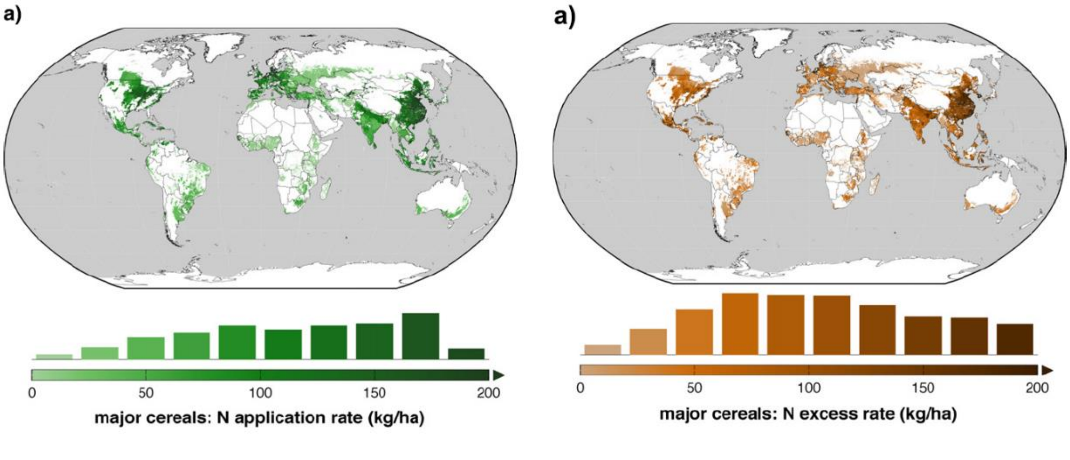


Figure 3.1. Nitrogen fertiliser application, and N excess (from Mueller)

Another factor leading to the risk of acidification is the predominant use of ammonia-based N fertilisers in India (Urea, DAP). Nitrogen fertiliser in India is currently almost exclusively ammonium (Figure 3.2), and hence results in net acid generation. Historically, calcium ammonium nitrate was widely used in India (reflected in the 1961 data below), it is less acidifying but is considerably more expensive per unit N than Urea (from Nishina 2017).

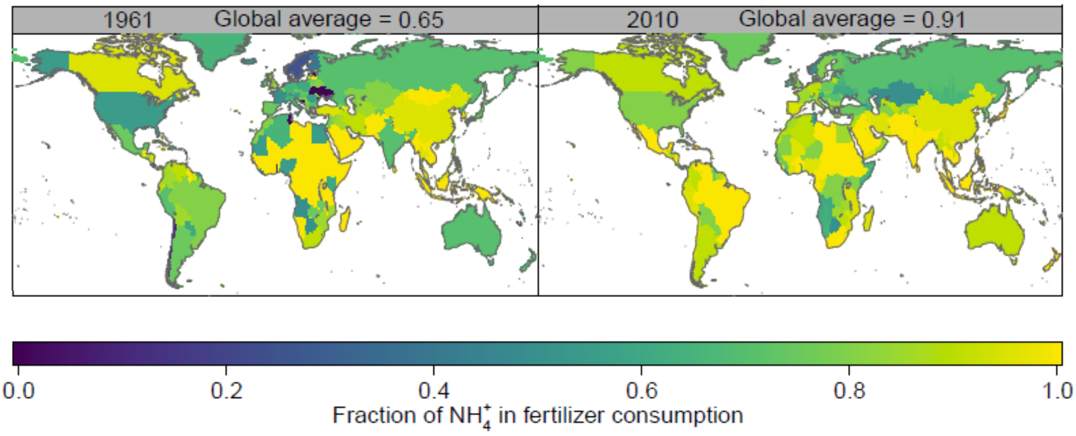


Figure 3.2. Fraction of NH4 in N fertiliser during 1961-2010

As a final facet to this problem, the soils of the Gangetic plain are relatively light textured and hence poorly pH buffered, with near-neutral to slightly acidic starting pH. So it does not take a great deal of acid addition to lower the pH, and the Eastern Gangetic Plains soils are considered sensitive to acidification (Figure 3.3).

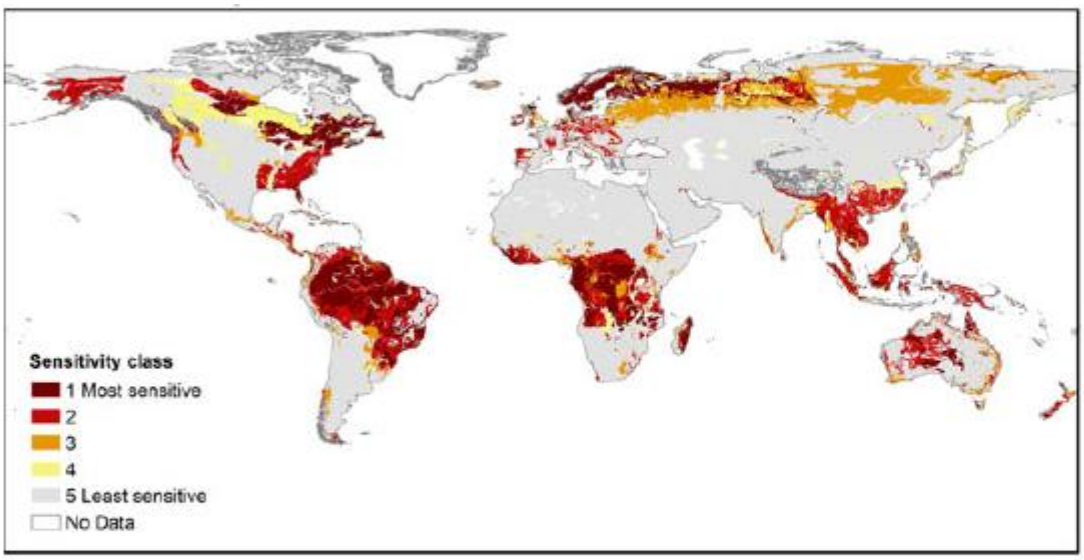


Figure 3.3. Soil sensitivity to acidification (from Smith et al 2016)

In summary, the Eastern Gangetic plain has soils that are susceptible to acidification, with productive agricultural systems where ammonium-N fertiliser is being applied (but poorly utilized by the crop) and substantial yield removed. So we would expect to see acidification, and therefore, must have soil management practices to deal with this problem.

The solution to this problem should not be seen simply as application of lime – to some extent, this is “treating the symptom”. A better approach is improvement in a range of aspects of agronomy (especially N fertiliser use practice and irrigation management), as well as building awareness of soil acidity as a potential problem, and of the incorporation of lime application in the management of the system as part of a good management practice. There is a need to develop means of monitoring acidification, of predicting the pH at which onset of substantial yield loss is likely to occur, and of managing soil pH efficiently. From the farmer's perspective, the most immediate gains will be through the reduction in fertiliser N cost, without loss of yield – and probably savings in water and pumping costs. However, the longer-term gain will be in avoiding degradation of the soil resource and maintaining sustainable crop production to meet food production for a growing population.

The simple aim of this SRA is to provide additional soil pH data to determine the extent to which soil acidification may already be a problem in the Eastern Gangetic Plains, and on the basis of buffer capacity, how quickly the problem may develop. In addition, APSIM modelling has been used to estimate likely future fertilizer N application rates as farmers increase applications in order to maximize yields for existing varieties using best available agronomic practices.

Eastern Gangetic Plains – Zn deficiency

Zinc deficiency in soils is known to be widespread in the Eastern Gangetic Plains, but Zn fertiliser is not commonly used. During field site visits as part of the SRFSI project, Dalal and Menzies frequently saw foliar symptoms on rice, consistent with Zn deficiency. However, these foliar symptoms are not a definitive diagnosis of deficiency, with similar foliar symptoms resulting from fungal disease, and long-term trials at some sites have not shown a Zn response (Haque et al. 2015). Given the clear impact of Zn on maternal and child welfare, it is important to understand if crops are responsive to Zn fertilization.

Within India, Zn is now considered to be the fourth most limiting nutrient for crop production after N, P, and K (Alloway 2008). Indeed, broadly across the Gangetic Plains, approximately 40-80% of soils have Zn concentrations lower than those required by plants, with 65% of trials in farmer's fields showing response to Zn fertiliser (Figure 3.4) (Alloway 2008). Furthermore, there are an estimated 2.5 million ha of the Indo-Gangetic Plains having severe Zn deficiency (Singh 2001). Although Zn is the most common (and important) micronutrient deficiency, B, Mo, and Fe deficiency also impact 10-30% of soils within India. In a similar manner, the deficiencies of Zn and B have also been reported to influence up to 85% of soils in Nepal (Alloway 2008), especially the Terai (Andersen 2007), and is also recognised as a widely occurring limitation in Bangladesh (Zofar et al 1997).

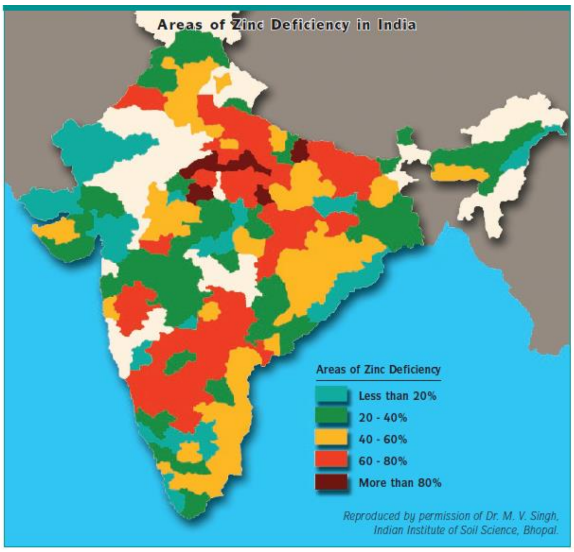


Figure 3.4. Distribution of Zn deficiency in India

Not only do micronutrient deficiencies reduce production, but they also have an adverse impact on human health. For example, it is estimated that 31% of the global population suffers from a dietary deficiency of Zn, causing a loss of 28 million life-years annually (Caulfield and Black 2004). India, Nepal, and Bangladesh are categorised as high risk countries, with > 25% of the population having inadequate intake of Zn within the diet (Figure 3.5) (Black et al. 2008).

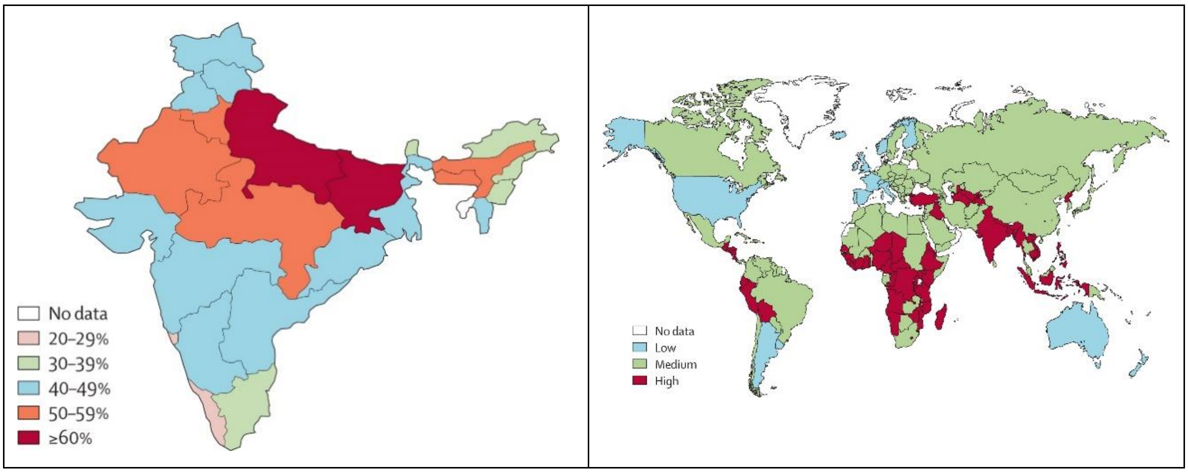


Figure 3.5. Prevalence of stunting among children under 5 years old (left). National risk of Zn deficiency in children under 5 years (right). Images from Black et al. (2008).

Studies of the effect of Zn deficiency on health outcomes using supplementation / fortification have indicated linkages between Zn deficiency and infant or neonatal, child or adult mortality, incidence of malaria, diarrhoea, measles, acute respiratory infection, prevalence of mental retardation, and risk of physical impairment such as hearing defects. Assessment of Zn deficiency in Bangladesh provides a useful insight to the situation across the Eastern Gangetic Plains. A cross-sectional 'nationwide' survey of Zn status in Bangladesh (Rahman et al., 2016) found that 45% of pre-school-age children (6–59 months) and 57% of non-pregnant non-lactating women (15–49 years) were Zn deficient. A correlation between Zn deficiency and diarrhoea has long been recognised, and interpreted as diarrhoea resulting in poor assimilation of dietary Zn. However, there is increasing evidence that Zn deficiency contributes to diarrhoea, with a short course of Zn supplementation able to prevent diarrhoea over the 3 months following treatment of a diarrhoeal episode (Alam et al., 2011). Zinc supplementation resulted in 15% less incidence of diarrhoea, thus saving the lives of 30,000-75,000 children per year. A reduction of 15% in the illness duration and 16% reduction in the likelihood of disease progression were observed as a positive effect of Zn supplementation in Bangladesh (Lindstrom et al. 2011).

The activities proposed for this SRA are simply intended to confirm that Zn deficiency is limiting rice growth, and that alleviating this deficiency results in increased yield.

4 Evaluation of the Risk of Soil Acidification

4.1 Mechanisms of soil acidification

In order to evaluate the current situation and risk of future soil acidification, soil samples were taken from farmer's fields (0-5 cm and 5-15 cm depth increments) and the soil pH measured. To evaluate sensitivity to acidification, pH buffer curves were developed. These buffer curves were then used to estimate the effect of acid input generated through cropping activities as currently undertaken, and in likely (and less likely) future scenarios.

In order to estimate acidification rates under current farming practice, rates of acidification through N cycle and product removal were considered. Nitrogen cycle acidification takes place when acidifying fertilizers (urea, mono-ammonium phosphate, di-ammonium phosphate) are used. The extent of acidification varies depending on the fate of the applied N. A simplified model of proton flows is provided for urea in the figure below (Figure 4.1). For urea, if all of the N applied is taken up by the plant then there is no net acidification. If a portion of the added N leaches as nitrate, then there is a net acidification (one H^+ for each NO_3^- leached). For the ammonium phosphates, there is net generation of acidity even if all of the N is taken up by the plant, and the extent of acid generation increases further if there is leaching of nitrate.

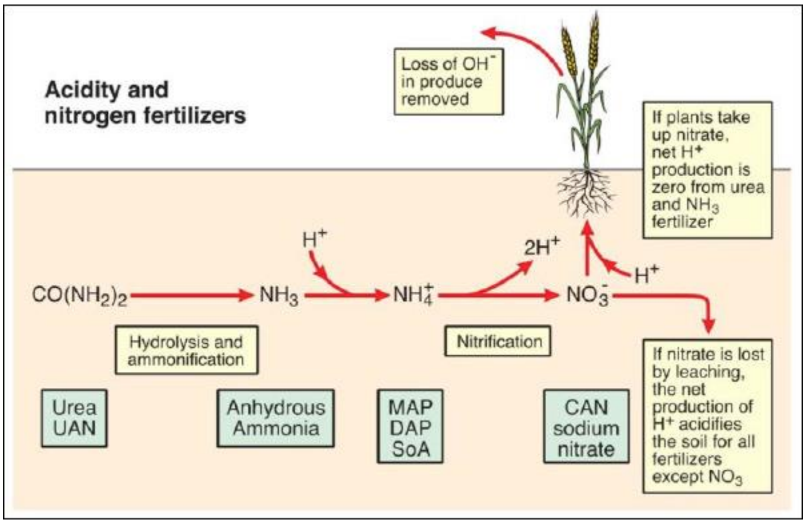


Figure 4.1. Acidification associated with urea application and the fate of the applied N.

The relatively light texture of Gangetic Plains soils, and hence high infiltration rates, result in considerable leaching of N through the soil profile. Nitrate leaching from wheat crops is reported as 17.2 kg/ha from a fertilizer application of 120 kg/ha (Dash et al 2016), while leaching from rice was 28.5 kg/ha from an application of 120 kg/ha (Dash et al 2015). Pathak et al (2006) reported similar nitrate leaching in wheat (18 kg/ha), but also noted a marked rise in the proportion of N that leached as fertilizer rates increased (11% at 60 kg/ha, 15% at 120 kg/ha, 22% at 240 kg/ha), with volatilization rising even more markedly (10% at 60 kg/ha, 26% at 120 kg/ha, 39% at 240 kg/ha). Note that while ammonium volatilization does not contribute to acidification, it does represent a greenhouse gas impact through low N use efficiency.

Loss of N by denitrification can also be considerable in paddy rice production, depending on the management of N fertilizer and water in the cropping system. Pathak et al (2006) estimated denitrification at 4 kg/ha from an N addition of 120 kg/ha in a well-managed continuously flooded system. In contrast, Katyal et al (1985) reported loss of up to 50% of applied urea through denitrification. From an acidification perspective, denitrification consumes one mole of H^+ per mole of NO_3 denitrified; so it is comparable to plant uptake. As nitrification typically occurs at the soil surface, and denitrification at depth, the spatial decoupling of these processes can result in the soil surface becoming acidic, and subsoil layers more alkaline. However, in the rice system considered here, cultivation will eliminate this spatial effect.

The Eastern Gangetic Plains are much less productive than comparable areas of the Punjab or Haryana (FAO, 2016), and it is anticipated that yields in the Eastern Gangetic Plains will be increased by the adoption of agronomic practices comparable to those in Haryana, including: higher rates of fertilizer application (N,P,K), broader adoption of zero-tillage practice, and increased use of irrigation (Park et al, 2018). These anticipated changes of increased yield (and hence increased base cation removal), and the increased use of N fertilizer, will further increase the rate of soil acidification in the Eastern Gangetic Plains. In order to evaluate this impact we assumed that farmers would increase their yield toward the yield potential of the region. The yield potential estimates of Aggarwal et al (2000) for rice are 9.73 t/ha in Bihar, and 8.07 t/ha in West Bengal, while estimates for wheat are 6.7 t/ha in Bihar and 5.30 t/ha in West Bengal. Park et al (2018) estimated that the average wheat yield for Eastern Gangetic Plains farmers at 2.80 t/ha (West Bengal ranging from 3.69 t/ha for elite farmers to 2.22 t/ha for poor-performing farmers, Bihar 5.23 t/ha for elite farmers to 2.48 t/ha for poor-performers, with similar estimates in Nepal 2.21 t/ha (range 3.19 to 1.51 t/ha). It is interesting to note that yield was not directly related to N fertilizer use. While N inputs varied across the regions, there was little difference between elite farmers N use, and the regional average (West Bengal elite 94 kg/ha, poor 95 kg/ha, average 95 kg/ha; Bihar elite 147 kg/ha, poor 118 kg/ha, average 132 kg/ha; Nepal elite 78 kg/ha, poor 76 kg/ha, average 77 kg/ha). This implies greater N loss from poorer performing farms.

In order to further evaluate likely N fertilizer use, we used APSIM modelling to evaluate optimum N use in rice-wheat and rice-maize cropping systems. As part of the SRFSI project the model was calibrated and validated for 12 locations across the Eastern Gangetic Plains. In this work, seven of these sites were used to determine the sensitivity of yield to altered fertilizer N supply. This work aimed to provide a better understanding of N use efficiency for CA and CT systems, including the impacts on emissions, productivity and soil acidification rates.

Our assumptions for the best-case current practice cropping assumes that all of the N fertilizer is applied as urea, as this is the least acidifying N fertilizer in common usage. Nitrate leaching is at the level observed for wheat and rice cropping, while acidification through the removal of crop residue biomass is moderated by the assumption that for wheat there is no removal, while for rice, residue is removed, but half of the alkalinity removed will be returned as farmyard manure. Our higher productivity system assumes that input of N and P has increased, with 40 kg/ha of N applied as DAP at planting. Yield is increased to 3.5 t/ha (still less than half of the yield potential), and for rice, biomass is removed, but not returned. This reflects cropping practice for wealthier farmers who have more crop productivity than animal demand for feed – crop biomass is assumed to be sold/traded to other farmers who have less land relative to their ownership of cattle.

4.2 Methods

Soil samples were collected from typical farmer's cereal cropping fields. Sampling increments of 0 to 5 cm, and 5 to 15 cm were used to ensure effects of conservation tillage were captured. Soils were air dried, mixed, then sieved to pass 2 mm. Soil pH was measured in a 1:5 soil:water suspension. Buffer capacity of the soil was determined by titrating the soil through acid and alkali addition. Aliquots of standardized 0.1M HCl (20, 40, 80 µmol H^+/g) or saturated $Ca(OH)_2$ solution (9.7, 19.4, 38.3, 77.6, 116.4, 155.2, 194 µmole OH^-/g) and balancing water addition were made to provide 1:5 soil:water suspensions across a range of pH values. The suspensions were shaken regularly, and the pH measured after 1 week. In addition to the project soil samples, two Australian soils, a highly buffered Vertosol, and a poorly buffered Kandosol, were included as comparison samples.

Rate of acidification

Assumptions for best case / current practice.

- Wheat production: 100 kg N /ha applied, with 50 kg/ha as urea at planting, 50 kg as urea in split application during crop growth. Of this, 16 kg/ha is leached as nitrate, the remainder is assumed to be taken up by the plant, denitrified or volatilized, and hence to cause no acidification. Yield is assumed to be 2.7 t/ha, residue is not removed (e.g. ploughed in, or burnt *in-situ*).
- Rice production: 100 kg N /ha applied, with 50 kg/ha as urea at planting, 50 kg as urea in split application during crop growth. Of this, 28 kg/ha is leached as nitrate, the remainder is assumed to be taken up by the plant, denitrified or volatilized, and hence to cause no acidification. Yield is assumed to be 2.6 t/ha, with 2 t/ha of straw removed, with half of the alkalinity returned to the field as farmyard manure.

Assumptions for increased productivity situation

- Wheat production: 160 kg N /ha applied, with 40 kg/ha as DAP and 40 kg/ha as urea at planting, 80 kg/ha as urea in split application during crop growth. Of this, 28 kg/ha is leached as nitrate, the remainder is assumed to be taken up by the plant, denitrified or volatilized, and hence to cause no acidification. Yield is assumed to be 3.5 t/ha, with no straw removed (e.g. ploughed in, or burnt *in-situ*).
- Rice production: 160 kg N /ha applied, with 40 kg/ha as DAP and 40 kg/ha as urea at planting, 80 kg/ha as urea in split application during crop growth. Of this, 35 kg/ha is leached as nitrate, the remainder is assumed to be taken up by the plant, denitrified or volatilized, and hence to cause no acidification. Yield is assumed to be 3.5 t/ha, with 3 t/ha of straw removed.

APSIM analysis of optimum N rates

Yield sensitivity to N fertilizer rate was estimated for seven sites; two in Bangladesh (Rajshahi and Rangpur), four in India (Dogachi and Tikapatti in Bihar, and Malda and Coochbehar in West Bengal), and one site in Nepal (Sunsari). For each location a fertilizer rate multiplier was applied to the current recommended N application rate for the site. Multipliers were 0, 0.25, 0.5, 0.75, 1.0, 1.25, 1.5, 1.75, 2.0, 2.25, 2.5, 2.75, and 3.0. Recommended rates are provided in Table 4.1. The impact of altering N fertilizer rate was considered for both crops in the sequence, with all combinations evaluated for each cultivation system (CT and CA) and each crop sequence (rice-wheat, rice-maize (676 separate simulations for each site). This analysis permitted the range of optimum fertilizer regimes to be considered for each cultivation system x crop sequence for each site. Yields are presented as rice equivalent yield (REY), and gross margin calculated (USD/ha).

Table 4.1 Recommended N fertilizer rates (kg/ha) for crops in each of the locations considered in crop simulations.

	Locations			
Crops	Bihar	West Bengal	Bangladesh	Nepal
Rice	100	88	90	120
Wheat	120	122	120	100
Maize	120	165	276	150

4.3 Results and Discussion

4.3.1 Soil pH

Soils across the sampling region were dominantly slightly acidic (Figure 4.2). The Nepalese samples had the greatest range and highest median, but if only samples from the Terai region were considered (<300 m elevation), the median drops to a value comparable to the other regions. Overall Gangetic Plains sites (<300 m elevation), the median pH was 5.75, with individual country values all being similar (West Bengal 5.81, Nepal 5.82, Bangladesh 5.69).

For India, these distributions show somewhat higher pH than those reported in the Regional soil sampling and mapping reported in Table 4.2 and Appendix 1. This difference is attributed to the restriction of sampling to cereal growing fields in this study. The regional sampling will also have included more acidic tea (*Camelia sinesis*) areas. The range for India is comparable with that reported by Bid (2017) (4.5 to 7.5, median 6.0) for 39 blocks in the Bardhaman district of West Bengal. However, other reports provide widely differing pH. For example, Sing et al (2012) reported pH ranging from 7.8 to 8.4 for 300 sites in the Muzaffarpur district of Bihar.

Figure 4.2. The distribution of pH values for sampled regions. Nepal data are presented for all sites sampled, and separately for sites on the Terai (<300 m elevation). The mid-line on the box plots is the median, the box extends to the 25th and 75th percentiles, with lines extending to the 10th and 90th percentiles.

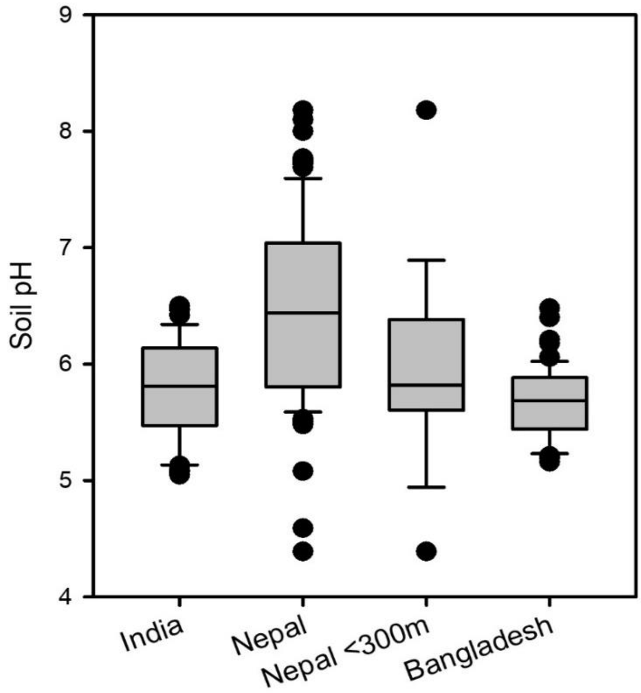


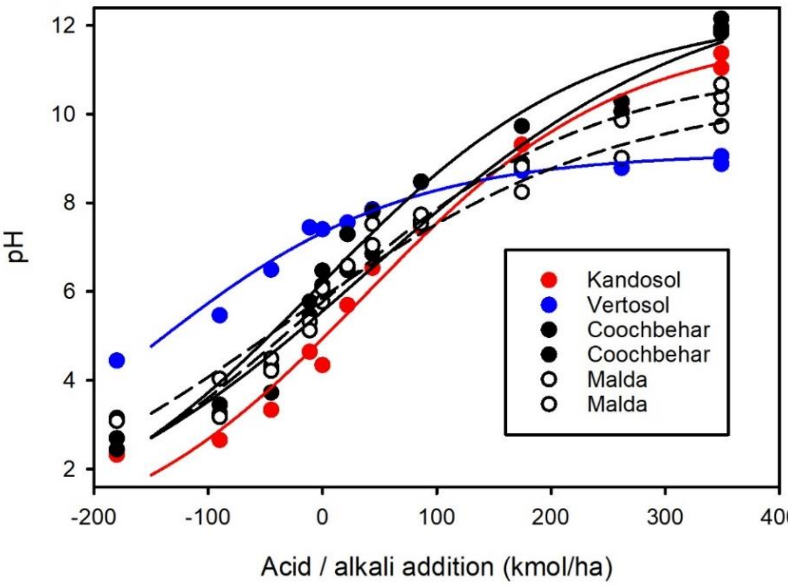
Table 4.2. Percentage distribution of soils falling within the more acidic classifications in the Regional Assessment of West Bengal soils.

	Strongly acidic pH < 4.5 (%)	Moderately acidic pH 4.5-5.5 (%)	Slightly acidic pH 5.5-6.5 (%)
Malda	1.2	12.5	28.6
Uttar Dinajpur	19.9	58.1	18.4
Jalpaiguri	28.0	27.8	7.8
Dakshin Dinajpur	16.3	57.8	22.3
Coochbehar	26.2	44.3	17.2

4.3.2 Soil Buffer Capacity

Soil buffer capacity curves were developed through addition of acid and alkali (Figure 4.2). Known comparison Australian soils were included to assist with interpretation of the data. The Kandosol represents a poorly buffered soil (i.e. one that will show a large change in pH for a given addition of acid or alkali), while the Vertosol represents a strongly buffered soil (i.e. one that shows a modest change in pH for a given addition of acid or alkali). The study soils were comparable to the poorly buffered Kandosol, and are thus readily susceptible to acidification.

Figure 4.2. pH buffer curves for two representative soils selected from the Coochbehar and Malda regions, and comparison with Australian soils.



The region of most interest on these buffer curves is that around the normal condition (i.e. small additions of acid or alkali). If only this region is considered, the relationships are essentially linear, with all soils (and both depths) showing similar slope. The data for the Coochbehar area are shown in Figure 4.3, with comparable slope values displayed by all of the soils evaluated (0-5 cm and 5-15 cm depths) (Table 4.2).

Figure 4.3. Buffer curves for the Coochbehar area. Surface samples (0 – 5 cm) are shown as solid lines, subsurface samples (5 – 15 cm) are shown as dashed lined.

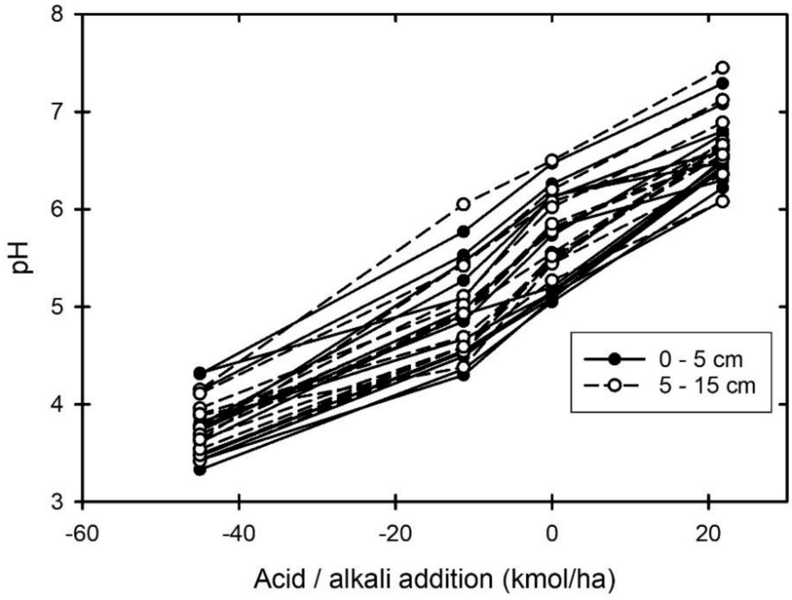


Table 4.2. Slope and intercept data for the linear mid-portion of pH buffer curves

Country	No. of Sites	Slope	Intercept
India	14 Coochbehar 8 Malda	0.034 0.043	5.95 5.62
Nepal	2 Sunsari	0.031	5.94
Bangladesh	No data		

4.3.3 Soil Acidification Rate

The rate that a soil will acidify to a pH sufficiently low that Al phytotoxicity will become a limitation to crop production depends on a range of factors, including, the initial pH of the soil, the soils buffer capacity, and the rate of acid addition. We measured the initial pH, have estimated the buffer capacity by making acid and alkali additions and permitting a short-equilibration period (7 days), and we made a number of assumptions regarding the acid generating aspects of the farming system. Other factors which clearly influence the pH at which an Al toxicity problem may become apparent, for example the crop grown and the mineralogy of the soils, were assumed to be equal across the study area, and a pH value for onset of Al toxicity of 4.5 was used.

Using the best case / current practice scenario (Figure 4.4), the predicted time for the system to acidify ranged from a little as three years, to more than 10 years. Given the profound impact that acidification would have on the productivity of the system, all of these values are sufficiently low that they are of considerable concern. It should be noted that the assumptions made are very conservative (acid inputs are limited to removal of yield, removal of one half of the alkalinity in the crop residue, and a modest nitrate leaching component), with an overall system acidification rate of 4.6 kmol H^+/ha. In many areas of the Eastern Gangetic Plains farmers remove all of the residue of both wheat and rice crops, with little or no return of material to cereal growing fields (Islam et al 2019). Removal of the entire crop residue (assuming a harvest index of 0.5) would result in an annual acid input of 6.8 kmol H^+/ha.

When inputs for a more productive cropping system are considered (use of P fertilizer as DAP, increasing yield to 3.5 t/ha, increased rice biomass removal, and a modest increase in nitrate leaching), the acidification rate is increased markedly, and the period of time before Al toxicity limits productivity drops to one to five years. Even the assumptions made in this scenario are modest, leading to an acid input of 13 kmol H^+/ha, a value considerably lower than inputs of 30 to 50 kmol H^+/ha reported for double cropping cereal systems in China (Guo et al 2010).

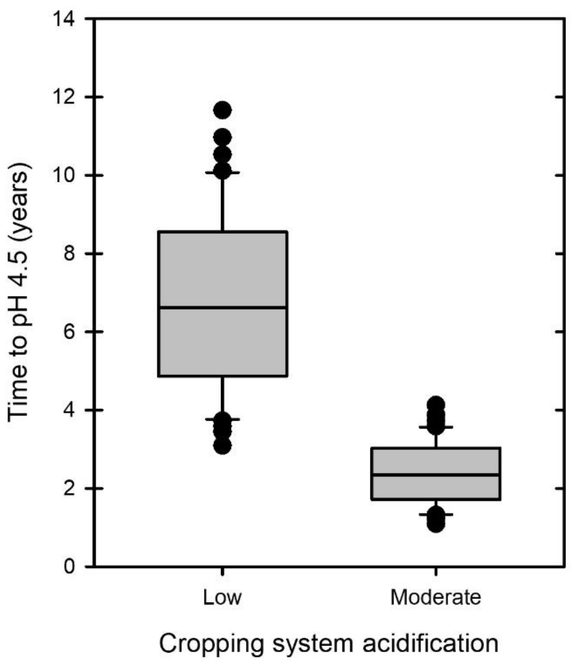


Figure 4.4. Predicted time for soil pH to reach 4.5 under conditions of a low rate of acidification reflecting current farming practice, and an elevated rate of acidification under conditions of increased productivity.

While there is some variation in buffer capacity between sites, the relationship between initial pH and time to acidify to pH 4.5 is sufficiently strong (Figure 4.5) that this can be used as a general prediction tool.

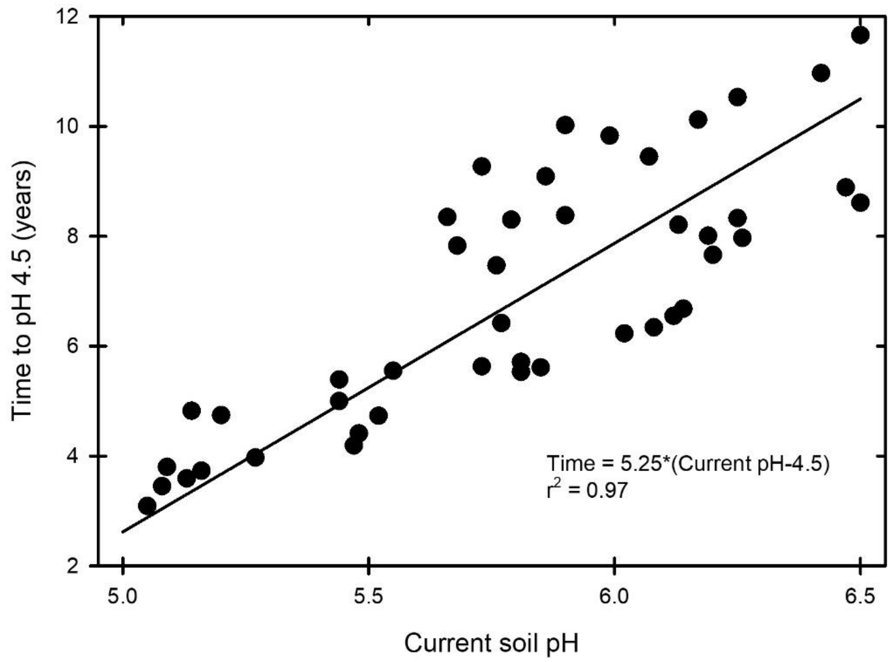


Figure 4.5 The relationship between initial soil pH, and the estimated time for the best case / current cropping system to acidify the soil to pH 4.5.

4.3.4 Potential errors in estimates of acidification rate

Irrigation water alkalinity

Our analysis may overestimate the rate of acidification for several reasons, the most important of these is likely to be because of alkalinity supplied in irrigation water from shallow aquifers. Given that access to irrigation varies (surface / groundwater), as will water quality and rates of application, no attempt was made to incorporate this in the estimates of acidification rate, nevertheless it is recognised as an important moderating factor.

Gangetic Plains soils are young from a soil mineralogy perspective, so weathering of silicate minerals will generate alkalinity. A crude calculation of weathering contribution indicates that this could account for as much as 1 kmol H^+/ha/yr of neutralization based on basin wide Si release (Lupker et al 2012; Fringes et al 2015). Note that this alkalinity is generated throughout the depth of the soil profile, so the direct contribution to neutralization of acidity in the surface soil will be small. However, that alkalinity generated throughout the profile will contribute to alkalinity of the groundwater, and hence this alkalinity will be important where groundwater is used for irrigation.

Irrigation of the wheat crop may supply a substantial input of alkalinity depending on the quality of the groundwater. Use of 100 mm of irrigation water on the wheat crop at 70 mg/l total alkalinity, a median value reported for wells in Coochbehar (Kumar 2012) would supply 1.4 kmol OH^- /ha. The same irrigation application at 220 mg/l total alkalinity, the median value reported for the eastern Terai (Mahato 2018) would provide 4.4 kmol OH^- /ha effectively balancing acidification under the conservative scenario evaluated here.

Thus, input of irrigation alkalinity to the system could reduce the rate at which the cropping system acidifies the soil. Nevertheless, the risk of acidification will remain high on areas without irrigation or irrigated with surface water. Even on groundwater irrigated areas, net acidification will occur as the cropping system is intensified.

Underestimation of nitrate leaching

Leaching of nitrate is a substantial contributor to the calculated rate of acidification. Unfortunately, the estimates of nitrate leaching available for the Eastern Gangetic Plains farming system are not robust. Nitrate leaching estimates are typically generated through modelling studies or represent an unmeasured balancing (error) term in mass balance studies.

Modelled nitrate leaching values vary widely. The value of 16 kg/ha N leached as nitrate used in the calculations in this study come from Dash et al (2016), and this is one of the lower published estimates. In a comparable study of Mittal et al (2007), 59 kg N/ha was leached as nitrate where 120 kg N /ha was applied as fertilizer (this would increase the modelled acidification rate to 7.7 kmol/ha/yr).

Mass balance nitrate leaching values could be subject to considerable error. A substantial amount of N is accounted for as lost by volatilization when urea is broadcast on crops. However, the residence time for ammonia in the atmosphere is low, and modelling suggests that 50% of ammonia emitted from the surface will be readsorbed by dry deposition (absorption by soil and vegetation) within 1 km even under conditions of fairly high wind speed (Asman 1998). In rice systems, recapture of ammonium may be even more efficient, Yi et al (2020) reporting 80% of NH_3 emitted from rice paddy fields was dry deposited within 100 m. This recapture of NH_3-N is not typically accounted for in mass balance studies, and where nitrate leaching is the balancing term, any recapture of NH_3-N would represent an underestimate of nitrate leaching. Thus, the acidification rate may be higher than predicted in this study as a result of underestimating the nitrate leaching term.

Methodological limitations

The 7 day equilibration period allows fast reactions to occur, but there may be slower neutralization reactions that would contribute to pH buffering over a longer period. Relative to the other potential errors listed above, this is likely to be an unimportant source of error.

4.3.5 Responses

Acidification is driven by two main factors, removal of produce and use of N fertilizer. Removal of grain is clearly unavoidable and is likely to increase considerably as the productivity of the system is increased. Indeed, this component is likely to double or more as farming practices approximate those of the Punjab. Removal of crop residue may be a practice worth revaluating when the cost in soil acidification, and more importantly cost in K removal is considered.

Clearly, N fertilization is currently the greatest driver of acidification, and this will increase disproportionately to the other factors as the system intensifies. Increased use of DAP will markedly increase acidification, as will increased nitrate leaching. A key need for the future is optimal management of N fertilizer to ensure that the financial return to the farmer is maximized, and to ensure that environmental insult is minimized.

While reducing biomass removal and increasing N use efficiency can reduce the rate of acidification, there will still be the need to add alkalinity. One aspect of this may be through increased irrigation, driven by farmer’s efforts to increase yield. However, aquifer overexploitation is already an issue in many areas, so the scope for increasing irrigation (with alkaline groundwater) is likely to be limited. The other alternative will be the integration of liming as a routine practice in the cropping system. The availability and quality of liming materials will need to be considered.

An important environmental consideration here will be the greenhouse gas impact of farming system intensification. Small gains are likely through increased soil C stocks as conservation agriculture practices are broadly adopted, and as the primary biological productivity of the system is increased through improved cropping practices (including increase fertilization). However, these gains will only occur until a new equilibrium C level is reached. In contrast, improved N management will continue to have a positive effect (or more accurately, a smaller negative impact). The Nature Conservancy (Griscom et al 2017) revisited the potential for soils to sequester C on a global scale, considering in their estimation realistic economic constraints. They estimated a C sequestration benefit of 0.4 Pg C /yr for conservation agriculture. They also estimated the benefit of better nutrient management (reduced N use) as contributing 0.7 Pg C /y. Increased N use efficiency on the Gangetic Plains would provide benefits through reduced CO_2 emission from manufacturing (because of reduced N fertilizer consumption), reduced N_2O emissions, and reduced CO_2 released through lime application to address N fertilizer induced acidification. This final component is certainly non-trivial, Zamanian et al (2018) estimate CO_2 release from liming and N acidification of carbonate-containing soils is 0.28 Pg C/y.

A final environmental impact aspect is the effect of acidification on denitrification. As soils become more acid, a greater proportion of N is denitrified to N_2O (Aulakh et al 1992). Thus, for the same amount of N lost by denitrification, the greenhouse gas impact increases as the soil acidifies.

4.3.6 APSIM analysis of optimum N rates

Simulation generally showed that there is potential to increase yield and productivity by increasing N fertilizer rates. In many of the sites and systems considered, optimum yield and profitability would be reached at fertilizer rates of around 1.5 times the current recommended rate. Data for the rice-wheat system in Tikappatti, Bihar is presented in Figure 4.6 to illustrate the form of the data generated.

Given the yield and gross margin response to fertilization (Figure 4.6), where optimum yields are achieved at around 150 kg/ha for rice and 180 kg/ha for wheat, the estimation of acidification rates for higher fertilization regimes of 150 kg/ha for both crops is well justified. Indeed, for maize where recommended fertilizer rates are higher (120 to 276 kg/ha Table 4.1), and optimum yield is typically achieved at multiplier values of around 1.5, application rates of 200 kg/ha may reasonably be expected in the future, potentially leading to higher acidification rates than estimated even for the higher productivity scenario.

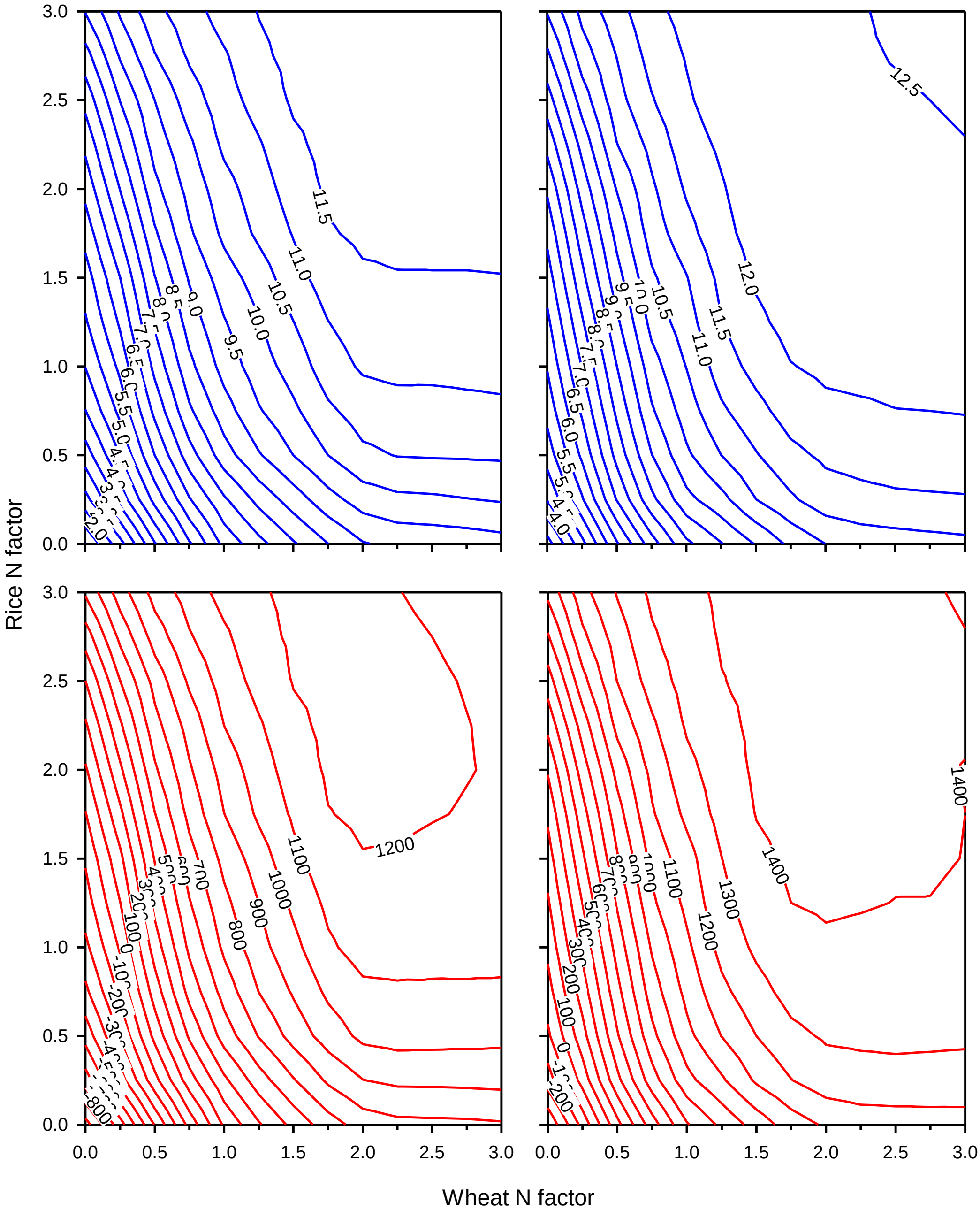


Figure 4.6 Upper graphs present effect of N rate on system rice equivalent yield (REY, t/ha) while lower graphs present gross margin (GM, USD/ha) at Tikapatti, Bihar, India. REY and GM are presented for each cropping system (conventional tillage-left and conservation agriculture-right) for the rice-wheat system. Where the contour lines are closer together, this indicates more rapid changes of system variables, while contour lines further apart indicate plateauing, or a small change of system variables per unit of change in fertilizer input.

5 Crop nutrition

5.1 Zinc and boron nutrition in rice

5.1.1 Introduction

Zinc deficiency in soils is known to be widespread in the Eastern Gangetic Plains. Indeed, broadly across the Gangetic Plains, approximately 40-80% of soils have Zn concentrations lower than those required by plants (Alloway 2008). Furthermore, there are an estimated 2.5 million ha of the Indo-Gangetic Plains having severe Zn deficiency (Singh 2001). Not only do micronutrient deficiencies reduce production, but they also have an adverse impact on human health. For example, it is estimated that 31% of the global population suffers from a dietary deficiency of Zn, causing a loss of 28 million life-years annually (Caulfield and Black 2004). India, Nepal, and Bangladesh are categorised as high risk countries, with > 25% of the population having inadequate intake of Zn within the diet (Black et al. 2008).

Despite the importance of Zn nutrition in the Eastern Gangetic Plains, Zn fertiliser is not commonly used.

5.1.2 Methods

Strip trials were undertaken in farmers' fields to determine if there was any benefit in fertilisation with Zn (and in some cases, B also) (Table 5.1). We assessed plant performance through visual assessment of plant growth, measurement of yield, and through analysis of plant tissue samples from the Zn-fertilised and unfertilised areas. Tissue samples were analysed at The University of Queensland.

Treatments were applied as follows:

- Bangladesh (BARI)
  - -Zn
  - -B
  - +Zn+B [5.5 kg/ha $ZnSO_4$, 6 kg/ha H_3BO_3]
- India (UBKV)
  - -Zn
  - +Zn [1 kg/ha Zn-EDTA as a foliar spray (2 × 0.5 kg/ha)]
- Nepal (NARC)
  - -Zn
  - +Zn [25 kg/ha $ZnSO_4$]

Table 5.1. Field trial locations for evaluation of zinc status of rice crops

Country	Region	Number of individual sites
Bangladesh (BARI)	Rangpur	16
	Dinajpur	4
India (UBKV)	Coochbehar	9
	Malda	7
Nepal (NARC)	Bhokraha	5
	Kaptanganj	5

5.1.3 Visual assessment

It is known that Zn deficiency causes "brown blotches and streaks in lower leaves" (Yoshida et al. 1973), often shown as an interveinal chlorosis or brown streaks (Yoshida and Tanaka 1969). For B, symptoms are similar to Ca deficiency given that both B and Ca are immobile within the phloem. Specifically, symptoms of B deficiency occur on the youngest leaves, with moderate B deficiency being as pale bands 2-3 mm in width, whilst more severe deficiency tips of emerging leaves being white and rolled (Yu and Bell 1998).

Sites were visited in mid-September 2019 following transplanting in July/August 2019. Although most sites had plants showing symptoms of Zn deficiency in the '-Zn' treatments, symptoms in these treatments were generally modest and were not severe. Symptoms were most pronounced in Rangpur (Bangladesh) and in India. It was also noted that the crops growing in the fields adjacent to the trial sites (i.e. managed by different farmers) regularly had more pronounced symptoms of Zn deficiency than did the crops growing in the trial sites themselves. It is likely that this is because of two reasons: (i) Zn had generally been applied to the trial sites in previous years, whereas adjacent farmer's fields had often never received Zn fertilisers, and (ii) it is possible that the adjacent farmers were using different varieties that were more susceptible to Zn deficiency.

Symptoms of B deficiency were less frequent and were most pronounced on the lighter textured (sandier) soils. However, even in these soils, symptoms of B deficiency were comparatively modest.

Figure 5.1. Symptoms of Zn deficiency in an adjacent farmers' field (Rangpur, Bangladesh)

Figure 5.2. Symptoms of B deficiency (Nepal)

Figure 5.3. Symptoms of Zn deficiency from the -Zn treatment (Satmile, India)

Figure 5.4. Symptoms of Zn deficiency from the -Zn treatment (Satmile, India)

5.1.4 Grain Zn concentration and human nutrition

Although addition of Zn (and B) fertilisers increased average grain yield in both Bangladesh (BARI) and India (UBKV), this was not associated with any marked increase in the grain Zn concentration. Indeed, for India, grain Zn concentrations were 16.8 mg/kg in the -Zn treatment and 17.1 mg/kg in the +Zn treatment for Coochbehar, and 19.0 mg/kg in the -Zn treatment and 19.2 mg/kg in the +Zn treatment for Malda (Table 5.3).

5.1.5 Grain yield

Generally, the addition of Zn (and B) fertilisers increased yield, although this was not observed at all sites. For Bangladesh, addition of combined Zn and B fertilisers resulted in an average increase in yield of 0.5 t/ha for Rangpur and 0.9 t/ha for Dinajpur compared to the -Zn treatments (Table 5.2). For B, the addition of combined Zn and B fertilisers increased yield by 0.6 t/ha for Rangpur and 1.0 t/ha for Dinajpur compared to the -B treatments (Table 5.2). In India, addition of Zn fertilisers increased average yield by 0.8 t/ha in Coochbehar and 0.4 t/ha in Malda (Table 5.3). Finally, for Nepal, the addition of Zn fertilisers did not appear to increase average yield (Table 5.4). Thus, there is a need for agricultural extension projects to ensure that adequate Zn fertilisers are applied to crops in order to maximise productivity. This is also illustrated by our observation that symptoms of Zn deficiency were generally most severe in adjacent farmers' fields rather than in the trial area itself, which was a reflection of better nutrient practices at these sites in the SRFSI project. These findings confirm the importance of Zn for the nutrition of crops for wide range of farmers in these regions.

Table 5.2. Average yield and grain nutrient concentrations for Bangladesh (BARI)

(Plant samples have not yet been sent to UQ due to COVID Lockdown in Bangladesh)

Region	Treatment	Grain (t/ha)	Grain Zn (mg/kg)		Grain N (%)	Grain P (%)	Grain K (%)	Grain S (%)	Grain Mg (%)	Grain Fe (mg/kg)	Grain B (mg/kg)
Rangpur	-Zn	4.8									
	-B	4.7									
	+Zn+B	5.3									
Dinajpur	-Zn	5.5									
	-B	5.4									
	+Zn+B	6.4									

Table 5.3. Average yield and grain nutrient concentrations for India (UBKV)

Location	Treatment	Grain (t/ha)	Straw (t/ha)	Grain Zn (mg/kg)		Grain N (%)	Grain P (%)	Grain K (%)	Grain S (%)	Grain Mg (%)	Grain Fe (mg/kg)	Grain B (mg/kg)
Coochbehar	-Zn	2.6	6.4	16.8		1.0	0.29	0.28	0.08	0.10	36	2.6
	+Zn	3.4	7.7	17.1		1.0	0.30	0.28	0.14	0.11	45	0.76
Malda	-Zn	3.1	7.1	19.0		1.2	0.28	0.30	0.14	0.10	43	1.4
	+Zn	3.5	7.7	19.2		1.2	0.27	0.29	0.20	0.10	57	0.76

Table 5.4. Average yield and leaf tissue nutrient concentrations for Nepal (NARC)

Region	Treatment	Grain (t/ha)	Leaf Zn (mg/kg)		Leaf N (%)	Leaf P (%)	Leaf K (%)	Leaf S (%)	Leaf Mg (%)	Leaf Fe (mg/kg)	Leaf B (mg/kg)
Bhokraha	-Zn	6.0	65		0.99	0.15	2.1	0.12	0.30	670	7.2
	+Zn	6.0	76		0.99	0.14	2.0	0.10	0.27	584	6.5
Kaptanganj	-Zn	6.3	55		1.0	0.15	2.0	0.14	0.28	580	7.7
	+Zn	6.3	96		1.1	0.18	2.2	0.14	0.29	758	6.8

5.2 Citrus nutrition (Nepal, NCRP)

5.2.1 Introduction

Citrus fruits are an important sector of agriculture in Nepal, with most citrus grown at altitudes of 800 to 1400 m across an area of 46,300 ha. Average productivity is 8.96 t/ha, which is markedly lower than the global average for citrus production. Furthermore, productivity in these orchards is gradually decreasing over time, decreasing from an average > 11 t/ha in 2010. Anecdotal evidence suggests that this decrease in productivity is likely due to decreasing soil fertility. Indeed, the only fertilisers applied by most farmers is compost, often applied at a rate of 40-80 kg per tree.

In this regard, NCRP has conducted an initial experiment at their experimental station (Paripatle, Dhankuta) to examine the impact of fertilisation on yield and fruit quality, finding that especially in older orchards, addition of fertilisers can increase yield and quality markedly (Table 5.5).

Table 5.5. Effect of fertilisation on citrus yield and quality (data from NCRP, Nepal)

Treatment	Total weight of A-Grade fruit (kg/plant)	Total fruit yield (kg/plant)
T1: FYM 100 kg/tree	7.8	44
T2: FYM 75 kg + Urea 400 g + DAP 200 g + Potash 400 g	14	53
T3: FYM 75 kg + Urea 400 g + DAP 200 g + Potash 400 g + Boric acid 20 g + Zinc sulphate 150 g + Copper sulphate 75 g + Manganese sulphate 75 g + Agri-lime 150 g	26	67
T4: FYM 75 kg + Boric acid 20 g + Zinc sulphate 150 g + Copper sulphate 75 g + Manganese sulphate 75 g + Agri-lime 150 g	13	53
T5: FYM 100 kg + Micronutrient spray	21	62

5.2.2 Methods

Leaf samples were collected from citrus plants from 93 different farmers. A total of 65 samples were collected for mandarin (*Citrus reticulata*), 19 for lime (*Citrus aurantifolia*), eight for sweet orange (*Citrus sinensis*), and one for Unshiu orange (*Citrus unshiu*). The samples were collected from across Nepal (Figure 5.5), from altitudes ranging from 27 to 1750 m. The tissue samples were analysed at The University of Queensland for nutrient concentration.

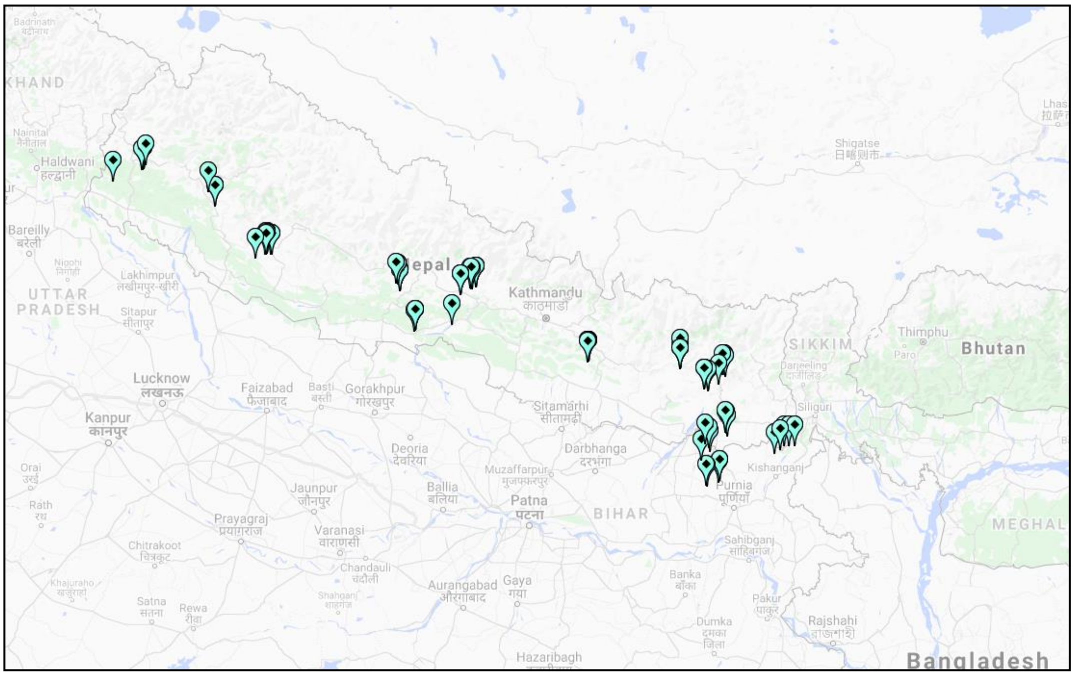


Figure 5.5. Locations of the orchards from which leaf tissue samples were collected.

5.2.3 Leaf tissue nutrient concentrations

Leaf tissue nutrient concentrations (Table 5.6) were compared to the criteria reported for citrus by Robinson et al. (1997) for the ‘marginal’ values and the ‘deficient’ values. Overall, it was found that citrus growth is likely highly restricted by a deficiency of Zn, with 98% of samples being marginal for Zn and 81% being within the deficient range (Table 5.6). Furthermore, N deficiency also appears to be highly important, with 67% of samples being marginal for N and 57% being within the deficient range (Table 5.6). Other nutrients likely limiting to be important were Ca (marginal in 65% of samples), Mn (marginal in 46% of samples), B (marginal in 31% of samples), Cu (marginal in 28% of samples), and Mg (marginal in 32% of samples) (Table 5.6). These findings are in agreement with the initial experiment at NCRP which found that applications of fertilisers, including micronutrients, could increase fruit yield and quality markedly (Table 5.6). In particular, it seems that Zn and N fertilisers are likely to be critical in improving citrus production. Thus, there would appear to be considerable scope for increasing citrus production through improved nutritional management.

Table 5.6. Average leaf tissue nutrient concentrations from 93 samples taken from across Nepal.

	N (%)	B (mg/kg)	Ca (%)	Cu (mg/kg)	Fe (mg/kg)	K (%)	Mg (%)	Mn (mg/kg)	P (%)	S (%)	Zn (mg/kg)
Average leaf tissue concentration	2.2	41.7	2.7	27.2	214.3	1.3	0.3	30.0	0.2	0.4	13.5
Minimum leaf tissue concentration	1.5	16.5	1.3	2.7	75.7	0.5	0.0	12.8	0.1	0.1	5.8
Maximum leaf tissue concentration	3.2	122.0	5.1	995	732	3.0	0.4	201	0.6	0.8	49.5
Number tissue samples < marginal	62	29	60	26	0	5	30	43	3	14	91
Number tissue samples < deficient	53	9	2	3	0	0	6	10	0	6	75
Percentage of tissue samples < marginal	67%	31%	65%	28%	0%	5%	32%	46%	3%	15%	98%
Percentage of tissue samples < deficient	57%	10%	2%	3%	0%	0%	6%	11%	0%	6%	81%
'Marginal' value (upper limit)[1]	2.30	30	2.9	5	60	0.69	0.25	24	0.11	0.2	24
'Deficient' value (upper limit)[1]	2.20	21	1.60	3	36	0.400	0.160	16	0.090	0.140	16

[1] *Values taken from Robinson et al. (1997)*

5.3 Partial nutrient budgets

5.3.1 Introduction

Partial nutrient budgets consider the most readily measured components; typically fertilizer inputs and removal in grain and straw. More difficult to evaluate components such as N lost by denitrification or volatilization, nutrient leached or lost in runoff water, or nutrient contributed by weathering or dust deposition are not considered. While incomplete, partial nutrient budgets for macro-nutrient elements where fertilizer addition and grain and straw removal are the largest components of the budget are nevertheless useful crude indicators of system sustainability.

In this study, partial nutrient budgets are calculated using the simplest datasets for P and K. N losses are not considered as loss by volatilization of fertilizer, denitrification during the rice crop, and leaching, which are all known to be substantial. This highly simplified approach is evaluated as a potential extension tool for use with farmers as a means of undertaking a conversation about nutrients for which a yield response may not be expected in the year of fertilizer application. In this context, residual availability of P from previous fertilizer application typically results in a progressive onset of P deficiency if fertilizer rates are inadequate, while for K we are typically concerned about the rundown of the soil K resource, rather than addressing an existing deficiency. In an assessment of fertilizer use in West Bengal, Datta et al (2015) found that of 180 farmers growing paddy rice surveyed, 120 of whom were using soil tests, only 9.2% actually applied the recommended fertilizer rate. More than 60% of the farmers considered that they lacked sufficient technical advice or understanding to use recommended rates of fertilizer, so there is a clear need for new extension approaches.

In this study we calculated simple budgets for P and K using nutrient composition data collected during this study, the broader SRFSI project, and from relevant publications. Doberman et al (1996b) collated P data for rice grain and straw across 11 Asian field trial sites, reporting that 50% of P concentration values for grain fell between 0.17% and 0.23%, while for straw the comparable range was 0.04 to 0.07%. Data for K from the same study (Doberman et al 1996a) showed 50% of values for K in grain fell in the range 0.25% to 0.33%, while for straw the range was 1.38% to 1.99%. These ranges are consistent with values from the SRFSI project and this study, and with other published studies. A general observation from all data considered is that while grain and straw nutrient concentrations were responsive to P or K fertilization, the range of concentrations was nevertheless reasonably small across the range of agronomically relevant fertilizer rates. Thus, for simple mass balance calculations, useful estimates of nutrient removal could be made using an assumed concentration. The following mass balance calculations were made assuming mean nutrient contents of 0.25% P and 0.29% K for rice grain, 0.25% P and 0.45% K for wheat grain, and 0.1% P and 1.85% K for rice straw. As used for the acidification modelling, wheat grain yield was assumed to be 2.7 t/ha, rice grain yield 2.6 t/ha, and 2 t/ha of rice straw was assumed to have been removed.

Using this simple approach removal of P was estimated to be 15 kg/ha/y, while K removal was estimated at 57 kg/ha/y. Given that typical recommended fertilizer rates for the EGP are around 8 kg P/ha and 25 kg K/ha for rice and around 10 kg P/ha and 20 kg K/ha for wheat, this low input/low output system would be anticipated to have a neutral nutrient balance for P and slightly negative for K. However, as recommended rates vary widely, these calculations need to consider the local yields and fertilizer rates. Recommended P rates for rice range from 5 kg/ha for Rajshahi up to 11 kg/ha for Malda, while K rates for rice range from 11 kg/ha in Coochbehar to 70 kg/ha in Malda (Islam et al, 2019). However, farmers seldom apply recommended rates of K fertilizer. In a study of nine regions of Bangladesh, K application to high yielding varieties of rice was around 15 kg/ha, while low yielding varieties received no K fertilizer in most regions (Mustafi and Harun, 2000). In higher productivity systems, N and P fertilizer application rates are typically increased to drive yield increase, though K application remains low. Thus, as productivity and K removal increases, this will not be balanced by fertilizer application. Using the higher productivity scenario considered for acidification where wheat yield increases to 3.5 t/ha, rice grain yield to 3.5 t/ha, and 3 t/ha of rice straw is removed, K removal increases to 81 kg/ha/y, a removal rate in excess of the recommended rates, and considerably exceeding the rates of K application actually being used. In contrast, P removal for the high productivity system only increased to 21 kg/ha/y, while recommended P rates are typically around 25 kg/ha per crop (50 kg/ha/yr).

It is important to note that the simple approach adopted here produced results consistent with other far more detailed nutrient balance studies. For example, Doberman et al (1996a, 1996b) reported for rice systems in Asia a positive balance for P with application rates of 20 – 25 kg P/ha sufficient to sustain rice yields of 5 – 6 t/ha, but a negative K balance across most sites with average net removal of 34 – 63 kg K/ha/season. Similarly, Saha et al (2018) reported positive P balance and negative K balance for sites on the IGP.

The net negative K balance of farming systems on the IGP is also reflected in soil analysis results, with many soils now showing available K concentrations for less than 0.1 cmol/kg despite originally high K test values (Dobermann et al., 1999; Regmi et al., 2002; Srivastavaet al., 2002; Singh et al., 2003). Response to K fertilization is being reported on the IGP (e.g. Singh et al 2013, Islam et al 2021, Ojha et al 2021), but is highly variable (e.g. Timsina et al 2013). Yield response has typically been reported in highly productive systems where N and P fertilization rates have increased, but K application rates have remained low.

While it is difficult to convince farmers anywhere to apply fertilizer when there is no yield response; the situation commonly encountered for K on the IGP, it may be possible to convince them to change practices that will cause more rapid rundown in soil nutrient stocks. In the simple analysis undertaken here, the majority of the K removal is in the straw (~65%), and this result is confirmed by more detailed analysis undertaken in published studies (e.g. Panaullah et al 2006 study of K in rice wheat system of IGP in Bangladesh). We consider that simple K mass balance calculations may be a useful means of demonstrating to farmers the K-cost of residue removal.

6 Soil structural benefits of conservation agriculture

6.1 Introduction

Conservation agriculture practices such as zero tillage are generally reported to increase soil organic matter contents, especially in surface soil layers (Six *et al*., 2000). As implemented in the Eastern IGP, the effect of retaining stubble and reducing tillage in the rabi season (e.g. wheat) crop, are dissipated to some extent in the kharif season (rice) crop. Thus, Sinha et al (2019) reported limited change in soil C as a result of the conservation tillage practices implemented in the SRFSI project. Nevertheless, even modest increases in soil organic C can result in improved soil physical characteristics, and this is an anticipated benefit of the adoption of conservation agriculture. While there are multiple reasons why increasing soil organic matter may be considered beneficial, the effects of organic matter which most directly impact on crop production are its effects on soil structure. This objective is to determine if adoption of conservation agriculture (as practiced in the Eastern IGP) has resulted in improved soil structure.

As a compliment to this work, APSIM modelling was used to estimate the financial benefit or cost of leaving crop residue in the field. We were interested in determining if there would be a financial incentive to drive residue retention, or where there was a financial cost rather than a benefit, whether soil structural benefits would off-set this cost.

6.2 Methods

Dual ring infiltrometer measurements were made at a number of sites throughout India (Coochbehar and Malda districts), Bangladesh (Dinajpur and Rajshahi) and Nepal (Bhokraha and Kaptanganj) where conventional tillage (CT) and conservation agriculture (CA) are being compared. Soil samples from the same locations were collected and transported to UBKV for wet sieving analysis of aggregate stability using an instrument based on the principle of Yoder wet sieving apparatus (Kemper and Rosenau, 1986; Yoder, 1936). The methodology used is outlined below.

- Use 2 to 5 mm air-dried original aggregates for analysis.
- Before sieving, slake 25g samples (2.0–5.0 mm) in duplicate by submerging in deionized water on top 2.0 mm sieve of the five nested sieves viz. 2.0, 1.0, 0.5, 0.25 and 0.1 mm aggregate size class for 5 min at room temperature. Keep one of the samples for determination of aggregate stability and the other for primary particles.
- Fill the drum of the sieve shaker with distilled water to a level slightly below that of the top screen.
- For determination of primary particles, samples were first dispersed by mechanical stirrer with 0.5% (w/v) sodium hexa-metaphosphate (1:3 soil:solution) for 15 minutes and then placed on the top sieve (2.0mm) of another nest of sieves.
- Immerse the nests of sieves in water and vertically shake for 30 min with a frequency of 30-35 cycles min^{-1} through a stroke length of 3.8 cm with an electric motor, taking care that the samples on the top sieve remain immersed throughout the full stroke.
- After 30 minutes, raise the sieve sets and allow to drain for 5 minutes.
- Remove the sieve nests and place in the oven at 105ºC and weigh the dried soil (aggregates and primary particles) retained on sieves. Record weights for correction of primary particles. With the data of soil aggregates and primary particles the following soil aggregate indices were calculated.

Water Stable Aggregates

From the weight of the soil particles (aggregates + primary particles) in each size group, its proportion to the total sample weight was determined. Water stable aggregate (WSA) was the mass of stable aggregates divided by the total aggregate (stable + primary particles) mass as:

$$WSA\ (\%) = \left[\frac{(Weight\ of\ soil\ aggregates + sand)i - (Weight\ of\ sand)i}{Weight\ of\ soil\ sample}\right]$$

where *i* denotes the size of the sieve.

Mean Weight Diameter (MWD)

After correction of sand content, the amount of aggregates remaining in each size fraction was used to calculate the mean weight diameter (MWD) of the water stable aggregates following Van Bavel (1949) which is equal to the sum of products of:

MWD (mm) = $\sum_{i=1}^{n} Xi\ Wi$

the mean diameter, *Xi*, of each size fraction, the proportion of the total sample weight, *Wi* (weight of aggregate, *i,* divided by the total soil sample weight) occurring in the corresponding size fraction, where the summation is carried out over all *n* size fractions (i.e., 0.1–0.25, 0.25–0.50, 0.50–1.0, 1.0–2.0, > 2.0mm).

Economic cost of retaining residue.

APSIM modelling was undertaken to determine the impacts of different residue management pathways (i.e. incorporated into soil; retained in situ; or sold as livestock feed source or fuel source) on the economic return to farmers. Seven sites were considered (two in Bangladesh (Rajshahi and Rangpur), four in India (Dogachi and Tikapatti in Bihar, and Malda and Coochbehar in West Bengal), and one site in Nepal (Sunsari)), and at each site three cropping systems were simulated (rice-wheat, rice-wheat-mungbean, and rice-maize). To evaluate the impact of residue removal, simulations were performed with retention from 0% to 100% in 5% increments (21 simulation runs).

Annual system productivity was calculated by summing up the simulated grain yield of component crops in each cropping cycle. The system productivity of different cropping system scenarios was compared by calculating the REY based on the price of alternative crops. For the calculation of GM, we used input and output values from published data for the study sites (Gathala et al., 2021). Production cost was calculated considering the amount and prices of all inputs used in simulating crop production. Gross return was computed from the amount and prices of simulated grain and straw, while the gross margin was calculated by deducting the production cost from the gross return.

The cost of residue was one of the main drivers influencing gross margin, but it is important to consider the level of demand for crop residue in the market. Rice residue is in high demand as cattle feed, and therefore, farmers can readily sell rice straw in the market. In contrast, in many parts of the EGP, a farmer can’t sell wheat or maize residue in the market i.e., there is no market demand for these residues. We calculated scenarios where wheat, maize, and mungbean residue have a value in the market, and their removal and sale is an economic driver, and scenarios where they have no market value and hence are left in the field with only rice straw removed and sold.

6.3 Results and Discussion

Data is presented for Indian sites only given data from Bangladesh and Nepal are yet to be received. Infiltration rate and aggregate stability data are presented for a number of sites in Coochbehar and Malda districts, India.

Infiltration Rate

Infiltration rates were higher in Malda district (15 – 30 mm/hr CA; 24 – 75 mm/hr CT) relative to Coochbehar (3 – 21 mm/hr CA and CT) (

Table 6.7). In Coochbehar district, infiltration rates were generally similar in CA relative to CT systems, with only one site showing a markedly higher infiltration rate in the CA relative to CT, and hence suggesting improved soil structural stability as a result of CA practices (i.e., reduced mechanical disturbance, increased organic matter content). Conversely, in Malda district, CA systems had lower infiltration rates relative to CT practices. This finding contradicts the expected impact of CA practices on soil infiltration rates, that is, improved soil structure and therefore infiltration. This is likely due to CA sites having received one pass during the rice season to transplant seedlings, leading to possible compaction in these soils. Soils in the Malda district are classified as loam to silty clay loam given their higher clay contents relative to Coochbehar (sandy loam to loam) (Table 6.8). Thus, compaction due to traffic under wet conditions in these soils could be significant, negatively affecting porosity, bulk density, and water infiltration. The relatively higher infiltration rates under CT soils may be due to tillage practices breaking up compacted soil layers.

Table 6.7: Infiltration rate (mm/hr) data for sites in Coochbehar and Malda districts, India.

Coochbehar district		Malda district	
Site 1 (UBKV site)		**Site 1 (Manan)**	
CA	3 mm/hr	CA	15 mm/hr
CT	9 mm/hr	CT	24 mm/hr
Site 2 (Harendra Barman)		**Site 2 (Mondal)**	
CA	15 mm/hr	CA	30 mm/hr
CT	12 mm/hr	CT	75 mm/hr
Site 3 (Nur Ali)			
CA	12 mm/hr		
CT	9 mm/hr		
Site 4 (Parmesor Roy)			
CA	21 mm/hr		
CT	3 mm/hr		
Site 5 (Samaru Das)			
CA	9 mm/hr		
CT	15 mm/hr		
Site 6 (Hossenara Bibi)			
CA	21 mm/hr		
CT	21 mm/hr		

Table 6.8: Soil chemical and physical properties in Coochbehar and Malda districts, India.

	Coochbehar district	Malda district
Soil organic carbon (%)	0.58 – 1.10	0.69 – 1.66
Sand (%)	60 – 71	28 – 45
Silt (%)	17 – 26	27 – 38
Clay (%)	11 – 19	27 – 40
Soil texture class	Sandy loam to loam	Loam to silty clay loam

Aggregate Stability

Water stable aggregates (%) and their mean weight diameter (MWD) were determined for five sites in Coochbehar district and two sites in Malda district (

Table 6.9). Data averaged across sites in each district indicate the proportion of WSA was marginally higher in Coochbehar, independent of soil depth or management type, relative to Malda. No significant differences were evident between soil layers or management type (CA and CT) across sites in Coochbehar district. In Malda there appeared to be a slight increase in WSA under CA compared with CT in both topsoil (~ 14%) and subsoils (~ 19%). This increase in WSA suggests an improvement in aggregation and therefore soil structural stability in soils under CA. The benefits of improved aggregation were largely offset by traffic from equipment during the rice season which negatively affected infiltration rates. No significant differences in MWD were observed between sites across both soil depths and management practices.

Table 6.9: WSA (%) and MWD (mm) data averaged across five sites (Coochbehar) and two sites (Malda).

	Coochbehar district	Malda district
Water stable aggregates (%)		
CA		
0-5cm	41.9	38.7
5-15cm	42.0	39.8
CT		
0-5cm	42.4	33.4
5-15cm	39.4	32.3
MWD (mm)		
CA		
0-5cm	1.8	1.7
5-15cm	1.4	1.6
CT		
0-5cm	1.4	1.6

5-15cm	1.2	1.4

Economic cost of retaining residue

In general, retention of residue increased yield, though the response varied widely amongst sites. In the most responsive sites, for example the rice-maize system at Baduria, Bangladesh where removal of rice and maize residue reduced CA yield to 11 t/ha REY from 13.5 t/ha REY when around 70% or more of the crop residue was retained on the field (Figure 6.1a), the value of increased yield exceeded the value of crop residue in the market, resulting in an optimum residue retention range between 40% and 70% for CA. For CT at this site, yield response to residue retention was less, so the optimum residue retention range was from 0% to 30%. However, we note that demand for maize residue is limited, so the majority of farmers only remove and sell rice residue. Removal of the rice residue alone had little impact on yield (Fig 6.1b), the effect of residue removal on yield is much lower. Thus, the gross margin reflects the value of the rice residue, with the greatest profit made through removal and sale of all of the rice crop residue.

At sites where the yield response was smaller, for example the rice-wheat system in Coochbehar, India (Figure 6.2), the value of the residue in the market exceeded value of the grain yield response, so the farmers profit increased with increased residue removal, encouraging complete removal of residue.

Calculations of GM here are on the basis of the value of residue in the market and the productivity cost of removing the residue from the field. This approach partly captures the cost of loss of nutrients like N because the yield of the crop in the simulation responds to removal of N in the residue. In contrast, for K where there is no impact on yield of the loss of nutrient in the residue. If we explicitly consider the cost of replacing the K lost in rice straw, the economic attractiveness of removal of rice straw is diminished. For example, at Baduria, Bangladesh, the removal of all of the rice straw (≈5 t) would remove ≈$35 US of K, while the additional profit made through this removal is ≈$150 US.

This analysis shows that for many of the sites and systems considered, there is a financial incentive for farmers to remove rice straw for sale, rather than leaving it in the field.

Fig. 6.1a Effect of residue retention rate on (a) gross margin (GM, USD ha-1) and (b) system rice equivalent yield (REY, t ha-1) at Baduria, Rajshahi, Bangladesh. REY and GM compared under each conservation agriculture (CA) and conventional tillage (CT) rice-maize (RM) system. Residue from all crops is considered for removal and sale

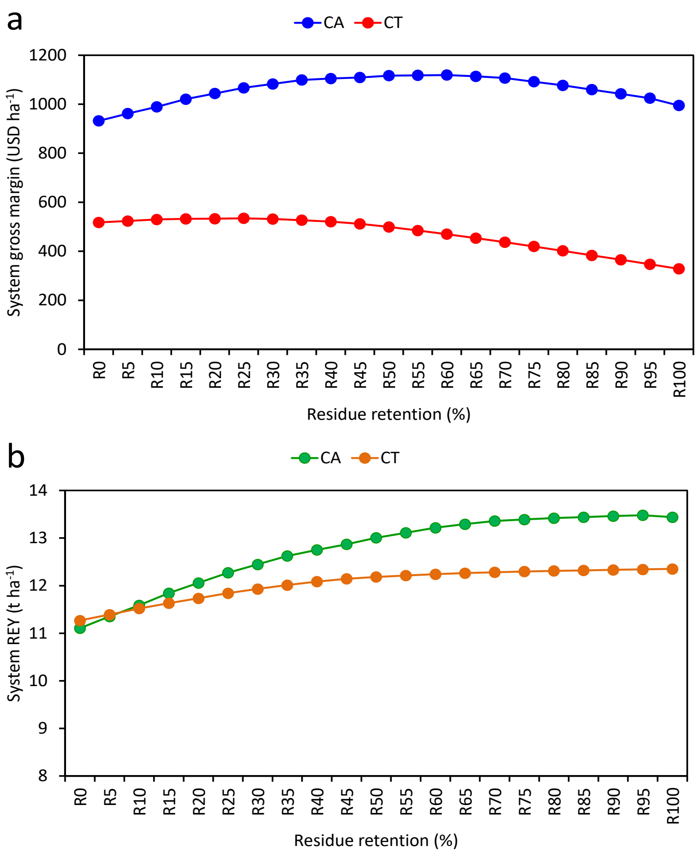
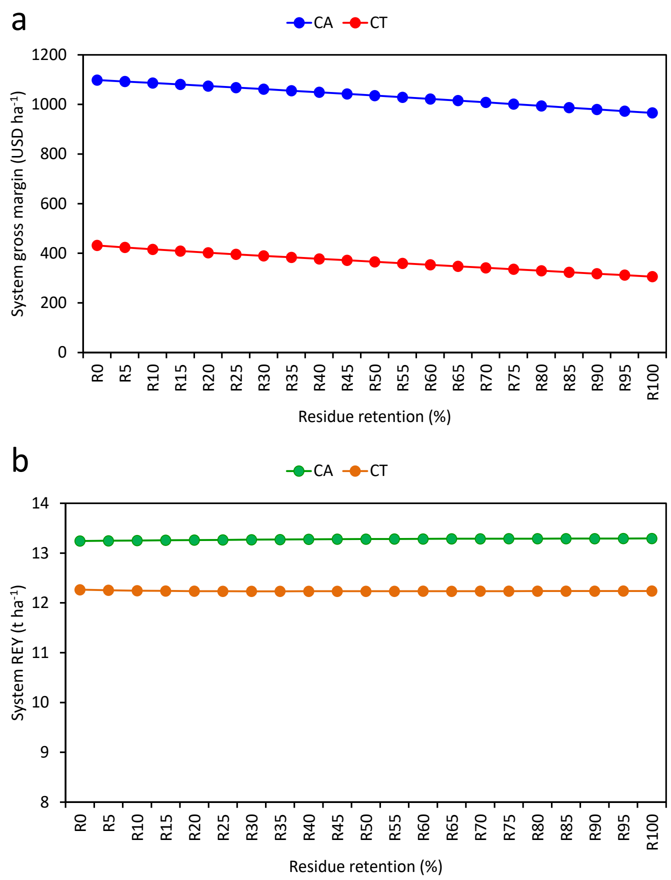


Figure 6.1b Effect of residue retention rate on (a) gross margin (GM, USD ha-1) and (b) system rice equivalent yield (REY, t ha-1) at Baduria, Rajshahi, Bangladesh. REY and GM compared under each conservation agriculture (CA) and conventional tillage (CT) rice-maize (RM) system. Residue from the rice crop alone is considered for removal and sale.



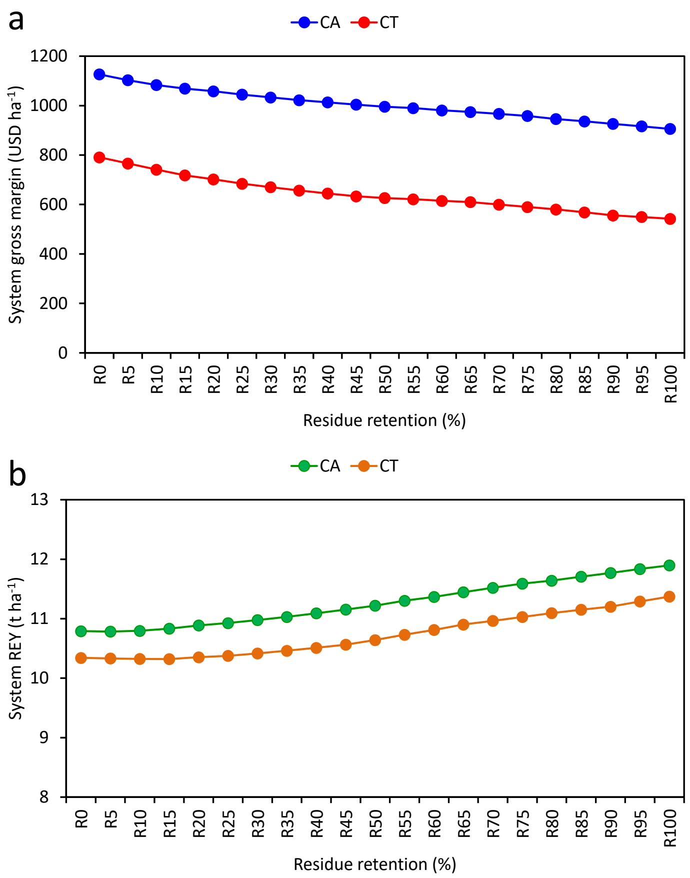


Fig. 6.2a Effect of residue retention rate on (a) gross margin (GM, USD ha-1) and (b) system rice equivalent yield (REY, t ha-1) at Coochbehar, West Bengal, India. REY and GM compared under each conservation agriculture (CA) and conventional tillage (CT) rice-wheat (RW) system. Residue from all crops is considered for removal and sale.

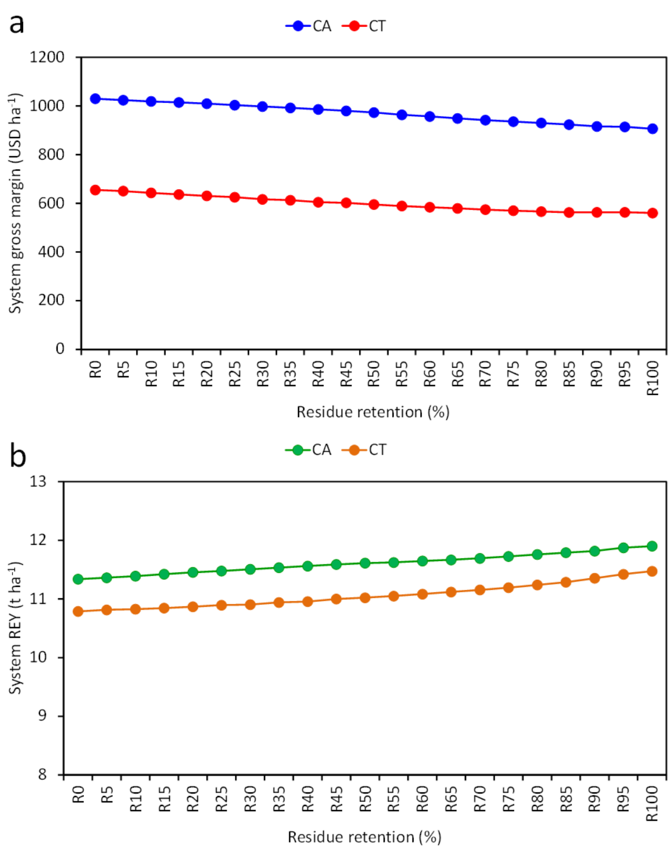


Figure 6.2b Effect of residue retention rate on (a) gross margin (GM, USD ha-1) and (b) system rice equivalent yield (REY, t ha-1) at Coochbehar, West Bengal, India. REY and GM compared under each conservation agriculture (CA) and conventional tillage (CT) rice-wheat (RW) system. Residue from the rice crop alone is considered for removal and sale.

7 Conclusions and recommendations

7.1 Soil Acidification

7.1.1 Conclusions

The results of this study confirm that the soils of the Eastern Gangetic Plains are poorly pH buffered, and hence at risk of acidification through product removal and N fertilizer use. While the current soil pH measured across a range of farmer's fields was only slightly acidic (pH < 6), with few sites having pH < 5, acidification of the soil could result in Al phyto-toxicity limiting yield within a relatively short time-frame. Even when conservative estimates of acid input are used (4.5 kmol H^+/ha/y), the predicted time for soil pH to drop to 4.5 is less than 10 years for the majority of sites.

Irrigation with alkaline groundwater has the potential to account for as much as half of the acidity generated in the conservative system modelled. Thus, the time taken to reach a point at which soil acidity limits productivity may be pessimistic. This was not factored into the time estimates because use of groundwater irrigation varies widely, while the acidification processes (product removal and N fertilizer use) are generally applicable.

It should be noted that the estimates used in the conservative scenario are indeed highly conservative (relatively low yield 2.5 t/ha, and moderate N input, 100 kg/ha). Even a moderate increase in productivity (3.5 t/ha yield, 160 kg/ha N fertilizer) substantially increases the rate of acid input (13 kmol/ha/y) and markedly reduces the time until soil acidity problems are likely to emerge.

7.1.2 Recommendation

While the estimates of acid input and rate of acidification are crude, they are undoubtedly sufficient to confirm that soil degradation through acidification is a considerable risk to agricultural productivity on the eastern Gangetic Plains. We consider that there is an urgent need to understand the risk of acidification more accurately. Key processes to understand are N cycle aspects (volatilization/deposition of NH_3, nitrate leaching, denitrification), and dynamics of alkalinity removal and return as farmyard manure.

An obvious aspect to addressing the acidification problem will be to ensure that as N fertilizer use increases, N use efficiency does not drop as has been observed in the more developed parts (but neutral to alkaline soils) of the Gangetic Plains (Punjab, Haryana). Increased nitrate leaching, in particular, has the potential to considerably increase the rate of acidification, or lime requirement as amelioration strategies are implemented. New fertilizer technologies (enhancing N use efficiency) being evaluated as a means of addressing N loss from Queensland sugarcane production systems may present opportunities to better manage N in the Gangetic Plains cropping systems.

We also note that efficient use of N fertilizer will have a positive greenhouse gas impact, and that in the long-term this may be more important than the carbon dynamics in the system. Any studies undertaken should consider the greenhouse gas impacts of the remediation approach. For example, poor N fertilizer management without correcting acidity, would result in a very poor greenhouse gas outcome.

Limited information from the sugarcane soil limed to raise the pH from 5 to 6 reduced nitrous oxide emissions by almost 80 percent (Das, Dalal, Dang, Kopittke 2021, unpublished data). In fact, liming of acidic soils has been recommended to reduce nitrous oxide emissions (Barton et al 2013)

7.2 Crop nutrition

7.2.1 Conclusions

This study has confirmed that Zn is present in many soils at levels that are inadequate for plant growth, with modest symptoms of Zn deficiency in rice being comparatively widespread, being most pronounced in Rangpur (Bangladesh) and India. Symptoms were generally more severe in adjacent fields than in the trial sites. Although the addition of Zn (and B) fertilisers remains relatively uncommon in many areas, their application often increased yields by ca. 0.5-1 t/ha. Although the dietary intake of Zn is inadequate for many people within the Eastern Gangetic Plains, Zn fertilisation did not increase Zn concentrations within the grain.

For citrus, preliminary data from a NCRP trial has shown that substantial increases in yield can be obtained from the addition of inorganic fertilisers. Analysis of 93 leaf tissue samples from across Nepal confirmed that growth (yield) is likely greatly reduced due to nutritional constraints. Of particular importance were Zn and N, with 98% of the leaf tissue samples having Zn concentrations lower than that considered to be marginal (81% below the value considered to be deficient), whilst 67% had N concentrations lower than that considered to be marginal (57% below the value considered to be deficient).

7.2.2 Recommendation

For rice production, there is a need for extension projects to ensure that Zn fertilisers are utilised in order to maintain productivity, with this being evident from our observation that symptoms were generally more severe in adjacent farmers' fields. For citrus, there is a clear need to more accurately determine the nutritional requirements across Nepal, especially for Zn and N. Of importance is impact that improved nutrition has on yield and profitability. Preliminary data from NCRP indicate that improving nutrition can result in marked increases in yield.

7.3 Soil Structural Benefits of Conservation Agriculture

7.3.1 Conclusions

No soil aggregation benefit, nor improvement in infiltration rate, was apparent as a result of the implementation of CA practices. The alluvial soils of the Eastern Gangetic Plains are typically dominated by silt and sand sized particles (e.g. silty loam / sandy loam), and are hence inherently difficult to aggregate. Given that CA had not resulted in substantial increase in soil organic matter, the results of this study are not unexpected. However, it is important to note that the infiltration rates measured are sufficiently high that they do not represent a limitation to the management or productivity of the system. Indeed, the surface ("hose pipe") irrigation approach typically used by farmers relies on relatively low infiltration rates in order to deliver relatively uniform water application rates across the field. Furthermore, adoption of CA can lead to inefficient water use during the paddy rice phase of the farming system (e.g. Chaki et al 2021). Thus, CA will need to be adapted to the needs of EGP farmers to exploit the benefits that can be obtained for crops such as wheat and mungbean, without impacting on water use efficiency in the paddy rice phase.

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8.2 List of publications produced by project

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Note – this paper reports research undertaken by the soil team during the SRFSI project and was prepared by the team during this SRA.

9 Appendixes

9.1 Appendix 1: Soil pH from West Bengal Regional Soil Assessment.

Method

Sampling grids on one km interval were organized on the base map of 1:50,000 scale using Survey of India toposheets. Soil samples for 0-25 cm depths on each grid points were collected and information on land use, and management was gathered simultaneously. Additional four soil samples were also collected 200 m apart around the grid points (Figure A1.1).

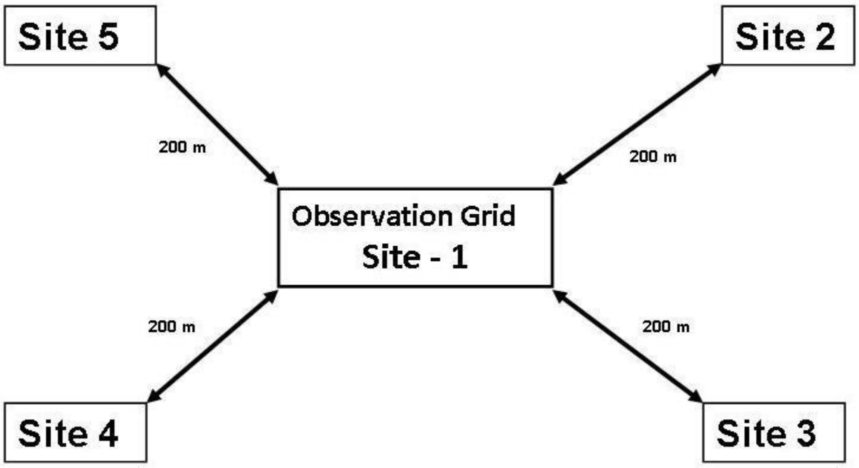
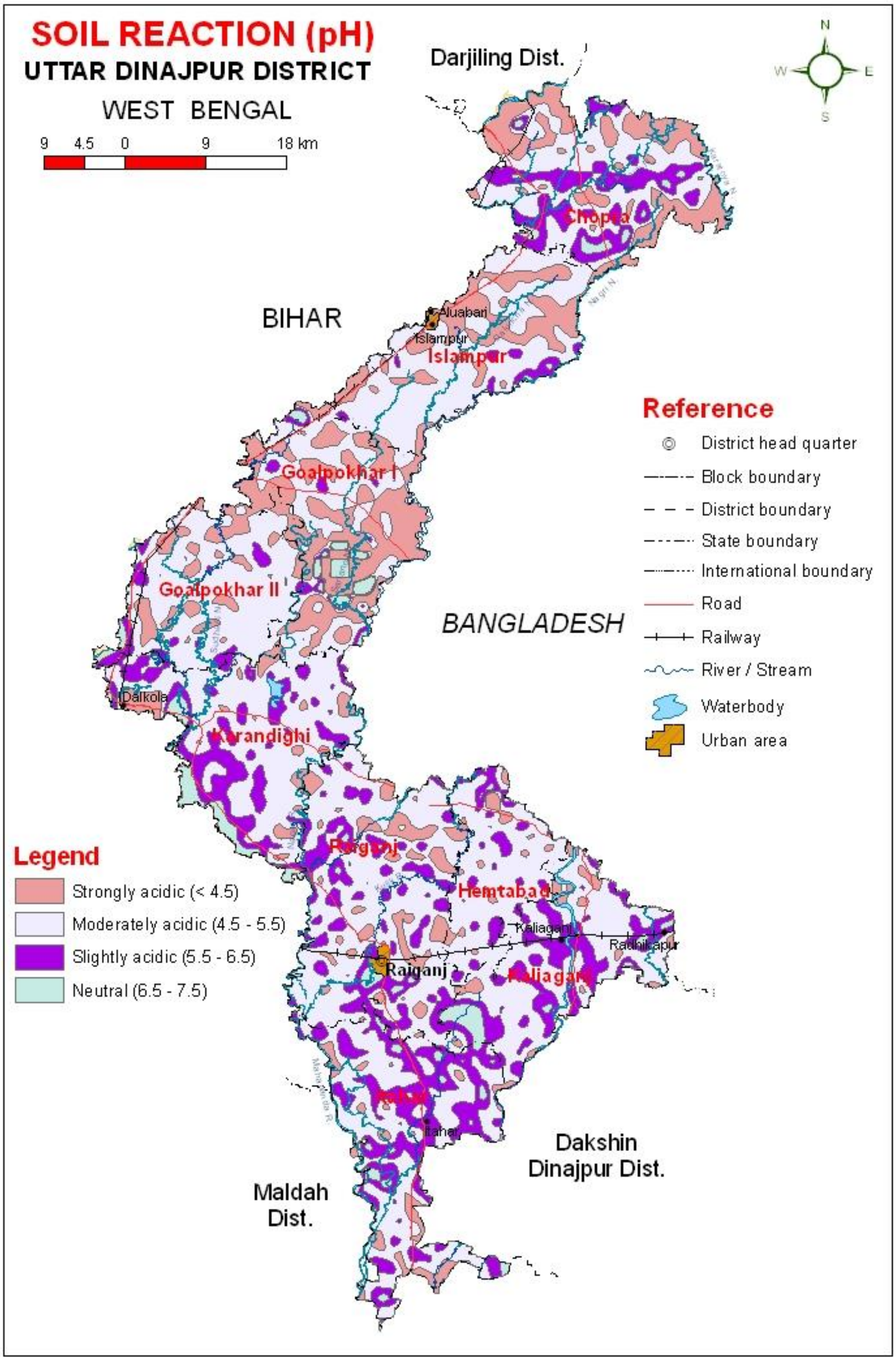
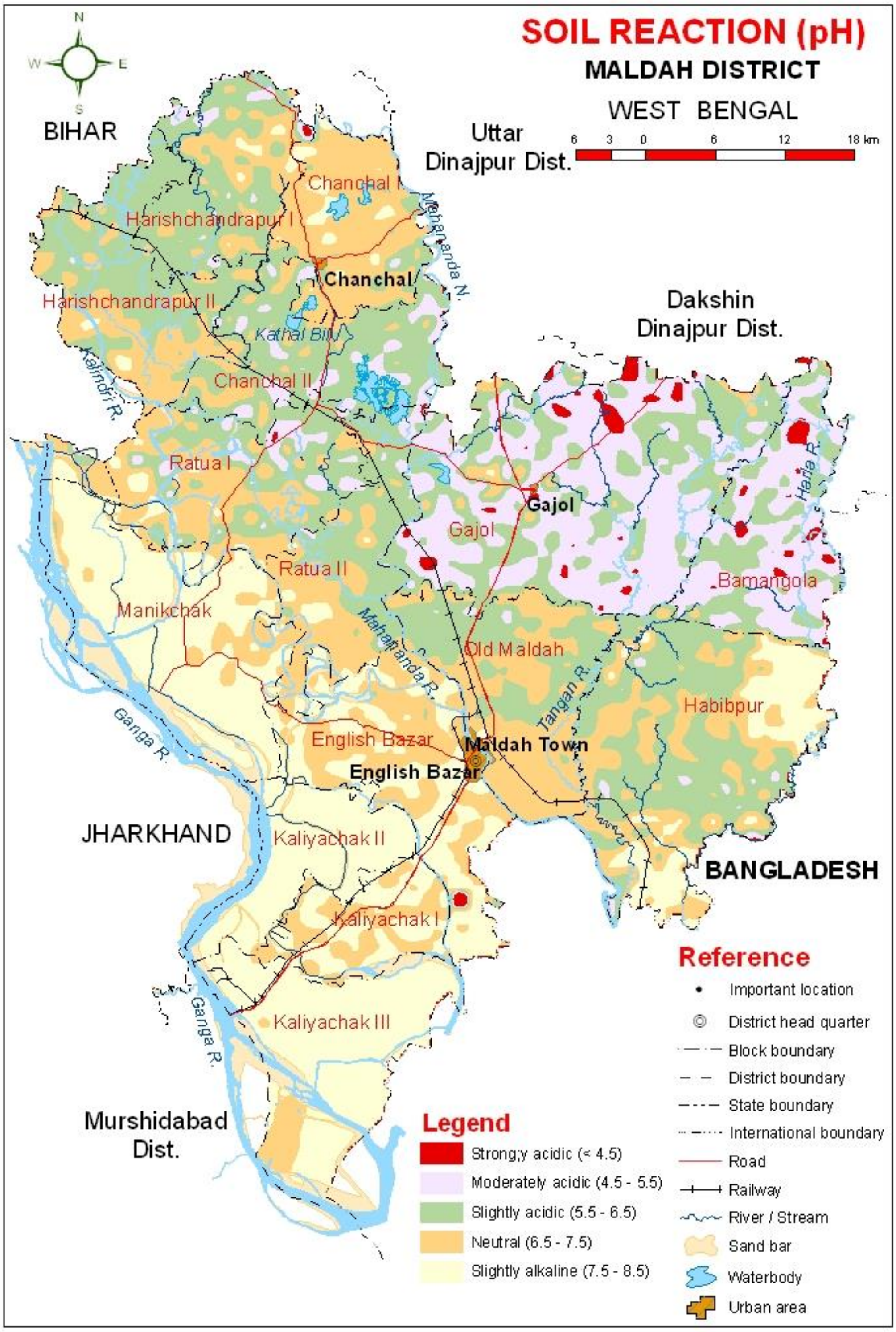


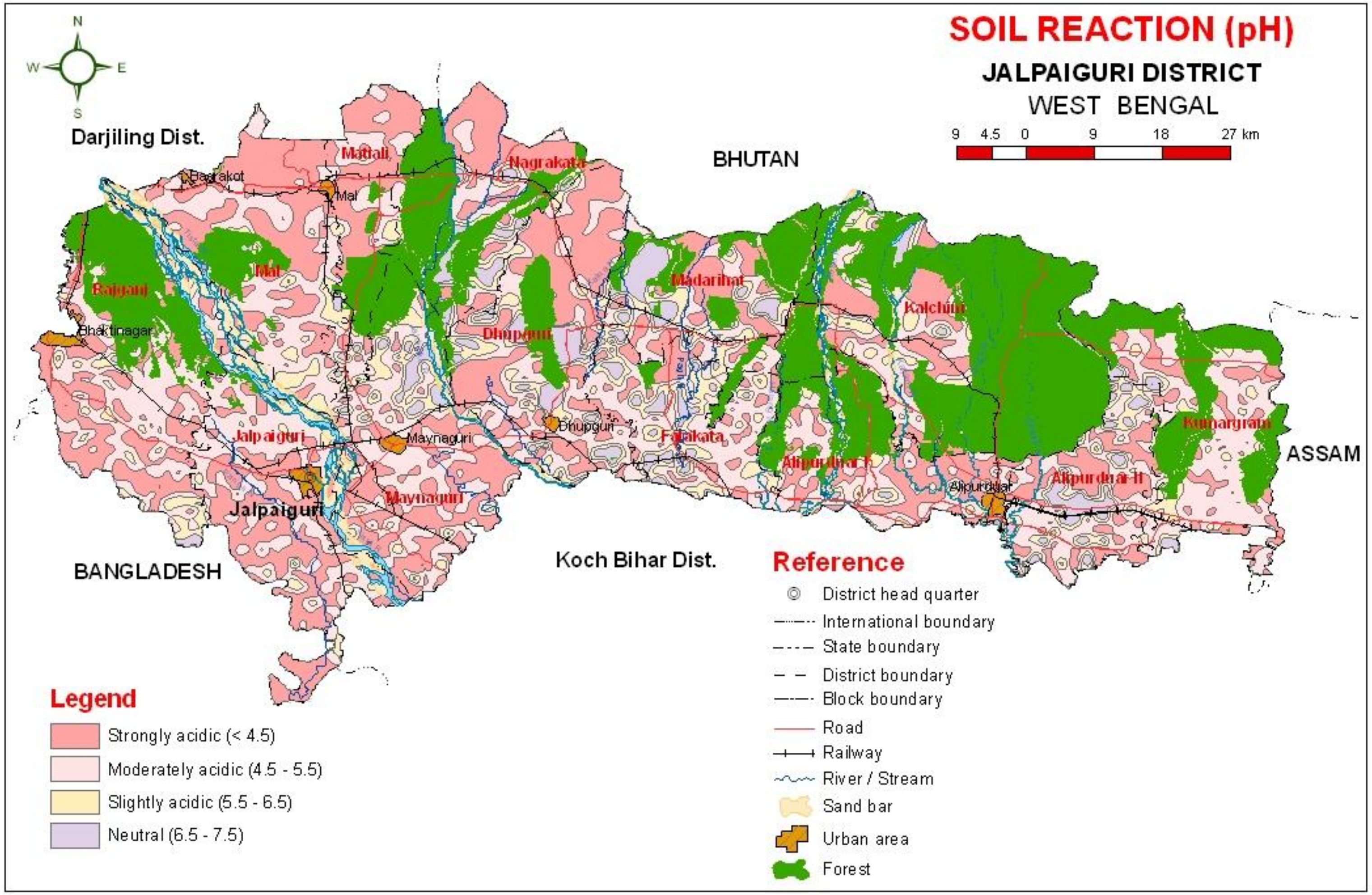
Fig. A1.1. Composite soil collection technique

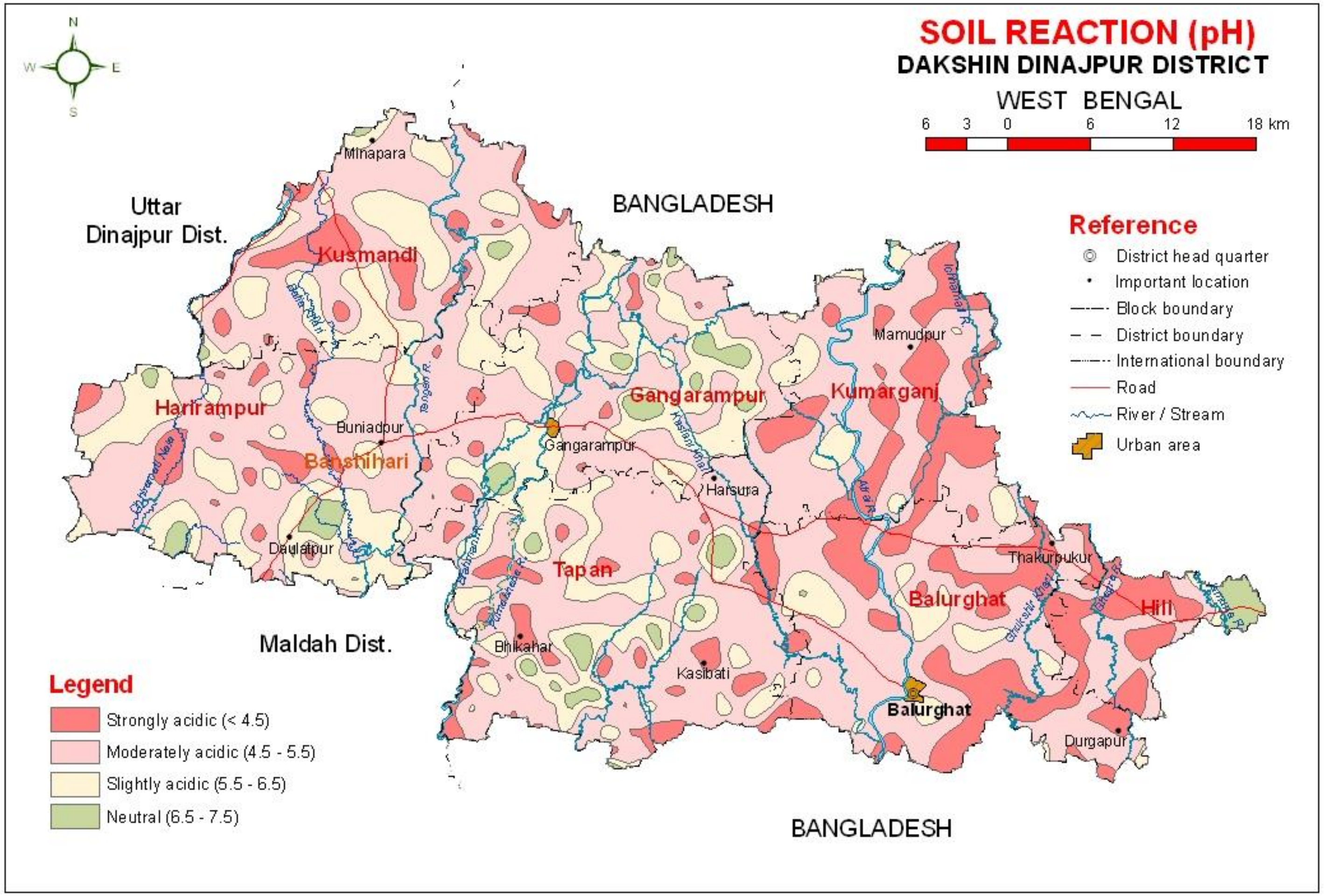
Thus, total five samples were mixed thoroughly to have one composite sample. Finally, a pack of one kilogram sample was collected for the laboratory investigation.

Soil pH was measured as I 1:5 soil:water suspension.


SOIL REACTION (pH)
UTTAR DINAJPUR DISTRICT
WEST BENGAL
9 4.5 0 9 18 km
Darjiling Dist.
BIHAR
BANGLADESH
Chopra
Islampur
Goalpokhar I
Goalpokhar II
Karandighi
Raiganj
Hemtabad
Kaliaganj
Itahar
Dalkola
Aluabari
Radhikapur
Dakshin Dinajpur Dist.
Maldah Dist.
Reference
District head quarter
Block boundary
District boundary
State boundary
International boundary
Road
Railway
River / Stream
Waterbody
Urban area
Legend
Strongly acidic (< 4.5)
Moderately acidic (4.5 - 5.5)
Slightly acidic (5.5 - 6.5)
Neutral (6.5 - 7.5)


SOIL REACTION (pH)
MALDAH DISTRICT
WEST BENGAL
6 3 0 6 12 18 km
BIHAR
Uttar Dinajpur Dist.
Dakshin Dinajpur Dist.
JHARKHAND
BANGLADESH
Murshidabad Dist.
Chanchal I
Harishchandrapur I
Harishchandrapur II
Chanchal
Kathal Bill
Chanchal II
Ratua I
Ratua II
Gajol
Bamangola
Manikchak
Old Maldah
Habibpur
English Bazar
Maldah Town
Kaliyachak II
Kaliyachak I
Kaliyachak III
Mahananda N.
Mahananda R.
Kalindri R.
Ganga R.
Tangan R.
Legend
Strong;y acidic (< 4.5)
Moderately acidic (4.5 - 5.5)
Slightly acidic (5.5 - 6.5)
Neutral (6.5 - 7.5)
Slightly alkaline (7.5 - 8.5)
Reference
Important location
District head quarter
Block boundary
District boundary
State boundary
International boundary
Road
Railway
River / Stream
Sand bar
Waterbody
Urban area


SOIL REACTION (pH)
JALPAIGURI DISTRICT
WEST BENGAL
9 4.5 0 9 18 27 km
N
W
E
S
Darjiling Dist.
BHUTAN
ASSAM
BANGLADESH
Koch Bihar Dist.
Jalpaiguri
Matiali
Nagrakata
Mal
Rajganj
Dhupguri
Madarihat
Kalchini
Kumargram
Jalpaiguri
Maynaguri
Falakata
Alipurduar-I
Alipurduar-II
Bagrakot
Bhaktinagar
Maynaguri
Dhupguri
Alipurduar
Legend
Strongly acidic (< 4.5)
Moderately acidic (4.5 - 5.5)
Slightly acidic (5.5 - 6.5)
Neutral (6.5 - 7.5)
Reference
District head quarter
International boundary
State boundary
District boundary
Block boundary
Road
Railway
River / Stream
Sand bar
Urban area
Forest


SOIL REACTION (pH)
DAKSHIN DINAJPUR DISTRICT
WEST BENGAL
6 3 0 6 12 18 km
N
S
W
E
BANGLADESH
Uttar Dinajpur Dist.
Maldah Dist.
BANGLADESH
Kusmandi
Harirampur
Banshihari
Gangarampur
Kumarganj
Tapan
Balurghat
Hili
Minapara
Buniadpur
Gangarampur
Harsura
Mamudpur
Daulatpur
Thakurpukur
Bhikahar
Kasibati
Balurghat
Durgapur
Reference
District head quarter
Important location
Block boundary
District boundary
International boundary
Road
River / Stream
Urban area
Legend
Strongly acidic (< 4.5)
Moderately acidic (4.5 - 5.5)
Slightly acidic (5.5 - 6.5)
Neutral (6.5 - 7.5)

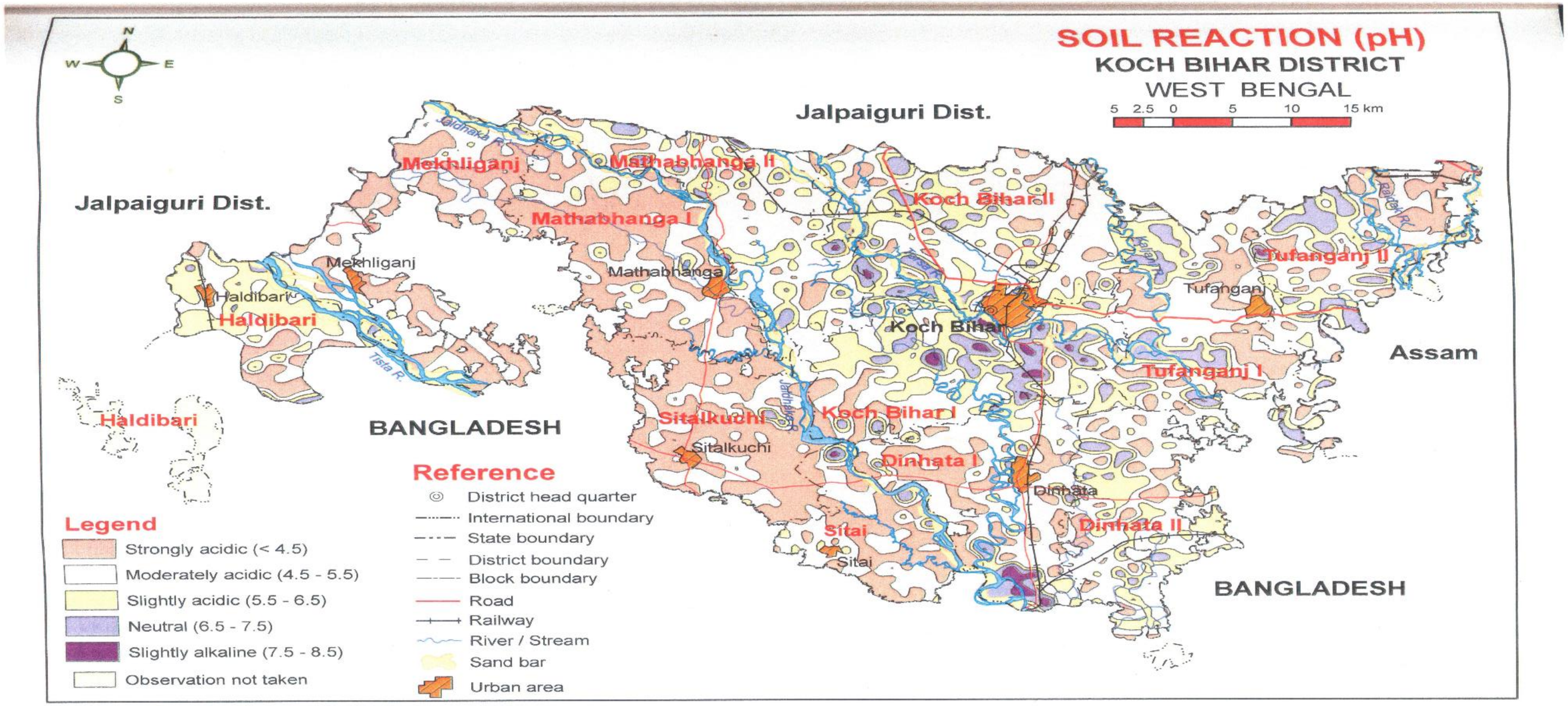


Fig. 5 Spatial distribution of soil reaction (pH) class