Enhancing the Productivity of High-Magnesium Soil and Water Resources

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Elevated levels of magnesium (Mg^{2+}) in soils result in severe structural degradation that leads to lower infiltration rates and hydraulic conductivities. These effects are similar to those observed in sodium (Na^{+}) dominated soils (i.e. sodic soils) that are characterized by structural instability resulting in poor crop growth. High-magnesium soils occur in several parts of the Aral Sea Basin in Central Asia (Figure 1) with more than 30% of the irrigated area in southern Kazakhstan having excess levels of magnesium with exchangeable magnesium percentages in the range of 25-45%, and in some cases, as high as 60%.

Arys Turkestan canal command area

Figure 1 Map of Central Asia and Kazakhstan indicating Turkestan area where high-magnesium soils have common occurrence

Although magnesium is a divalent cation, its presence at excessively high levels on the cation exchange complex of soils, either alone or in combination with sodium, results in deterioration in soil physical properties (Figure 2). The hydration energy and radius of magnesium is greater than calcium and this weakens the attractive forces between individual soil particles thereby causing them slump or disperse.

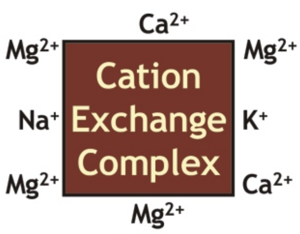

Figure 2 Cation exchange complex of a Typical high-magnesium soil

When magnesium dominant soils are plowed they characteristically form massive clods that impede the flow of water down furrows and across irrigated fields resulting in poor water distribution (Figure 3). The problem is compounded where magnesium concentrations are higher than calcium in irrigation water. Arys Turkestan canal command area is a typical example where excess levels of magnesium are present in both the soil and irrigation water.

Figure 3 Formation of massive clods after plowing in a high-magnesium soil that has a negative impact on hydraulic properties and water flow rate

Consequently, there has been a gradual decrease in cotton (*Gossypium hirsutum* L.) yields in the area. Farmers rely heavily on this crop for their livelihoods and hence a decline in productivity has a significant impact on the profitability of their farming enterprise (Figure 4). Similarly, yields of winter wheat (*Triticum aestivum* L.) are negatively affected by this soil related problem.

Figure 4 Patchy growth of cotton on a high-magnesium soil is a common occurrence without the application of a source of calcium (gypsum or phosphogypsum)

High-magnesium soils can be brought back to their original productive state by increasing the levels of calcium to counteract the deleterious effects of magnesium. This is accomplished through the application of a source of calcium to the soil in sufficient amounts. Gypsum or phosphogypsum are often used as a calcium source. Gypsum ($CaSO_4 \cdot 2H_2O$) is a mineral, which is found in sedimentary environments. Phosphogypsum is a by-product from the production of phosphoric acid from rock phosphate (apitite), which is used in the production of phosphate fertilizers. Phosphogypsum is widely available in Kazakhstan and could be used to enhance the productivity of high-magnesium soils in Arys Turkestan canal command area and elsewhere in Central Asia at an affordable cost to the farmers (Figure 5).

Figure 5 Phosphogypsum — an affordable source of calcium — can bring prosperity in southern Kazakhstan through productivity enhancement of high-magnesium soils

Phosphogypsum can be applied in winter before snowfall or after plowing the field for seed-bed preparation. In low rainfall years, incorporation of the applied phosphogypsum by harrowing the field is recommended in order to reduce the risk of the material being blown away due to strong winds that are common in the region. Snow melt and rainfall in winter season accelerate the dissolution rate of phosphogypsum and concentrations the calcium in the soil. This is followed by the replacement of magnesium from the cation exchange complex by calcium as a result of mass action. The replaced magnesium is leached to depth in the profile by the application of an excess irrigation or rainfall. In ameliorated soils, water and air movement is improved along with increased root penetration, seedling emergence, decreased runoff and erosion. Such changes have a positive effect on water use efficiency as well as the activity of plant roots that ultimately enhances crop growth and yield (Figure 6).

Figure 6 Excellent growth performance of cotton after application of phosphogypsum to a high-magnesium soil

In addition to mitigating the deleterious effects of magnesium, phosphogypsum application improves nutrient availability status of the soil. Earlier studies have shown that an application of 4.5 t ha^{-1} increased phosphorus (P_2O_5) levels in the top 0.2 m soil layer from 82 kg ha^{-1} to 106 kg ha^{-1}, indicating an increase in phosphorus levels by 29% (Table 1). There was a substantial increase of 62% in phosphorus levels (from 87 kg ha^{-1} to 141 kg ha^{-1}) in the same soil depth after application of phosphogypsum at the rate of 8 t ha^{-1}. At the 0.2-0.4 m soil depth, the percent increase in phosphorus levels was 18 and 28% for the 4.5 and 8 t ha^{-1} phosphogypsum treatments, respectively. There was also a small increase in potassium levels (3-5 %) in the soil after the application of phosphogypsum to the soil. Long-term studies carried out under field conditions reveal the beneficial effects of the amendment application on the yield of cotton variety C-4727.

Table 1 Phosphorous (P_2O_5) levels (kg ha^{-1}) in the soil as affected by the application of Phosphogypsum

Soil depth (m)	Phosphogypsum (4.5 t ha^{-1})		Phosphogypsum (8 t ha^{-1})	
	Initial soil	Post-amendment	Initial soil	Post-amendment
0.0-0.2	82	106 (29)[a]	88	141 (62)
0.2-0.4	75	89 (19)	87	112 (29)

[a] Figures in parenthesis indicate percent increase over the respective initial P_2O_5 level.

There were improvements in germination, and bud and boll formation, all of which contributed to an increase in crop yield (Figure 7). Cotton yield in the control plots (1.4 t ha^{-1}) was almost half of the yield harvested from phosphogypsum treatments. There was a 93% increase in cotton yield from the phosphogypsum treatment (4.5 t ha^{-1}) over the control. In the case of the 8.0 t ha^{-1} treatment, cotton yields increased to 114% over that harvested from control plots. The enhancement in cotton yield in the phosphogypsum treatments was due to the improved levels of calcium in soil solution and on the cation exchange complex. This improved the ionic balance and physical properties of the soil. The increase in phosphorous levels in the soil as a result of the amendment application also helped improve the phosphorous nutrition of the plants. The yield responses observed in the first year were similar in subsequent years indicating persistence in effects.

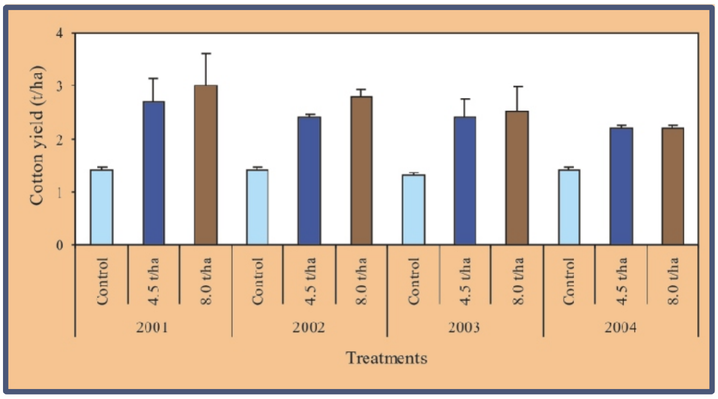

Figure 7 Cotton yield as affected by different rates of phosphogypsum application (0, 4.5, and 8.0 t ha1) on a high-magnesium soil in Southern Kazakhstan

The beneficial effects of phosphogypsum in enhancing the productivity winter wheat and cotton on high-magnesium soils have also been demonstrated on farmers' fields (Figure 8).

Figure 8 Improved growth of wheat after phosphogypsum application to a high-magnesium soil in a farmer's field

Application of phosphogypsum by the farmer Muborakov at 2.5 t ha^{-1} in the Arys Turkestan canal command area improved water use efficiency and crop yield. In the control plots (without amendment application), wheat yields were 1.8 t ha^{-1} while in the amendment treatment (phosphogypsum application at 2.5 t ha^{-1}) wheat yields increased to 3 t ha^{-1}, resulting in an overall increase of 1.2 t ha^{-1}. In two different farmers' fields, phosphogypsum was applied at different rates (2.5 and 4.0 t ha^{-1}) before plowing the field for cotton. The farmer Mirhaidarov applied phosphogypsum at 4 t ha^{-1} an observed improved water-use efficiency and cotton yields which increased from 1.8 t ha^{-1} (in plots where no phosphogypsum was applied) to 3 t ha^{-1}. Soil application of phosphogypsum (2.5 t ha^{-1}) by the farmer Kasymov resulted in an increase in cotton yield to 3.5 t ha^{-1}.

The determination of an appropriate rate of phosphogypsum to a high-magnesium soil is a crucial step (Figure 9). This depends on the initial level of magnesium in the soil that needs to be reduced to a critical level to restore the soil to its highly productive state. The application of phosphogypsum without adequate assessment may lead to under or over estimation. The application of amendment lower than actual requirement partly ameliorates the soil, while the excess application has economic consequences for the farmers.

Figure 9 Critical evaluation of high-magnesium soil along with determination of its phosphogypsum requirement are the crucial steps in recommending the appropriate rate of phosphogypsum application

The rate of phosphogypsum application to a high-magnesium soil can be estimated from phosphogypsum requirement (PGR) of the soil, which is calculated from the quantity of gypsum requirement (GR) as given in Equation 1.

$$\text{PGR} = \text{GR}/0.8 \qquad [1]$$

Where

PGR = Quantity of phosphogypsum required ($t\ ha^{-1}$)

GR = Quantity of gypsum required ($t\ ha^{-1}$)

0.8 = Conversion factor between phosphogypsum and gypsum

The GR can be estimated using Equation 2

$$\text{GR} = 0.086\ (E_{Mg} - 0.3\ \text{CEC})\ (100\ d_s)\ \rho_b \qquad [2]$$

Where

E_{Mg} = Exchangeable Mg^{2+} level ($cmol_c\ kg^{-1}$ soil)

CEC = Cation exchange capacity of the soil ($cmol_c\ kg^{-1}$ soil)

d_s = Depth of soil amelioration (m)

ρ_b = Bulk density of the soil ($t\ m^{-3}$)

Phosphogypsum is incorporated into the soil by plowing. A good rainfall or snow melt after amendment application contributes to the dissolution of phosphogypsum. Alternatively, a pre-sowing irrigation helps the amendment to dissolve.

The effects of phosphogypsum applied to a high-magnesium soil according to the PGR may last for several years. Studies have shown that under conditions where high-magnesium waters are used to irrigate the post-amelioration soils, the levels of magnesium tend to increase and that of calcium gradually decrease 4-5 years after the initial application. These conditions underscore the need for further application of phosphogypsum to maintain the magnesium concentrations at desirable levels in order to ensure sustained and profitable crop yields.

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