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# IMPORTANCE OF MICRONUTRIENTS IN CROP NUTRITION

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# Importance of Micronutrients in Crop Nutrition

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## INTRODUCTION

This paper will focus on highlights and recent advances in understanding the importance of micronutrients for crop production. We will not discuss Fe, as this is the subject of regular international meetings (the 11$^{th}$ Symposium was held in Udine, Italy, in June, 2002 and papers published in Journal of Plant Nutrition, Vol 26). Besides, Fe is different from the other micronutrients in that there is relatively little use of fertiliser to correct the disorder despite the extent of the problem. The consequences of grain nutrient composition for humans and animals are dealt with in other papers, as are the effects of micronutrients on efficient use of macronutrients.

The most complete recent review of micronutrients was published in 1991 (Mortvedt et al. 1991). Subsequently, International Symposia on zinc (Robson 1993), boron (Dell et al. 1997; Goldbach et al. 2002) and silicon (Datnoff et al. 2001) have updated knowledge on each of those elements.

Whilst we have tried to highlight principles and emerging trends, where possible we have used examples with which we are familiar from collaborative research in Asia (especially Thailand and China) and Australia.

## IMPORTANCE

We have defined "importance" as the product of the magnitude of the impacts per unit area and the area of impact. Impact is most commonly measured as crop yield. However, for a range of crops, aspects of crop quality such as oil, protein or fibre content, are equally important in markets. Peanuts sold for human consumption should be free of internal defects such as "hollow heart", caused by boron deficiency. For mung bean, the viability and vigour of germinating seed may be a prime quality characteristic that determines market price in those parts of Asia favouring bean sprouts in the diet. For legumes, the main impact of micronutrients may be on amounts of N fixed. Limitations of symbiotic nitrogen fixation decrease current crop production, but may have equally significant impacts on subsequent crops in the rotation due to lower residual soil nitrogen levels (Wood and Myers 1987). Another aspect of impact is the effect of micronutrient concentrations in planting seed on the vigour of the next season's crop. This may impose hidden costs in the extra seed needed for crop establishment, or poor, low yielding stands that under perform (Ascher-Ellis et al. 2001). An emerging area of interest is the impact of micronutrient supply on grain quality for human nutrition, a subject dealt with in another paper. For fertiliser retailers, the total value of micronutrient fertiliser sold is small compared to macronutrient fertilisers (Mortvedt 1991).

However, the real economic impact of micronutrients is in the increased efficiency of macronutrient fertilizer. Another paper deals with this relationship.

The second component of importance is the area affected. Traditional approaches to defining the area of impact consider topsoil levels of micronutrients (Takkar et al. 1989). There is emerging evidence that low sub-soil micronutrient status is an under-recognised constraint.

Reports on the area of impact suggest a static nutrient status, and fail to recognise changes in micronutrient status or land use over time. In Australia for example, micronutrient deficiency was first treated 30-50 years ago and depending on the residual value of the added fertiliser, soils are often still considered adequate for crop yields. Hence areas of southern Australia that were once mapped as almost entirely deficient in Zn, Cu and Mo (Donald and Prescott 1975) are now largely adequate for crop growth. However, changing from cropping with annual species to perennial plants has seen the emergence of deficiencies especially of Cu and Mn in southern Australia in recent years (Dell et al. 2003). This appears to be related to roots having poor access to micronutrients in surface soils during the dry season when most of the plant biomass is being laid down. Changes in genotypes over time may also change the status of an area once considered adequate to deficient. In Nepal, traditional lentil varieties tended to be B efficient and so the prevalence of reported B deficiency for this crop was low. Improved varieties have higher yield potential but are also more prone to B deficiency (Kataki et al. 2001). Finally, as yield output from farming systems rise, areas that were previously adequate are now declining in micronutrient reserves in soils, and hence deficiency is reported with increased frequency.

## ESSENTIAL ELEMENTS

The list of essential micronutrients for plants remains unchanged since 1987. This is fortunate since we are having enough trouble looking after the present ones. The most exciting recent development is a field report of Ni deficiency in pecan in southeast USA (Dr Bruce Woods, USDA, personal communication), the first since Brown, Welch and colleagues at Cornell University showed that Ni satisfies the criteria for essentiality (Brown et al. 1987).

Silicon which is presently not classified as an essential element nevertheless remains the subject of significant research in the USA, Japan, and China (Datnoff et al. 2001), and international symposia on silicon were held in Florida in 1999 and Japan in 2002. Graham and Webb's (1991) review on the role of Si in disease suppression is still worth reading for a better understanding of the unrecognised potential of Si to enhance crop production.

Boron is essential for plants, but was not previously considered essential for animal and humans. Recent research in the US is gradually changing that perception (Nielsen 2002). This work comes at the same time as a new emphasis on micronutrient levels in staple grains because of their critical importance for the supply of micronutrients in the human diet.

## CLASSICAL APPROACH TO ASSESSING MICRONUTRIENT LIMITATIONS

The classical approach to assessing micronutrient limitations is based on the law of limiting factors (sometimes also referred to as Liebig's law of the minimum. See Black 1993). It has been applied in most countries over the last 50 years (e.g. Anderson 1970; Bell et al. 1990). The approach involves extensive soil analysis, either as part of a soil survey or for the purposes of assessing nutrient status. This body of soil analysis data provides a benchmark for the range of values to be expected in soils, and the proportion of sites that might be deficient. The pioneering work of Prof Liu Zheng in China for example produced a set of national maps for the average levels of each micronutrient (Liu 1992). The global, FAO-funded study of Sillanpaa (1982) is another notable example.

However, to confirm a deficiency a yield response in the field is necessary evidence (Craswell et al. 1987). Such trials would then normally be followed by other experiments to establish minimum fertilizer rates, fertilizer types, and may also be used to generate critical levels in plants and soils. Finally, the varied requirements of different plant species on the same low micronutrient soils need to be assessed.

India has a most impressive database of such information from its All-India Coordinated Micronutrients study (Takkar et al. 1989). We used a similar systematic approach to defining micronutrient (mostly boron) constraints to food legume production in Thailand (Bell et al. 1990).

This approach continues to be relevant and in use. In the past 6 years several studies of this type have been published from Pakistan (e.g. Rashid et al. 2002). The principle of limiting factors remains valid and will continue to play a useful role in identifying nutrient constraints. In parts of SE Asia there are still significant tracts of land that are yet to be developed. The uplands of Cambodia for example are only sparsely settled, in part because of the predominance of lowland rice in the nation's agriculture, and in part because of the insecurity of these areas for the last 30 years. However, there are prospects for a significant increase in the utilisation of this land for upland field crops, fruit trees, grazing, and agro-forestry. Developing this land requires a systematic examination of the potential nutrient limitations of the type carried out in Thailand with respect to legume production (Bell et al. 1990). Similar efforts are required for sustainable land utilization of steep slopes especially in parts of the Philippines, Nepal and China where soil fertility has declined with loss of topsoil.

Farming systems continually change with new crops and cultivars introduced in response to market opportunities. An example is the decline in cassava planting and its replacement by sugar cane in NE Thailand in the 1990's (Limpinuntana 2001). As a consequence, research was needed on fertilizer requirements of sugar cane where it had not been widely grown previously.

In addition to new crops, significant changes in crop establishment and weed control can have significant implications for nutrient management. The widespread adoption of direct seeding to establish rice because of labour shortages for transplanting (Fujisaka et al. 1993) requires a different strategy for fertilizer use to that recommended for transplanted rice (Bell et al. 2001). In the lowlands of SE Asia, double cropping systems are emerging in many areas where irrigation is available (Wood and Myers 1987). The limiting nutrients for new crops introduced for dry season production will often differ from those of rice in part because the soil is maintained in an oxidised rather than a flooded condition, and in part because of the effect of rice nutrient management strategies on soil nutrient pools.

A fourth case where the principle of limiting factors will continue to be useful is when yields progressively increase over time in a farming system, causing nutrient levels to decline in the soil. The relationship for lowland rice between increasing yield and increasing nutrient uptake has been established (Dobermann and Fairhurst 2000). Few places in Asia have not experienced an increase in rice yields in the last two decades. Increased incidence of K deficiency in rice (Wihardjaka et al. 1998) is an example of how the decline in nutrient levels is revealing deficiencies that did not previously limit crop production. Further such cases are expected to occur in the future (Dobermann et al. 1998) including micronutrients (Ladha et al. 2003). Soil and plant analysis will be useful tools for the monitoring of declining nutrient status in soils, and to determine when intervention through a change in fertilizer applications is necessary to maintain soil productivity. Many parts of Asia have undeveloped uplands about which there is little known information on micronutrients (e.g. see Dierolf et al. 2001) and often limited capacity for laboratory analysis of soils and plants.

One of the outputs of classical studies might be a map such as that presented by Shorrocks (1997) for low B soils globally. Such maps might be based on point source data, and identify contiguous regions with responsive soils. Or they might be based on the average status of soil types and then mapping micronutrient status based on the soil type as in the micronutrient maps for China (Liu 1992). Other studies report proportions of soils or crops in a region that are likely to suffer a deficiency (Nayyar et al. 2001). Nayyar et al. (2001) reported a high incidence of Zn deficiency in 5 states of India and more B deficiency in the eastern states than the west.

Whilst the classical approach is very powerful, and has been very useful, it has to be recognised as a relatively costly approach. Ideally for each soil or group of similar soils, a set of soil and plant test calibrations needs to be developed for the diagnosis and prediction of mineral disorders and to determine fertilizer requirements (Craswell et al. 1987). The relationship between seed yield and plant B concentrations for oilseed rape shown in Figure 1 involved field experiments on 3 sites repeated in 2 years (Wei et al. 1998). This is about a minimum data set to develop accurate soil and plant analysis standards for use in soil and plant testing. Yet in rice-based cropping systems in southeast China, three major soil groups are important for oilseed rape production (Wei et al. 1998) and other parts of central China, with different soils, also have B deficiency problems with oilseed rape. Hence to develop a complete package of recommendations and tools for B fertilization and management required a 5-year programme for a single crop in one province. For a soil with many deficient elements even to carry out this research on one soil and one crop is a substantial effort. To repeat this for several crops and over 2-3 seasons to assess the effect of seasonal variation on the reliability of the calibrations is already more than most research organisations are able or prepared to fund. For this reason, alternative approaches for developing fertilizer recommendations with greater economy of resource inputs need to be pursued.

## NEW APPROACHES TO MAPPING MICRONUTRIENT DEFICIENCY

As discussed above, the present approach to mapping impact areas presumes a static pattern of micronutrient status in soils. However, cropping systems and farming systems are dynamic. Even in traditional farming communities substantial changes in farming practices (e.g. new varieties, fertilizer use, changed weeding regimes) and systems (e.g. double cropping) have occurred. Each of these changes can have significant implications for micronutrients. So the critical question is how can our assessment be continually updated. One thing is obvious- that it will not be possible to repeat the vast body of research undertaken in the 1960- 1990's on micronutrients. We will have to find more cost effective ways of updating our knowledge base on micronutrients.

An example of a new approach to assessing the area of impact of micronutrient disorders is based on work we did on B in southwest Australia (Wong 2003). Boron fertiliser is not currently used in this region on a regular basis but we could see emerging trends that might induce deficiencies during the next decade- new crops, higher yields, soil acidification. Through pot experiments, soil analysis and field trials, we assessed soil properties and correlated them with soil B status: the properties, which we have termed risk factors were soil pH, clay content of soils and geology.

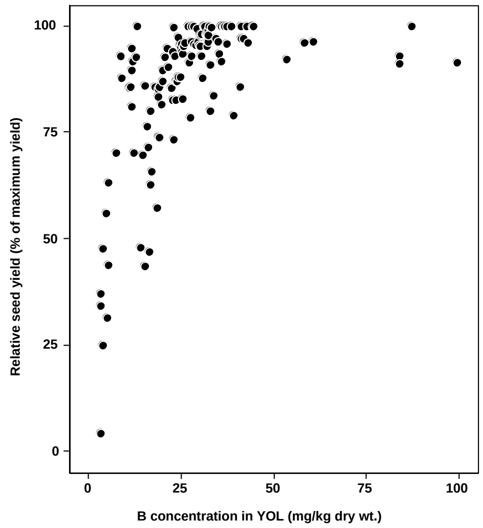


**Figure 1.** Relationship between oilseed rape and leaf boron (B) concentrations.
Source: Wei et al. (1998).

We then used weight of evidence modelling to construct a B risk map (Fig 2). The red areas are considered high risk, and the green areas, the most prevalent, as low risk. Of course this is a small scale map so it does not preclude a small amount of low B soil in the vast low risk green areas (due to the problem of map scale).

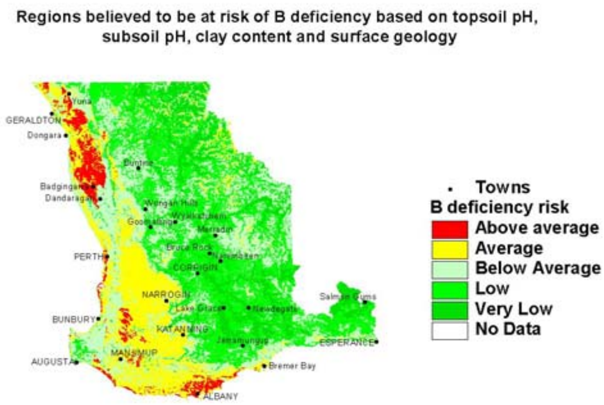


**Figure 2.** Boron risk map for southwest Australia (from Wong 2003).

From analysis of benchmark soils of southwest Australia, it was obvious that low pH soil had low extractable B levels. It was also known that high pH in sub-soils in southwest Australia was generally associated with high sub-soil B, possibly even toxic B levels. So maps of topsoil and sub-soil pH were used. Those areas with pH < 5.5 would have an increased risk of B deficiency. By contrast those with pH > 7 in the sub-soil almost certainly had no B deficiency risk.

In the same benchmark soil collection, there was a positive correlation between clay content and extractable B levels. Soils with < 15 % clay had a higher risk of low B. So in the clay map, soils in the eastern wheatbelt with > 15 % clay had low B risk.

Finally, in pot experiments we noted that B deficiency was most prevalent in our test crop, canola, when grown on soils derived from siliceous sediments. Hence we used the geology as an attribute and gave a high weighting to this geological theme. By contrast sandy soils derived from granite were less likely to show B deficiency in canola crops.

There are various programs that can be used for weight of evidence modelling. The underlying principle of all is: evidence layers; weighting of evidence, and; categories of evidence. Some weight of evidence models use Bayesian statistics to generate the risk map. The risk map is flexible. It can be updated as new evidence emerges or new research strengthens or weakens evidence. Different crops might have different tolerance to low B and hence a changed species weighting can be used.

Whilst it is valuable to have hard data on relationships between soil properties and B status, expert judgement can be used as a proxy. Most parts of the world have simple rules that are used to predict micronutrient deficiencies and these could be used in weight of evidence models also.

This type of risk mapping can be output for fertiliser retailers and manufacturers to estimate market size. Planners might use it to estimate what new infrastructure in roads, grain storage etc are needed to cope with widespread use of micronutrients. Research organisations need this information to design priorities for research and target areas where trials should be carried out.

## RESIDUAL VALUE OF MICRONUTRIENT FERTILISERS

It is often asserted that micronutrient research is simple compared to that with macronutrients like N because once a deficiency is identified, correction involves addition of fertiliser and then reliance on residual value to maintain supply for a considerable time. Like any generalisation it is based on an element of truth but may be an over simplification. It fails to account for those soils where chemical properties make the micronutrient fertiliser ineffective almost immediately, such as the vast areas of alkaline low Mn soils in SA (Reuter et al.1988). Secondly, in intensively cropped systems, where extremely high yields are harvested each year, residual value of micronutrient fertilisers is relatively short.

Brennan (personal communication) recently calculated the number of wheat crops that a single Zn application of 0.75 kg Zn/ha would support in southwest Australia. The number varies from 6 to an infinite number depending on yield, Zn sorption of the soils, and the presence or absence of Zn impurities in the P fertilisers.

Brennan then calculated for typical rotations the length of time that a single Zn application would likely maintain adequate Zn supply. This scenario assumes an initial application of 0.75 kg Zn/ha, plus 90 g Zn/ha once every rotation cycle as a contaminant in superphosphate. At yield levels that are relatively high for south west Australia, he calculates 18 years before a repeat Zn application is needed. Field experiments in WA have been running for over 20 years without evidence of Zn deficiency emerging (R. Brennan, personal communication).

If we complete the same calculations for a rice-wheat rotation which is common in south Asia, with total grain yields of 10-12 t/ha/yr, the same amount of initial Zn fertiliser would only remain effective for 2-5 years, depending on Zn sorption capacity of the soil. Substantial removal of straw from fields would further decrease the length of residual Zn effects.

Boron has different behaviour in soils to zinc because it is more prone to leaching and the risk of toxicity is greater (Shorrocks 1997). In our studies in southeast China we have examined B cycling behaviour in the oilseed rape-rice-rice triple cropping system on three key soils (Wang et al. 1997; Wei et al. 1998; Wang et al. 1999; Yang et al. 2000). Even with repeated annual applications of 3.3 kg B/ha/yr to the oilseed rape for three years, no evidence of B toxicity was found. This was consistent with the extractable B levels that only increased modestly in the 0-20 cm layer. Part of the reason for the small increase in extractable B in the 0-20 cm layer was that B redistributed to greater depths in the soil. However, no leaching loss of B occurred below 80 cm depth even on the sandy alluvial soil. Over 40 % of the B added initially was removed over a 3 year period in harvested grain and straw. Hence in this intensive triple cropping system in southeast China, we concluded that B toxicity risk was low, that little B was lost by leaching, but that removal of B in harvested crops and crop straw was a major cause for the decline in residual B over time. We estimated that 1.65 kg B/ha should be re-applied every 3 years in this cropping system. By contrast, on sandy loams derived from sandstone in the uplands of southwest China, repeat applications of B are required to meet the requirements for eucalypt foliage replacement following harvest for essential oils. This is partly because the soil has limited capacity to retain B added as fertilizer, and partly because the B, which is taken up and sequested in the plant is mostly unable to be redistributed to the new shoots as they develop. Hence, steep B gradients develop in these woody plants following fertilizer application and B rundown over time (Dell et al. 2001).

## PARTNERSHIPS FOR ADOPTION OF MICRONUTRIENT FERTILIZERS IN CROP PRODUCTION

Nutrient management formerly was considered to be largely a matter for the individual farmer taking advice perhaps from government extension services. In recent years, it has become obvious that there are many more stakeholders in sustainable nutrient management, and the roles of farmers and government extension services are changing. The notion of the government as the provider of a nationwide extension service is in transition (Wall 2001). In developed countries, most governments have withdrawn substantially from the provision of a comprehensive national extension service. This has been driven by: concerns about the growing cost; a questioning of the necessity or the desirability of such government-provided services; and the emergence of a private sector that supplies many of these services. Meanwhile extension-related work has had to deal with new issues from increased regulations, environmental factors, market pressures and changed societal perceptions about agriculture. By contrast, many developing countries are still striving to create a comprehensive national extension network (Lathvilayvong et al. 1995). In many cases, the ratio of extension officers to farmers in developing countries is so small that alternative ways of delivering information such as the mass media have to be examined. Non-governmental organisations often provide advice on nutrient management in developing countries, generally based on a particular set of belief systems that are sometimes at variance with mainstream science. Many of these NGO's promote practices such compost, permaculture, and discourage the use of inorganic fertilizers. Farmers' grassroots organisations are also emerging with a voice on nutrient management. The local "farmer wisdom groups" in NE Thailand are a case where small community groups are seeking self-reliance and apply this thinking to nutrient management as well as other facets of agriculture and community development (S. Ruaysoongnern, personal communication). The Farmer Training Schools set up in Cambodia to promote integrated pest management are having spillover effects on nutrient management by encouraging groups of farmers to experiment with nutrient management practices (Robinson and Nugent 2002).

International aid projects have in many countries in SE Asia played a leading role in the development of national fertilizer recommendations. In Thailand, a FAO project developed fertilizer recommendations for field crops based on on-farm experiments (Ho and Sittibusaya 1984). In Cambodia and Laos, IRRI-led projects have developed rice fertilizer recommendations ( Linquist et al. 1998; Seng et al. 2001). Such inputs will tend to be once-off contributions using resources and trained personnel that may not be available to the national agencies responsible for updating and adding to the sets of recommendations.

Hence the new approach that has emerged to influence sustainable nutrient management is based on partnerships amongst the different stakeholders. Improved decision making and improved sustainability depends on accessing a much broader range of information than in the past and from many more sources. Partnerships amongst stakeholders facilitate information sharing, and collective action for sustainable nutrient management. The quality of leadership in the key stakeholder bodies is critical since partnership requires a collective will amongst stakeholders and involves many changes in traditional roles and attitudes of the individual stakeholders and their representatives. The role of extension officers in a partnership will be characterised by group facilitation, motivation and activation, rather than direction or simply dispensing advice. The technical skills of the extension officer may be less in demand in their new role.

The emergence of the private sector in developing technologies and products, and disseminating information is a potentially beneficial one for micronutrient management. Agents of fertilizer companies can increase the access of farmers to information and expert advice either by direct visits to farms or through the mass media. Fertilizer companies have a real interest in understanding blockages to the adoption of micronutrient fertilizer including markets, supply chains, product labeling and price sensitivity. But there are risks for sustainable micronutrient management. Fertilizer manufacturers and sellers in general have shown less rigorous standards of proof when promoting the benefits of their products than scientists. Hence there is a risk of many ineffectual products being sold leading to economic hardship for farmers and loss of confidence in the use of fertilizers of all sorts. Fertilizer salespersons may also have less concern about environmental protection than is prudent. Scientists can either enter the relationship between farmers and the private sector as antagonists towards the private sector, or seek a more conciliatory role. Defending the farmers against unscrupulous claims and practices has to be one of the roles of public sector scientists. However, if scientists fail to develop a constructive relationship with the private sector, many useful products and services may fail to reach farmers. Other products will be used by farmers despite their poor quality or ineffectiveness. Scientists can seek to engage in partnerships with the private sector to provide independent evaluation of products under controlled conditions, and to review, audit, and edit information provided to farmers. The challenge for scientists in this partnership is to maintain their independence whilst not alienating either farmers or fertilizer companies, the community, or government. It should be possible to convince all groups of their mutual benefits when scientists provide an independent review of products, services and information that reaches farmers.

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## REFERENCES

Anderson, A.J. (1970). Trace elements for sheep pastures and fodder crops in Australia. J. Aust. Inst. Agric. Sci. 36: 15-28.

Ascher-Ellis, J.S., Graham, R.D., Hollamby, G.J., Paull, J., Davies, P., Huang, C., Pallotta, M.A., Howes,N., Khabaz-Saberi, H., Jeffries, S.P. and Moussavi-Nik, M. (2001). Chapter 19. Micronutrients. In Application of Physiology to Wheat Breeding. Reynolds, M.P., Ortiz-Monasterio, J.I. and McNab, A. (eds). CIMMYT, Mexico DF. pp. 219-240.

Bell, R.W., Ros, C. and Seng, V. (2001). Improving the efficiency and sustainability of fertiliser use in drought- and submergence-prone rainfed lowlands in Southeast Asia. In: Fukai, S., and Basnayake, J. (Eds.), Increased Lowland Rice Production in the Mekong Region. Australian Centre for International Agricultural Research, Canberra, Australia, pp. 155-169.

Bell, R.W., Rerkasem, B., Keerati-Kasikorn, P., Phetchawee, S., Hiranburana, N., Ratanarat, S., Pongsakul, P. and Loneragan, J.F. (1990). Mineral Nutrition of Food Legumes in Thailand with particular reference to micronutrients. ACIAR Technical Report. 19, pp.52.

Black, C.A. (1993). Soil Fertility Evaluation and Control. Lewis Publishers, Boca Raton, Florida.

Brown, P.H., Welch, R.M., and Cary, E.E. (1987). Nickel: A micronutrient essential for higher plants. Plant Physiol. 85, 801-3.

Craswell, E.T., Loneragan, J.F., and Keerati-Kasikorn, P. (1987). Mineral constraints to food legume crop production in Asia. In: Food Legume Improvement in Asian Farming Systems. Wallis, E.S., and Byth, D.E. (eds). ACIAR Proc. Series 18. Inkata Press, Melbourne. pp. 99-111.

Datnoff L. E., Snyder G. H. and Korndorfer, G. H. (2001) Silicon in Agriculture. Elsevier Press. p.424.

Dell, B., Brown, P.H. and Bell, R.W. (Eds) (1997). Boron in Soils and Plants: Reviews. Dev. in Plant and Soil Sciences Vol. 77. Kluwer Academic Press, Dordrecht, The Netherlands. p. 219.

Dell, B., Malajczuk, N., Xu, D. and Grove, T.S. (2001). Nutrient Disorders in Plantation Eucalypts. 2nd Ed. Canberra, ACIAR Monograph No 74. p. 188.

Dell, B., Xu, D., Rogers, C. and Huang, L. (2003). Micronutrient disorders in eucalypt plantations: causes, symptoms, identification, impact and management. In: Eucalyptus Plantations - Research, Management and Development. Wei, R.P., and Xu, D. (eds). World Scientific Publishing Co. Singapore. pp. 241-252.

Dierolf, T.S., Fairhurst, T.H. and Mutert, E.W. (2001). Soil Fertility Kit: A Toolkit for Acid Upland Soil Fertility in Southeast Asia. PPI, Singapore.

Dobermann, A. and Fairhurst, T. (2000). Rice: Nutritional disorders and nutrient management. Potash and Phosphate Institute and Potash & Phosphate Institute of Canada (PPI/PPIC) and International Rice Research Institute (IRRI), Singapore and Makati City, The Philippines.

Dobermann, A., Cassman, K.G., Mamaril, C.P. and Sheehy, J.E. (1998). Management of phosphorus, potassium and sulfur in intensive, irrigated lowland rice. Field Crops Research 56, 113-118.

Donald, C.N. and Prescott, J.A. (1975). Trace elements in Australian crop and pasture production, 1924-1974. In Trace Elements in the Soil-Plant-Animal Continuum. Nicholas, D.J.D. and Egan, A.R. (eds). Academic Press, New York. pp. 7-37.

Goldbach, H. E., Rerkasem, B., Wimmer, M. A., Brown, P. H., Thellier, M. and Bell, R. W. (eds) (2002). Boron in Plant and Animal Nutrition. Kluwer Academic Publishers, Dordrecht, The Netherlands. p. 410.

Graham, R.D. and Webb, M.J. (1991). Micronutrients and disease resistance and tolerance in plants. In Micronutrients in Agriculture. Mortvedt J. J., Cox F. R., Shuman L. M. and Welch R. M. (eds). 2nd Ed. Soil Sci. Soc. Amer. Book Series No. 4. pp. 329-370.

Ho, C.T. and Sittibusaya, C. (1984). Fertilizer requirements for field crops in Thailand. In: Proceedings of the 5 th ASEAN Soils Conference. Bangkok, Thailand pp. H1.1-1.19

Kataki, P.K., Srivastava, S.P., Saifuzzaman, M. and Upreti, H. K. (2001). Sterility in wheat and response of field crops to applied boron in the Indo-Gangetic plains. J. Crop Production 4, 133-165.

Ladha, J.K., Pathak, H., Padre-Tirol, A. and Dawe, D. (2003). Productivity trends in intensive rice-wheat cropping systems in Asia. In: Improving the Productivity and Sustainability of Rice-Wheat Systems: Issues and Impacts. Ladha, J.K., Hill, J.E., Duxbury, J.M., Gupta, R.K. and Buresh, R.J. (eds). ASA Special Publication No. 65. pp.45-76.

Lathvilayvong, P., Schiller, J. M., Phommasack, T. and Chanphengsay, M. (1995). Soil fertility management in rainfed lowland environment of the Lao PDR. In: Soil Organic matter

Management for Sustainable Agriculture. Lefroy, R.D.B., Blair, G.J. and Craswell, E.T. (eds.). Australian Centre for International Agricultural Research, Canberra, pp. 91-97.

Liu, Z. (1992). Characterization of content and distribution of micronutrients in soils of China. In: Proc Int Symp Role of S, Mg and Micronutrients in Balance Plant Nutrition, Portch S (ed.) Potash and Phosphate Institute, Hong Kong. pp. 54-62.

Mortvedt, J.J. (1985). Micronutrient fertilizers and fertilization practices. Fertilizer Res. 7, 221-235.

Mortvedt J. J., Cox F. R., Shuman L. M. and Welch R. M. (eds) (1991). Micronutrients in Agriculture. 2nd Ed. Soil Sci. Soc. Amer. Book Series No. 4.

Nayyar, V.K., Arora, C.L. and Kataki, P.K. (2001). Management of soil micronutrients deficiencies in the rice-wheat cropping system. J. Crop Production 4, 87-131.

Nielsen, F. (2002). The nutritional importance and pharmacological potential of boron for higher animals and human. In: Boron in Plant and Animal Nutrition. Goldbach, H. E., Rerkasem, B., Wimmer, M. A., Brown, P. H., Thellier M., and Bell, R. W. (eds). Kluwer Academic Publishers, Dordrecht, The Netherlands. pp. 37-49.

Rashid, A., Rafique, E. and Ryan, J. (2002). Establishment and management of boron deficiency in field crops in Pakistan. A country report. In: Boron in Plant and Animal Nutrition. Goldbach, H. E., Rerkasem, B., Wimmer, M. A., Brown, P. H., Thellier, M. and Bell R. W. (eds). Kluwer Academic Publishers, Dordrecht, The Netherlands. pp. 339-348.

Rerkasem, B. and Jamjod, S. (2001). Overcoming wheat sterility problem with boron efficiency. In: Plant Nutrition Food Security and Sustainability of Agro-ecosystems through Basic and Applied Research. Horst, W., Schenk, M. K., Burkert, A., Claasen, N., Flessa, H., Frommer, W. B., Goldbach, H., Olfs, H-W., Romheld, V., Sattelmacher, B., Schmidhalter, U., Schubert, S., von Wiren, N. and Wittenmayer, L. (eds.). Kluwer Academic Publishers, Dordrecht. Developments in Plant and Soil Sciences 92: 82-83.

Reuter, D.J., Alston, A.M. and McFarlane, J.D. (1988). Occurrence and correction of manganese deficiency. In: Manganese in Soils and Plants. Graham, R.D. (ed.). Kluwer Academic publishers, Dordrecht, The Netherlands. pp. 205-224.

Robinson, M. and Nugent R. (2002). IPM Farmer Training Schools in Cambodia. Cambodian Journal of Agriculture 5, 27-35.

Robson, A.D. (Ed.) (1993). Zinc in Soils and Plants. Kluwer Academic Publ, Dordrecht, The Netherlands.

Seng, V., Ros, C., Bell, R.W., White, P.F. and Hin, S. (2001). Nutrient requirements for lowland rice in Cambodia. In: Increased Lowland Rice Production in the Mekong Region. Fukai, S., and Basnayake, J. (eds.). Australia Centre for International Agricultural Research: Canberra, Australia, pp. 170-178.

Shorrocks, V. M. (1997). The occurrence and correction of boron deficiency. Plant Soil 193, 121-148.

Sillanpaa, M. (1982). Micronutrients and the nutrient status of soils: a global study. Soils Bulletin 48. FAO Rome.

Takkar, P.N., Chhibba, I.M. and Mehta, S.K. (1989). Twenty Years of Coordinated Research on Micronutrients in Soils and Plants. Indian Inst. Soil Science, Bhopal.

Wall, E. (2001). New models for extension: Introduction. Journal of Sustainable Agriculture 19, 3-7.

Wang, K., Xu, J. M., Wei, Y. Z., Yang, Y. and Bell, R. W. (1997). The influence of boron fertilizer on distribution of extractable boron in soil profiles in rape-rice rotations in south east China. In Boron in Soils and Plants. Bell, R.W. and Rerkasem, B. (eds) Development in Plant and Soil Sciences Vol 76. Kluwer Academic Publ, Dordrecht, The Netherlands. pp. 57-61.

Wang, K., Yang, Y., Xue, J.M., Ye, Z.Q., Wei, Y. and Bell, R.W. (1999). Low risks of toxicity from boron fertiliser in oilseed rape-rice rotations in south east China. Nutrient Cycling in Agro-ecosystems 54, 189-197.

Wei, Y.Z., Bell, R.W., Yang, Y., Ye, Z.Q., Wang, K. and Huang, L. (1998). Prognosis of boron deficiency in oilseed rape (*Brassica napus* L.) by plant analysis. Australian Journal of Agricultural Research 49, 867-874.

Wihardjaka, A., Kirk, G.J.D., Abdulrachman, S. and Mamaril, C.P. (1998). Potassium balances in rainfed lowland rice on a light-textured soil. In: Rainfed Lowland Rice: Advances in Nutrient Management Research. Ladha, J.K., Wade, L.J., Dobermann, A., Reichardt, W., Kirk, G.J.D. and Piggin, C. (eds.). International Rice Research Institute, Los Banos, Philippines, pp. 127-137.

Wong, M. (2003). Monitor crops closely for signs of low boron. Farming Ahead No. 135.

Wood, I.J. and Myers, R.J.K. (1987). Food legumes in farming systems in the tropics and subtropics. In: Food Legume Improvement for Asian Farming Systems. Wallis, E.S. and Byth, D.E. (eds.). Australian Centre for International Agricultural Research: Canberra, Australia, pp. 34-45.

Yang, X., Yu, Y.G., Yang, Y., Bell, R.W. and Ye Z.Q. (2000). Residual effectiveness of boron fertilizer for oilseed rape in intensively cropped rice-based rotations. Nutrient Cycling in Agro-ecosystems 57, 171-181.