INTRODUCTION

Maize (*Zea mays* L.) is one of the oldest food grains. It belongs to the grass family Poaceae (Gramineae), tribe Maydeae, and is the only cultivated species in this genus. By volume of production, maize is the most important cereal grain before wheat, with milled rice occupying third place. However, among food grain crops, maize ranks third in terms of production and acreage. Maize is widely grown throughout the world and in Asia is planted in subtropical and temperate agroclimatic regions (Fageria *et al*., 1991; Martin *et al*., 1976). Maize has great economic significance worldwide, providing nutrients for human food and animal feed and a source for a large number of industrial products at various stages of plant development. For example, it provides basic raw materials for the production of starch, oil and protein, alcoholic beverages, sweeteners and, more recently, biofuel (Duvick, 2005; FAO, 1992; Paliwal, 2000). It is the only cultivated species of significant economic importance in the tribe. It is a cross-pollinating species, with the female (ear) and male (tassel) flowers in separate places on the plant (FAO, 1992). Some crops are harvested for industrial use when the ears are still green and are used for food and the residue makes good forage. This aspect is particularly important as the pressure on limited land increases and even more intensive cropping patterns must be practiced in order to produce enough food for a vastly increased population (Byerlee and Saad, 1993).

Globally, maize is grown on 140 million ha with an annual production of about 600 million tonnes. Tropical maize is grown in 66 countries and is of major economic significance in 61 countries, each having 50,000 ha or more (ca. 62 million ha with an annual production of 111 million tonnes) (Paliwal, 2000). The average yield of maize in the tropics is 1.8 t ha^{-1}, as against the global average of 4.2 t ha^{-1}. The average yield of temperate maize is 7 t ha^{-1} because temperate cultivars have a longer growing season than most tropical cultivars. The maize situation in the tropics is changing rapidly. Superior germplasm of high productivity is becoming increasingly available for most tropical maize environments. With expansion of the production and marketing of seeds in both the public and private sectors, superior hybrids and improved varieties are now more readily available to farmers. Most researchers believe that the future of maize in the tropics is brighter than in the past. Because of heavy population pressure, most tropical countries are faced with a high rate of population increase. Not only is there a need to produce food to sustain this expanding population but there is an urgent need to improve the nutritional level, particularly of the poorer sector of the population (Paliwal, 2000).

In the United States, maize is produced on 28 to 32 million ha annually and plays an important role in the economy of the country. Hybrid maize was introduced to the United States corn belt in the 1930s, and average production per unit area increased more than three times from 1.5 to 8.5 t ha^{-1} in the 20^{th} century. Globally, maize yield during the period 1961-2002 increased about two times, from 1.9 to 4.3 t ha^{-1} or a linear increase of 61 kg ha^{-1} $year^{-1}$. In south Asia, yield did not start to rise significantly until 1985, and annual gains have averaged only 38 kg ha^{-1} $year^{-1}$. Changes in agronomic practices have been responsible for about half of the yield gains with breeding contributing the other half. One of the most important management tools has been synthetic fertilizers, the use of which has increased markedly in developed countries (Duvick, 2005).

Thailand was Asia's major maize producer and exporter in the 1960s to 1980s. In 1996, all maize production was domestically used, mainly as animal feed, and to a small extent for home consumption, as vegetables: baby corn, sweet corn and green ear. Thailand moved from being a net exporter of maize in 1966 to being a net importer in 1995 (Ekasingh *et al.*, 1999). Recently, domestic consumption has become more important in the Thai maize commodity system because of the expansion of swine and poultry industries in the country (Wattanutchariya, 2001). Maize can be grown in many parts of the country. The major maize growing areas are concentrated in the upland rain-fed areas of lower northern, northeastern and upper central regions, where farms are relatively large. However, in lowland irrigated areas, maize can be grown throughout the year. Maize yield was only about 2.8 t ha^{-1} in 1994/1995 and total production was about 4.0 million tonnes. Recently, the yield increased to 3.9 t ha^{-1} in 2003 and total production was about 4.5 million tons (FAO, 2003). A good rainfall pattern during the wet season contributes to larger planted areas for the crop. The Thai government has encouraged the use of new improved varieties, chemical fertilizers, and proper cultivation techniques.

Boron (B) deficiency in plants is one of the most widespread nutrient disorders in the field, having been reported in over 80 countries (Shorrocks, 1997). Crop requirement, uptake, factors affecting levels of deficiency and toxicity and the physiological role of B in plants have been reviewed by Gupta (1979; 2007), Lewis (1980), Marschner (1995), Sillanpää (1982) and Dell and Huang (1997). Boron deficiency of cereal crops had been widely reported in Asia, for example in wheat in

Nepal (Sthapit, 1988), India (Tandon and Naqvi, 1992) and China (Li *et al.*, 1978); in wheat and barley in Thailand (Rerkasem and Jamjod, 1989) and in sorghum in India (Tandon and Kanwar, 1984; Grundon *et al.*, 1987). Boron deficiency is also widespread in northern and northeastern Thailand and has been reported in mungbean, peanut, sunflower, wheat and barley (Rerkasem, 1986; Rerkasem *et al.*, 1989; Rerkasem and Jamjod, 1989). The main symptom of B deficiency is male sterility in wheat, resulting in grain set failure and yield reduction (Rerkasem *et al*., 1997). Grain set of wheat has been correlated with B concentration in the ear and flag leaf (Rerkasem and Lordkaew, 1992).

In maize, B deficiency reduced grain yield (Berger, 1962). However, maize has generally been considered to have low sensitivity to low soil B (Gupta, 1993; Martens and Westermann, 1991). Maize is grown in many parts of the world where the soil has low B status (Sillanpää, 1982). In field experiments in the United States and China, respectively, Berger *et al.* (1962) and Li and Liang (1997) found that the application of B increased maize yields by an average of 9%. In spite of these observations, there is little detailed information about B deficiency in maize.

The objectives of the present study were

1. To determine the response of maize to B supply during vegetative and reproductive growth,

2. To evaluate genotypic variability in response to B deficiency, and

3. To identify likely B efficiency mechanism(s) for management and breeding of maize in the future.

The overall approach of this study is shown in a flow diagram (Figure 1).

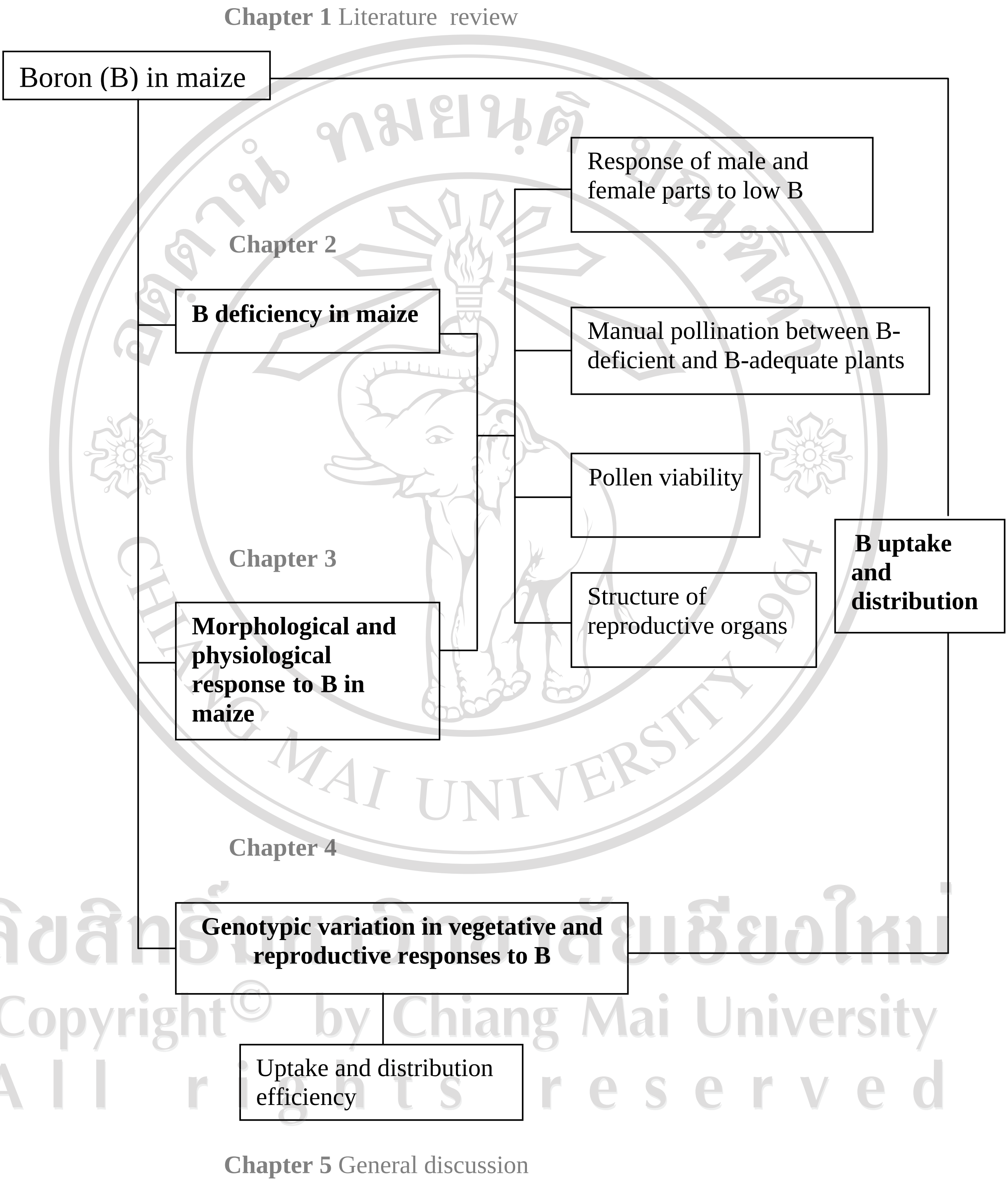

Figure 1 Structure of the thesis.

CHAPTER 1

LITERATURE REVIEW

1.1 Introduction

Boron (B) is essential for plant growth especially was expressed to be essential to plant growth by Warington (1923) that plants required a continuous supply of B as an important concept of essential element. As B dealing deficiency is widespread in many part of the world (Figure 1.1) there is a large body of information with the essentially of B for a variety of agricultural crops in many countries of the world over last the 80 years (Gupta, 2007; Shorrocks, 1997). In northern and northeastern Thailand has been reported B deficiency in mungbean, peanut, sunflower, wheat and barley (Rerkasem *et al*., 1989, Rerkasem and Jamjod, 2004). The requirement of B in plants differs markedly within plant species. Most Graminaceous species such as wheat (*Triticum aestivum* L), oat *(Avena sativa* L.) and barley (*Hordeum vulgare* L.) have a much lower requirement for B than do dicots and other monocots (Gupta, 2007). According to Marschner (1995) referred that plant species were grown in the same soil they differed characteristically in the capacity to take up B in which reflect typical species differences in requirement of B for growth. For example, in wheat and maize contained B approximately 6-9 mg B kg^{-1} DW compared with dicots such as alfalfa red clover higher had about 37 and 32 mg B kg^{-1} DW and whereas in vegetable such as sugar beet had up to 102.3 mg B kg^{-1} DW.

Because little is known about the physiological response of maize to low B supply, this chapter reviews the role of B in plants with an emphasis on cereals.

1.2 Factors influencing soil B supply for crop production

1.2.1 Parent materials

Generally, the distribution of B is associated with rock types (Garrett, 1998). Primary igneous rocks such as gabbro and basalt contained B from 5-20 mg B kg^{-1} whereas sedimentary rocks contain higher amount of B e.g. 30 mg B kg^{-1} in sandstone and up to 120-130 mg B kg^{-1} in shale (Shorrocks, 1997). Because rock is one of the main parent materials of soils, then B distribution in soil is closely associated with soil groups or types. For example, in the South of Yangtze, among parent materials in the Acrisol soil group, granite contained approximately 4-16 mg total B kg^{-1} whereas Phyllite contained about 15-40 mg B kg^{-1}. The soil groups with low B concentration include strongly weathered soils (Acrisols:Ultisol, Podzols:Spodosol, Ferralsols:Oxisol); coarse textured soils (Arenosols:Psamment); shallow soils (Lithosols:Lithic); thin soils over calcareous material (Rendzinas:Rendoll); and volcanic ash soils (Andosols:Andept). All these soils contain an average of 0.5-0.6 mg B kg^{-1} (hot water soluble).

The most important of soil group for B deficiency is Acrisols. These soils are strongly weathered and frequently have low base exchange capacity. Over 50% of the soils in southeast Asia are Acrisol. Boron deficiency on Acrisols have been reported in Indonesia, Malaysia, Thailand, Laos, Vietnam and Myanmar, where soil B levels were approximately 0.1-0.7 mg B kg^{-1} (Gyul'akhmedov and N and Mamedov, 1984 cited by Shorrocks, 1997). The deficient of B are covered about 30–100 million ha in Myanmar, Indonesia, Tanzania and Thailand and about 14-40 million ha included in Australia, Bolivia, Cambodia, Colombia, India, Ivory Coast, Laos, Malaysia, Peru,Venezuela, Vietnam, Central African Republic, Ghana, Guinea, Japan, Mexico, Nicaragua, Nigeria, Papua New Guinea, Paraguay, Philippines and Suriname. For Podozols that are the soils with commonly develop under coniferous forest in climates often unsuitable for agriculture. This soil is mostly occurred in Scandnevia, Eorope and North America.

1.2.2 Soil properties

Boron is normally presented in the soil as an un-ionized molecule that is very mobile and supplied to root primary by mass flow. A greater quantity of B (hot water soluble:HWS) on eastern Canada was found in the fine-textured soils than in the coarse-textured soil (Gupta, 1968). Factors affecting B deficiency to plants apart from parent material were soil pH, organic matter and moisture.

In case of soil pH, availability of B in soil depended on pH, in excess of approximately 6.5 probably is associated with decreased B activity in the soil solution as a consequence of adsorption on clay and hydroxyl-Al surface (Karen and Bingham, 1985). At the soil pH below 7, B is present mainly as $B(OH)_3$ which is not absorbed very extensively by the colloid fraction where as the soil pH over 7 the concentration of $B(OH)_4$ increased. These only monomeric form of B are usually present in soil solution at the concentration less than 25 mM, thus polymeric B species are unlikely to present in plants except under B toxicity (Marschner, 1995). Boron deficiency occurred when susceptible crops are grown on freshly limed soils with pH more than 6.5.

Organic matter is not released B immediately available to plants, it is considered to be a main source of available B when released through mineralization (Gupta *et al.*

cited by Moraghan and Mascagni, 1991). The amount of B (HWS) in soil has been found to be positively relative to the organic matter content in soil (Gupta, 1968).

The reduction of soil moisture (or soil water content) was associated with the levels of B in soil solution in which connection with reduced mass flow and limited transpiration. During drought periods (or dry soil), plant may be causative of B deficiency in spite of an adequate supply of B in the soil.

The occurrences of B deficiency are based on reported positive responses to B application in the field over 60 years (Shorrocks, 1997). Geographical pattern of a shortage of B involved broad regions where the problem is almost universal on agriculture land (Figure 1.1). Some pattern may be localized and involved only certain parts of field whereas the other parts or area being free from the problem. For example, B deficiency in USA is the most of all micronutrient deficiencies covered 41 states (Berger, 1962). Especially, alfalfa (*Medicago sativa* L.) is the most B deficiency crops was found in 38 states in which localized largely in more humid regions (Berger, 1962) where low amounts of plant-available B due to leaching (Gupta, 2007). These area including the states along the Atlantic and Gulf of Mexico, the Pacific Northwest and the Great Lakes region in which the soil of Podzols, Acrisols and Andosols.

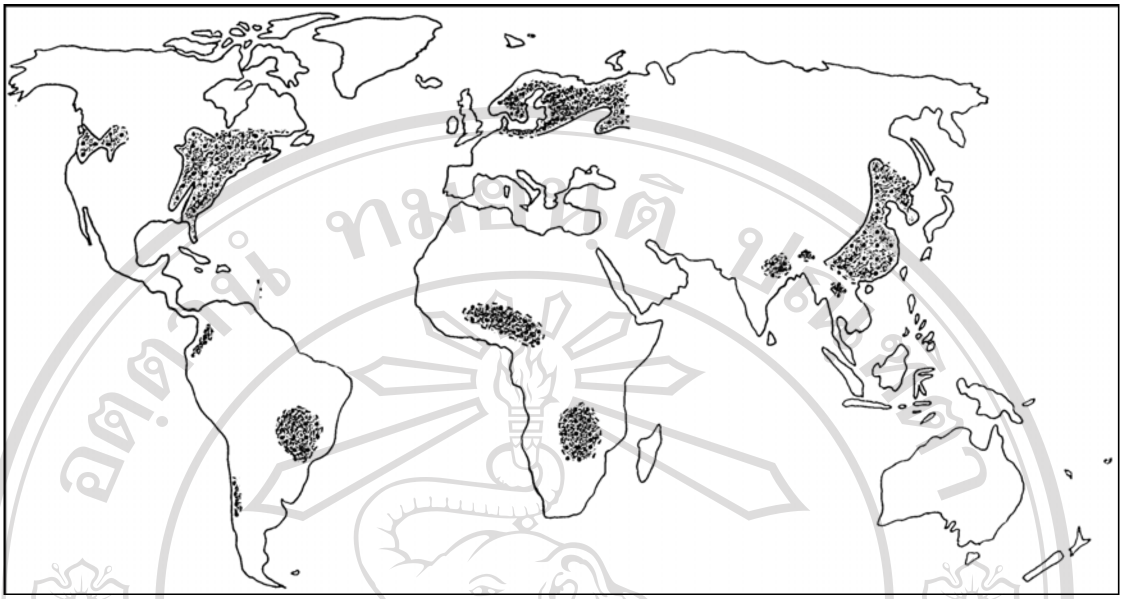

Figure 1.1 Boron deficiency is widespread area (Adapted from Shorrocks, 1997)

For Asia, in China, the geographical distribution of B deficiency in crops associated with the distribution of B-deficiency soils (with low level of hot water soluble B<0.25 mg B kg^{-1}) in the South, the East, south of the Yangtze and the Northeast China (Zheng *et al*., 1982 cited by Welch *et al*., 1991). Several evidences of B deficiency, especially in maize based on responses to B application has been reported including Columbia, Bulgaria, France, Netherlands, Poland, Switzerland, USSR, India, Korea, Pakistan, Nigeria, South Africa, Zimbabwe and Zambia (Shorrocks, 1997). Shorrocks (1997) concluded that soil parent material and texture are considered to be the major soil factors associated with the occurrence of B deficiency. In contrast, B toxicity was most likely in Iraq, Mexico, Pakistan and Turkey particularly at irrigated sites (Sillanpää, 1982).

Boron deficiency can also be found in northeastern and northern Thailand where crops were grown in which have been reported in peanut (Keerati-Kasikorn *et al*., 1987 and 1991), soybean (Rerkasem *et al*., 1988) sunflower and green gram (Rerkasem, 1986) and wheat and barley (Rerkasem and Jamjod, 1989) these locations included a sandy loam of San Sai series of the Typic Tropaqualf.

1.2.3 Crop species

The sensitivity of crops to B deficiency varies with species. Mortvedt and Woodruff (1993) summarized that generally B requirement of some crops into high, medium and low that was presented in Table 1.1. The primary cell wall of higher plants is an important factor determining cell size and shape during plant development (Blevins and Lukaszewski, 1998). Loomis and Durst (1992) revealed that the cellular B was localized in the cell wall fraction up to 90%. In case of monocotyledons, especially some graminaceous species have a lower B requirement than dicotyledons with lower concentration of B-binding sites in the cell wall (Marschner, 1995) or primary cell wall contained very little of the B-complexing pectin. Matoh (1997) reported that the occurrence of purified B-polysaccharide complex in the cell walls of 24 species differed between species. For example, the content of B in the cell wall of maize (*Zea mays* L.) contained only 6.8 mg B kg^{-1} cell wall (CW), cucumber (*Cucumis sativus*) higher contained 36.5 mg B kg^{-1} CW whereas duckweed (*Lemna pausicostata*) in which grouped of monocotyledons contained a lot of B up to about 780 mg B kg^{-1} CW.

Table 1.1 Boron requirement of some crops

High	Medium	Low
Alfalfa	Asparagus	Barley
Apple	Carrot	Beans
Broccoli	Cherry	Blueberry
Cabbage	Corn (sweet)	Cereals
Cauliflower	Cotton	Citrus
Celery	Lettuce	Corn (maize)
Clovers	Onion	Cucumber
Mustard	Parsnip	Flax
Peanuts	Peach	Grasses
Rape	Pear	Oat
Red beet	Potato (sweet)	Peas
Rutabaga	Radish	Pepper
Sugar beet	Spinach	Potato (white)
Sunflower	Tobacco	Raspberry
Turnip	Tomato	Rye
		Sorghum
		Strawberry
		Wheat

1.2.4 Other factors

According to Vlamis and Williams (1970) reported that increased temperature in nutrient solution did not increased the concentration of B in root of barley (*Hordeum vulgare* L.), but resulted in higher B concentration in shoots in which associated with temperature effect on the rate of transpiration. The influence of high light intensity was stimulated B deficiency due presumably to increased transpiration (Oertli, 1963 cited by Moraghan and Mascagni, 1991).

1.3 Boron deficiency in crop production

1.3.1 The response of vegetative growth to low B

The cessation of root elongation is a parameter indicated that of the most rapid response to B deficiency in higher plant (Marschner, 1995; Shelp, 1993; Dell and Huang, 1997). The earliest of visible response to B deficient plant is the total root elongation was inhibited, due to impairing of cell enlargement and division in the meristematic region (Loomis and Durst, 1992). The B-deficient plant, the cell wall are dramatically altered in both the rate and process of carbohydrate condensation into wall material. Some cells failed to develop typical normal thickening such as collenchyma cell, instead of forming a uniform thick (Spurr, 1957 cited by Matoh, 1997). Similar, in B-deficiency tomato root tips during 3-6 days in nutrient solution, cell wall suffered an irregular thickening and that the cell wall altered longitudinal walls appearance by thickened walls and lost their ability to elongate and divide (Kouchi and Kumazawa, 1975).

Responses to low B of plants during early vegetative growth is much less readily inducible in monocotyledons than in dicotyledons. Some Graminaceous species have a lower B requirement than broad-leaf species due to the lower concentration of B-binding sites in the cell wall (Marschner, 1995). Boron is a component of pecto-cellulosic walls as the borate ion cross- links two chains of pectic polysaccharide to form the borate-dimeric-rhamnogalacturonan II (RG-II) complex in the cell wall (Matoh, 1997) of radish roots (*Raphanus sativus* L. cv Aokubi-daikon) (Kobayashi *et al*., 1999; Matoh *et al*., 1998). Snowball and Robson (1983) reported that wheat roots continued to grow normally in nutrient solution without added B whereas root growth of subterranean clover stopped immediately when plants were transferred from +B to -B. Asad *et al*. (1997) measured lower external and internal B requirements in 10-20 day-old canola seedlings in nutrient solution, at ≤ 0.13 μM B, the growth of wheat seedlings was normal and plants did not show any B-deficiency symptoms whereas growth of marri (*Corymbia calophylla*) and sunflower (*Helianthus annuus*) was severely depressed in a buffer solution system with <0.6 μM B. Dry weight was depressed when the solution B in marri and sunflower was <1.2 μM B. Symptoms of B deficiency have not been observed in vegetative parts of the wheat shoot in young plants in the field. Under pot conditions where the B supply can be depleted to very low levels, young leaves show a saw tooth symptom, because of abnormal cellular development (Snowball and Robson, 1983). In the field, B-deficiency symptoms have been observed near the flowering stage. For maize, no symptoms of B deficiency have been published for plants in the field or in containers, even though the application of B increased maize yield in China (Li and Liang, 1997), Switzerland (Mozafar, 1989) and in the United States (Peterson and MacGreger, 1966; Woodruff *et al*., 1987).

1.3.2 The response of reproductive growth to low B

1.3.2.1 Male development in cereals

Microsporogenesis of maize has been described in detail (Chang and Neuffer, 1989; Goss, 1968). In general, reproductive growth is more sensitive to low B supply than vegetative growth in cereals. For example, grain production was impaired more than vegetative growth in white clover (Johnson and wear, 1967) and maize (Vaughan, 1977). Roles for B in pollen development and pollen tube growth have been reviewed by Dell and Huang (1997) and Dell *et al*. (2002). Withdrawing B from solution for three days between premiotic interphase through meiosis to late tetrad resulted in limitation of anther elongation and loss of pollen viability (Huang *et al*., 2000). A study on pollen development in wheat failed to detect any abnormality in pollen until after the uninucleate vacuolated stage had been reached (Rerkasem *et al*., 1997). Reduction in starch accumulation in the anther close to anthesis is an indicator of a potential problem. In wheat, visible impairment in pollen development due to low B did not appear until after the microspores were released from the tetrad (Huang *et al.*, 2000).

Boron deficiency resulted in grain set failure due to male infertility in wheat in Brazil (da Silva and de Andrade, 1980), China (Li *et al*., 1978), and Thailand (Rerkasem *et al*., 1989). An adverse effect of B deficiency on pollen viability was demonstrated using fluorochromatic (FCR) or DAPI (4′,6-diamidino-2-phenylindole·2HCl) tests which confirmed the absence of one or more of the nuclei (NaChiangmai *et al*., 2002). In wheat, grain set in B-deficient female flowers was increased by hand pollination using fertile pollen, confirming that male fertility is the primary cause of low grain set in B-deficient plants (Rerkasem *et al*., 1993). Furthermore, anthers with low B contents had normal vegetative tissues, e.g. the tapetum, and the lignified endothecium, indicating a specific requirement of B for microsporogenesis (Rerkasem *et al*., 1997).

1.3.2.2 Female development in cereals

In flowering plants, the pistil differentiates into three regions differing in function: pollen germination (stigma), pollen tube growth (style) and embryo sac formation (ovule). In general, the pistil is less sensitive than the anther to B supply during organogenesis. Dell and Huang (1997) explained that ovary development lags behind growth of the anther. Furthermore, unlike during microsporogenesis where a large number of cells undergo simultaneous cell division, only one cell in each ovule undergoes meiosis. Further, the ability of the pistil to support pollen germination and tube growth can extend over a longer period than early microsporogenesis. This factor may make the pistil less sensitive than the anther to variation in B supply during organogenesis. Another factor that may be important is the degree of vascularization of the pistil.

In addition to the role that B plays in microsporogenesis, B also has a role in pollen germination, pollen tube growth and post-fertilization growth (Cheng and Rerkasem, 1993; Dell and Huang, 1997). For example, in wheat, B deficiency affected both male and female development resulting in reduction in grain set. Manual cross pollination using a B-deficient female with pollen from a B-sufficient plant produced grain set of only 28%, whereas when a B-sufficient female plant was fertilized with pollen from a B-sufficient plant there was up to 94% of grain set (Rerkasem *et al*., 1993). Thus B deficiency in the female part had some effects on grain set.

However, this effect of low B on reproduction in wheat is not universal as in avocado (*Persea americana*), the stigma was more sensitive to B supply than was pollen development (Coetzer and Robberttse, 1987). By contrast, Smith *et al*. (1997) found that application of B to soil at the rate of 1.6 g m^{-2} resulted in the germination of pollen grains in the medium without added B increased up to 47% compared with no B application had only 3%. Foliar B application in the field, at the beginning of anthesis, increased avocado fruit set by 42% (Smith, 1997). In other crops, low B supply resulted in arrestment in the development of some ovules and embryo sacs in oilseed rape (Xu *et al*., 1993) and there was abnormal fiber development on ovules of cotton (*Gossypium hirsutum*) grown *in vitro* (Birnbaum *et al*., 1974). For maize, low B has been reported to be more limiting for pistil than pollen function (Vaughan, 1977) even though the style had lower B concentration than the pollen (Agarwala, 1981). A further effect of low B soils supply is reduced seed quality, for example, hollow heart in peanut (*Arachis hypogaea* L.) and soybean (*Glycine max* L. Merr.). Moreover, low B concentration in seed has impaired the viability and vigour of seed in soybean (CDC 7-10 mg B kg^{-1}) and black gram (*Vigna mungo* L. Hepper: CDC 6 mg B kg^{-1}) (Bell *et al*., 1989; Rerkasem *et al*., 1989, 1993, 1997). Bell and Frost (2002) reported that lupin (*Lupinus angustifolius*) has a lower internal B requirement in seed than other legumes, and decreases in seed viability may be expected when seed B was below 12 mg B kg^{-1} and especially below 6 mg B kg^{-1}.

1.4 Nutrient efficiency

The investigation of nutrient efficiency is used generally for increasing productivity in low fertility soils or nutrient stress condition and emphasizing the internal nutrient requirement of plant (Gourley *et al*., 1994). The definition of nutrient efficiency has been used widely as a measure of the capacity of a plant to acquire and utilize nutrient for production timber and crops. Similar, the term "nutrient efficiency" base on yield parameters, has been defined as the ability to produce a high plant yield in soil or other media, that would otherwise limit the production of a standard line (Buso and Bliss, 1988). Clark (1976) defined a mineral efficient plant that is a plant grows better, produces more dry weight and develops fewer deficiency symptom than another plant when grown at low levels a mineral element and may have a greater ability to take up and make mineral elements more available and have a lower requirement for growth.

The definition varied greatly and some case may be misleading to interpretation of increased productivity and identification of mechanisms for enhanced nutrient acquisition and utilization (Clark cited by Gourley *et al*., 1994). There were many different definitions for efficiency make the use of the term ambiguous.

Investigation of Gourley *et al.* (1994) proposed that the equivalent yield of cultivars should be measured where nutrients (e.g. P) are not limiting in identify nutrient (P) efficiency of two cultivars of the forage legumes *(Medicago sativa* L.) (EG2:a low tolerant; low P intolerant :IG2) and white clovers *(Trifolium repens* L.) (Gandalf: P efficient; moderately P efficient: Huia) over a range of P rates. Since cultivars differed in some parameter such as maximum shoot and total dry weight and in external P concentration that required to achieve the maximum yield at 80%. The relationship between shoot dry weight and external concentration of P, in a efficient cultivar (EG2) had a predicted maximum shoot yield of 4.4 g pot^{-1} compared with 3.2 g pot^{-1} for inefficient cultivar (IG2). In white clover, Gandalf had shoot yield of 4.4 g pot^{-1} compared with 2.1 g pot^{-1} for Huia. This response curve was derived from the relationship between shoot dry weight (g pot^{-1}) and concentration of P in solution (μM), using the Michaelis-Menten equation:

$$\text{Shoot dry weight} = (\alpha \times \text{solution [P]}) / (\beta + \text{solution [P]})$$

Where α and β were estimate of maximum shoot dry weight and solution [P] at half maximum shoot dry weight, respectively. However, there was not affected in others parameter e.g. tissue P concentration and P uptake per unit of fine root dry weight (total P accumulation divided by fine root dry weight) in which to identify nutrient efficiency these cultivars.

According to definition proposed by Moll *et al*. (1982) that useful in looking at genetic differences in nitrogen use efficiency among wheat cultivars. For nitrogen and phosphorus use efficiency in wheat as grain yield per unit of nutrient supplied (from the soil and/or fertilizer). Nutrient use efficiency was divided into two components: uptake, or the ability of the plant to extract the nutrient from the soil, and utilization efficiency, or the ability of the plant to convert the absorbed nutrient into grain yield. Hence,

Nutrient use efficiency = Uptake efficiency x Utilization efficiency

$$\frac{Gw}{Ns} = \frac{Nt}{Ns} \times \frac{Gw}{Nt}$$

where Gw is grain dry weight, Nt is total above-ground plant nutrient at maturity, and Ns is nutrient supplied. All units are in g m^{-2}. Utilization efficiency can also be subdivided into two components, as suggested by Ortiz-Monasterio *et al*. (1997) and expressed as follows:

Utilization efficiency = Harvest index x Nutrientbiomass production efficiency

$$\frac{Gw}{Nt} = \frac{Gw}{Tw} \times \frac{Tw}{Nt}$$

where Tw is total above-ground plant dry weight at maturity.

Utilization efficiency can also be expressed as:

Utilization efficiency = Harvest index x Inverse of total nutrient concentration in the plant

$$\frac{Gw}{Nt} = \frac{Gw}{Tw} \times \frac{1}{Nct}$$

where Nct is total nutrient concentration in the plant as a percentage.

Gerloff (1977) proposed the nutrient efficiency (NPK) classification systems that consideration the performance in both the presence and in the absence of nutrient stress. With based on responses to phosphorus (P) of plant, cultivars would be separated into four groups as follows: (1) efficient, responder; (2) inefficient, responder; (3) efficient, non-responder, and (4) inefficient, non-responder. The efficient cultivar is the higher yielding cultivar than the other cultivars under low nutrient supply, while a responder cultivar is the higher yielding cultivar under high nutrient supply. This identification system used to classification plant cultivars with adaptation to a widely range of nutrient conditions.

1.4.1 B-efficient and B-inefficient genotypes in cereals

A B-efficient genotype is defined as the ability of a genotype to grow without any adverse effect in soil or other media with a low level of B that is limiting to other genotypes (Rerkasem and Jamjod, 1997b). For convenience, Rerkasem and Jamjod (1997a) identified five levels of B efficiency in wheat: very inefficient, inefficient, moderately inefficient, moderately efficient and efficient. Possible mechanisms of B efficiency include: enhanced capacity to acquire B from soil that is low in B; and more efficient distribution, utilization and redistribution of B within the plant. Large genotypic variation in response to B has been reported in wheat from Brazil, China, India, Nepal and Thailand. Rerkasem and Jamjod (2004) concluded that variation in B efficiency of this plant is may the widest possible of any species in response to a deficiency in any nutrient element.

Nachiangmai *et al*. (2004) investigated wheat plants grown with adequate ^{11}B until the premiotic interphase stage , then transferred into ^{10}B at 0.1 or 10 μM B for 5 days. In low B (0.1 μM B), pollen viability in SW41 (B-inefficient genotype) was depressed (47%) with B concentration in the ear dropping to 3.8 mg kg^{-1} but Fang 60 (B-efficient genotype) was not affected due to maintaining B concentration at 6.8 mg kg^{-1}. Boron efficiency was associated with the transport of B from roots to the developing ear rather than retranslocation of B from vegetative parts. In an earlier study, Bellaloui and Brown (1998) concluded that differential B uptake was the mechanism for B efficiency in a number of other cultivars.

1.4.2 Mechanisms for uptake efficiency, mobility, requirement

The mechanism of nutrient efficiency, such as zinc (Zn) efficiency researchers suggested that can be partitioned into uptake, utilization and translocation or remobilization efficiency, all or some of which collective evaluate the level of Zn efficiency in particularly genotype. Genc *et al*. (2004) reported that under Zn deficiency condition of two barley genotypes, in Zn-efficient genotype (cv.Unicorn) showed less severe deficiency symptoms and produced more dry weight and grain yield compared with the Zn-inefficient genotype (Amagi Nijo). At maturity, Unicorn was greater translocation of Zn from vegetative to reproductive organ or greater ability to produce higher grain with limited Zn rather than Zn uptake from soil. The critical deficiency concentration in grain of Unicorn was 12 mg Zn kg^{-1} DW in which lower than the Zn-inefficiency Amagi Nijo of 18 mg Zn kg^{-1} DW. It is suggested that a lower requirement for metabolic processes in Zn-efficient Unicorn.

Loneragan (1976) suggested that the movement of nutrients to functional sites involved two processes, including transport in the xylem root to the plant tops and retranslocation in the phloem from those organs. In tomato cultivar T3238 accumulated B in its root against transport to tops was evidenced at high as well as at low concentration in solution and caused this cultivar to tolerant unusually high concentration of B. The brittle stem symptom of B deficiency in T3238 due to the failure of absorbed

B to move from root to top of plants when grown in nutrient solution with ranged of B (10, 50, 100, 500, 1000 and 5000 μM). Then, the concentration of B in leaves of T3238 cultivar have much lower than the normal Rutgers cultivar. It has been reported that B accumulated to toxic levels in the old leaves of plants cannot be redistributed to the young leaves fast enough to prevent from the developing of B deficiency after transferred in to B-free nutrient solution. Boron appeared to behave like Ca in which the efficiency of use by plant varied in a striking way under developed-deficiency condition (Brandenburg cited by Loneragan, 1976). In maize, Oh43 grew better and developed fewer Ca deficiency or toxicity symptoms and produced more dry weight when grown in low and high levels of calcium (Ca). At the same amount of dry weight, Oh43 (Ca-efficient) required about one-fourth the amount of Ca in solution that of A251 (Ca-inefficient) did (Clark, 1976).

Since maize is cultivated in Thailand and widely in the world, also is extended to new area or replaced by cash crops. There will be a need to produce in area where manipulation of fertility levels will be less feasible than it has been in the developed sections. Information on the physiological and morphological responses to B conditions (low B and supply B) for maize, may be a valuable tool for use in plant selection in breeding programs or to improve the cultural practices for growing area with low B in soils. The objectives of the present study were: 1) to determine the response of maize to B level during vegetative and reproductive growth, 2) evaluate genotypic variability in response to B deficiency, and 3) to identify likely B efficiency mechanism(s) for management and breeding of maize in the future.