Europ. J. Agronomy 80 (2016) 137–153

Contents lists available at ScienceDirect

European Journal of Agronomy

journal homepage: www.elsevier.com/locate/eja

Dynamic change of mineral nutrient content in different plant organs during the grain filling stage in maize grown under contrasting nitrogen supply

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ARTICLE INFO

Article history:
Received 28 June 2015
Received in revised form 10 July 2016
Accepted 1 August 2016

Keywords:
Grain nutrient concentration
Low nitrogen
Maize
Mineral nutrient
Remobilization
Vegetative organs

ABSTRACT

The introduction of new hybrids and integrated crop-soil management has been causing maize grain yield to increase. However, less attention has been paid on the nutrient concentration of the grain; this aspect is of great importance to supplying calories and nutrients in the diets of both humans and animals worldwide. Increasing the retranslocation of nutrients from vegetative organs to grain can effectively increase the nutrient concentration of grain and general nutrient use efficiency. The present study involved monitoring the dynamic change of macro- and micronutrients in different organs of maize during the grain filling stage. In addition, the mobility of different elements and their contribution to grain nutrient content were evaluated in a 2-year experiment under low (LN, no N supplied) and high N (HN, 180 kg N ha^{-1}) supply. Under HN supply, the net remobilization efficiency (*RE*) of the vegetative organs as a whole (calculated as nutrient remobilization amount divided by nutrient content at silking) of N, P, K, Mn, and Zn were 44%, 60%, 13%, 15%, and 25%, respectively. The other nutrients (Mg, Ca, Fe, Cu, and B) showed a net accumulation in the vegetative organs as a whole during the grain filling stage. Among the different organs, N, P, and Zn were remobilized more from the leaves (*RE* of 44%, 51% and 43%, respectively) and the stalks (including leaf sheaths and tassels) (*RE* of 48%, 71% and 43%, respectively). K was mainly remobilized from the leaves with *RE* of 51%. Mg, Ca, Fe, Mn, and Cu were mostly remobilized from the stalks with the *RE* of 23%, 9%, 10%, 42%, and 28%, respectively. However, most of the remobilized Mg, Ca, Fe, Mn, Cu, and Zn were translocated to the husk and cob, which seemingly served as the buffer sink for these nutrients. The *RE*s of all the nutrients except for P, K, and Zn were vulnerable to variations in conditions annually and were reduced when the grain yield and harvest index were lower in 2014 compared with 2013. Under LN stress, the *RE* was reduced in P and Zn in 2013, increased in Cu and unchanged in other nutrients. The concentration of these nutrients in the grain was either unchanged (P, K, Ca, Zn, and B) or decreased (N, Mg, Fe, Mn, and Cu). It is concluded that grain N, P, K, Mn, and Zn, but not Mg, Ca, Fe, Cu, and B concentration, can be improved by increasing their remobilization from vegetative organs. However, enhancing the senescence of maize plant via LN stress seems unable to increase grain mineral nutrient concentration. Genetic improvement aiming to increase nutrient remobilization should take into account the organ-specific remobilization pattern of the target nutrient.

1. Introduction

As a valuable staple food worldwide, maize provides proteins, carbohydrates, and minerals for human beings and animals. During the past several decades, maize breeding has resulted in dramatically increased yield while grain protein and mineral nutrient concentrations have decreased (Duvick and Cassman, 1999; Anandan et al., 2011; Chen et al., 2013). The nutritional value of food is of great importance to human and animal health (Grusak and DellaPenna, 1999). For example, Fe and Zn deficiencies can cause impairments of the immune system and increases in anemia (Cakmak et al., 2004). In addition, the concentration of the nutrients in maize seed greatly affects the ability of a seedling to tolerate various biotic (such as diseases) and abiotic stresses (such as mineral nutrient deficiency) (Masclaux-Daubresse et al., 2010). Thus, the

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http://dx.doi.org/10.1016/j.eja.2016.08.002

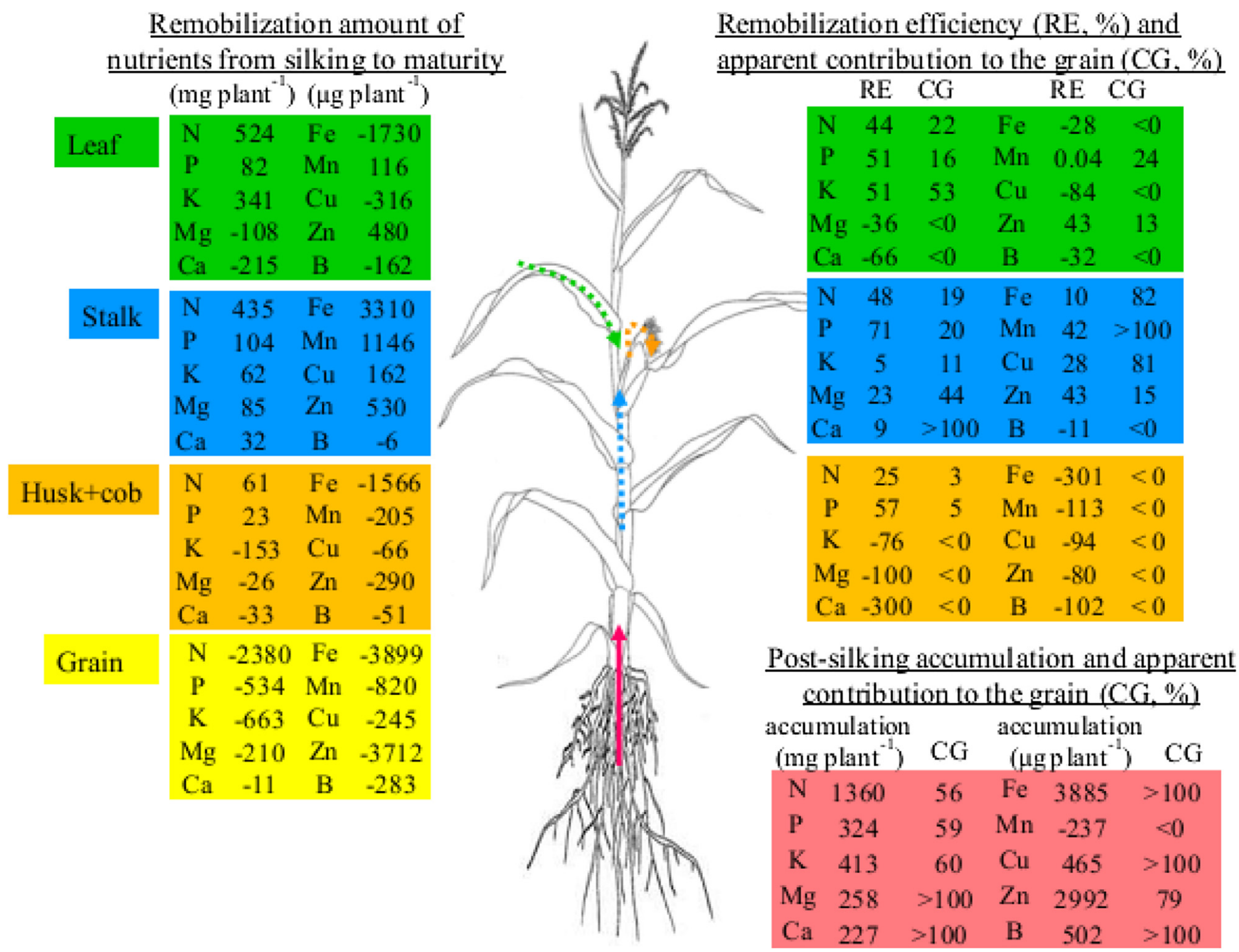

Fig. 1. Remobilization of mineral nutrients from different organs and the related post-silking accumulation as well as nutrient contribution to grain nutrient content. RE: remobilization efficiency; CG: apparent contribution to grain nutrient content. Data are the average of applied nitrogen (HN) treatment in 2013 and 2014. Negative values indicate net accumulation of the indicated nutrient in the indicated organ.

primary target for genetic improvement is increasing the mineral nutrient concentration of maize grain.

Nutrients in maize grain are derived from post-silking uptake and the remobilization of nutrients accumulated in vegetative organs during the pre-silking stage (Hirel et al., 2007). While post-silking nutrient uptake depends on soil nutrient availability and may require additional nutrient input, increasing nutrient remobilization from vegetative organs can make the best use of nutrients already in the plant to increase grain nutrient content, and thus increase nutrient use efficiency (Masclaux-Daubresse et al., 2008, 2010). In addition, the capacity of maize to redirect nutrients from vegetative organs to grain would be even more important when nutrient uptake is severely restricted during the grain filling stage because of biotic and/or abiotic stresses (Marschner, 1993). In maize, 25–82% of grain N is derived from the remobilization of vegetative N accumulated before silking (Ta and Weiland, 1992; Ma et al., 1998; Mi et al., 2003; Lemaire and Gastal, 2009; Chen et al., 2014). The contributions of vegetative P and K to the grain are 1–75% and 45–447%, respectively (calculated from the results of Ning et al., 2013). In contrast, the contribution to grain from the remobilization of most micronutrients such as Fe, Mn, Cu, and B seems very low (Karlen et al., 1988; Brown and Shelp, 1997; Bender et al., 2013). The remobilization efficiency (*RE*) may be different among different vegetative organs. For example, Chen et al. (2014) found that the *RE*s of N in the stalks and leaves were 49–55% and 65–70%, respectively. P and K were also remobilized more intensely from the leaves than from the stalks (Shi, 2010; Ning et al., 2013). Mg and Ca were remobilized only from old leaves, while Fe, Mn, and Zn were only remobilized from stalks under high N supply (Grzebisz et al., 2008; Shi, 2010; Bender et al., 2013). Less information is available about whether the remobilized nutrients from various organs are directly translocated into the grain or have been redistributed into other organs.

Nitrogen nutrition plays an essential role in plant senescence, and therefore may greatly affect the remobilization of various nutrients from vegetative organs. Low-N stress may increase, or does not have an effect on the remobilization of N from vegetative organs (Ta and Weiland, 1992; Mi et al., 2003; Chen et al., 2014), but reduces the redistribution of P from vegetative parts into the grain (Venekamp et al., 1986). The transport of many metal ions (Fe, Mn, Cu, and Zn) depends greatly on chelates such as organic acids, nicotianamine, and mugineic acids etc. (Marschner, 1995; Curie et al., 2009; Sperotto et al., 2012). Nitrogen deficiency may possibly affect the remobilization of these elements by regulating the synthesis of the nitrogenous chelates.

Few studies have investigated the remobilization characteristics of all mineral nutrients simultaneously. Further, the analysis of nutrient remobilization has been largely focused on the net change of the nutrients in vegetative organs as a whole between silking and maturity. However, the net change of the content of a nutrient in the vegetative organs as a whole may mask the behavior of that nutrient in different organs. A nutrient remobilized from an