INTRODUCTION

Micronutrients, such as metals, are essentials for cell functions. Zinc (Zn), which exists only as divalent cation, plays an important role in protein structure and function thanks to its Lewis acids properties. Transition metals such as iron (Fe), copper (Cu), or manganese (Mn), which have unpaired electrons that promote their involvement in redox-reduction reactions, are used in a wealth of biological processes (Pierre and Fontevre, 1999). A third of the proteins characterized at the structural level are metalloproteins, highlighting the need of metals for cell functions (Finney and O’Halloran, 2003).

In plants, transition metal functions are mainly associated to energy production mechanisms, thereby about 80% of Fe in mesophyll cell is localized in chloroplasts (Nouet et al., 2011). Fe is essential for chlorophyll synthesis, nitrogen fixation, DNA replication, reactive oxygen species (ROS) detoxification, and electron transport chain in both mitochondria and chloroplasts (Nouet et al., 2011; Yruela, 2013). Mn plays a central role in the photosystem II (PS II) where it catalyzes water oxidation (Trommsdorff et al., 1998). This element is also involved in sugar metabolism, Mn-superoxide dismutase (SOD), and chloroplastic enzymes such as decarboxylases and dehydrogenases (Lu and Culeotta, 2001; Horsburgh et al., 2002; Agarwal et al., 2012). Cu is integrated into plastocyanines involved in electron transfer of chloroplasts (Yruela, 2013). It plays also an essential role in the cytochrome c oxidase of mitochondria (Blackley and Macgillivray, 2011). Zn is required for carbon fixation through the carbonic anhydrase (Badger and Price, 1994). It is also needed for the Cu/Zn-SOD, transcriptional regulation by zinc-finger DNA binding proteins and for the turnover of PSII in chloroplasts (Kurrepa et al., 1997; Blackley and Macgillivray, 2011; Lu et al., 2011). Therefore, plants need metals to achieve vital functions in all their organs.

Among all plant organs, seed is a special one because it has to store metals required for germination and during the first days of seedling development. Hence in annual plants, seed formation is a crucial step in which plant sacrifices itself to store nutrients for its offspring. Seed filling depends on nutrient originating from de novo uptake by roots or remobilization from senescent organs.

Here, we review genes and processes involved in metal remobilization during seed filling. We will discuss methodologies that can be used to study metal fluxes in plants and thereby determine the relative contribution of uptake and remobilization pathways. Autophagy is a ubiquitous process involved in cellular nutrient recycling. Because it was recently shown to play a critical role in nitrogen remobilization (Htwe et al., 2011; Guiboileau et al., 2014), this review focuses on autophagy as a potential mechanism to make metal available for subsequent remobilization during senescence.

ORIGIN OF SEED METALS: UPTAKE FROM SOIL VS REMOBILIZATION FROM SENESCENT TISSUES

CIRCULATION OF METALS INTO THE PLANT AND MICRONUTRIENT USE EFFICIENCY

Understanding metal seed filling requires knowledge on the general micronutrient pathways which was already summarized in several recent reviews (Pittman, 2005; Palmgren et al., 2008; Morrissey and Guerinot, 2009; Puig and Penarrubia, 2009; Yruela, 2013). Among all plant organs, seed is a special one because it has to store metals required for germination and during the first days of seedling development. Hence in annual plants, seed formation is a crucial step in which plant sacrifices itself to store nutrients for its offspring. Seed filling depends on nutrient originating from de novo uptake by roots or remobilization from senescent organs.

Here, we review genes and processes involved in metal remobilization during seed filling. We will discuss methodologies that can be used to study metal fluxes in plants and thereby determine the relative contribution of uptake and remobilization pathways. Autophagy is a ubiquitous process involved in cellular nutrient recycling. Because it was recently shown to play a critical role in nitrogen remobilization (Htwe et al., 2011; Guiboileau et al., 2014), this review focuses on autophagy as a potential mechanism to make metal available for subsequent remobilization during senescence.

Keywords: transition metal, isotopic labeling, nutrient use efficiency, leaf senescence, nutrient fluxes, autophagy, Fe, Zn
On the whole, both uptake from soil and remobilization from senescent organs may participate in metal loading in seeds (Figure 1). To date, little is known about the contribution of metal remobilization from senescent organs to seed filling. In contrast, this topic is well documented regarding nitrogen. It was shown that uptake and fixation of nitrogen dramatically decrease at the onset of reproductive stage in cereals, oilseed rape and legumes (Salon et al., 2011). Accordingly, 50 to 90% of nitrogen grain of rice, wheat, or maize originate from leaf remobilization (Masclaux-Daubresse et al., 2001). This highlights that the importance of nitrogen remobilization for seed filling is conserved in most plants. However, some species, such as oilseed rape, have a low nitrogen remobilization capacity resulting in low nitrogen use efficiency (Schoeiring et al., 1995; Etienne et al., 2007).

As for nitrogen, it is necessary to better understand metal remobilization from senescent organs during seed filling with the aim to increase micronutrient use efficiency in the context of intensive agriculture, fertilization limitations, and biofortification. This is especially important as metal availability may become limiting under certain environmental conditions (drought, low temperature) and soil characteristics (low metal content, high salt content, ionic imbalance, low pH, high bicarbonate concentration; Chen and Barak, 1982; Karamanos et al., 1986; Graham, 1988; Alloway, 2009).

**METHODOLOGIES TO DETERMINE NUTRIENT FLUX**

The most common way to study nutrient fluxes within the plant is to determine the "apparent remobilization" which consists in the measurement of the total amount of element of interest present in different plant organs at different times (Masclaux-Daubresse et al., 2010). However, this approach does not provide sufficient resolution and does not allow distinguishing nutrients coming from different pathways, such as nutrient uptake from soil and nutrient remobilization from senescent leaves.

The most appropriate approach to study short-term accumulation, uptake from soil and fluxes between tissues is the use of isotopes as tracers. Isotopic labeling can be implemented with different protocols (Gruisak, 1994; Wu et al., 2010; Erenoglu et al., 2011; Heghland et al., 2012).

Metal fluxes may be monitored by pulse-chase labeling using radioactive or stable isotopes. The 32P, 65Zn, and 64Zn radioisotopes have been used for pulse labeling on specific organs followed by a chase period to facilitate the identification of source organs contributing to seed filling in peas, wheat and rice (Gruisak, 1994; Wu et al., 2010; Erenoglu et al., 2011; Zheng et al., 2012). Following this approach, it was demonstrated that nutrient supply can affect Zn remobilization in wheat (Erenoglu et al., 2011). In rice, differences in Zn remobilization efficiency between genotypes were observed using isotopic pulse-chase on specific organs (Wu et al., 2010).

Recently, pulse labeling using very short life 86Cu radioisotope like 54Fe, 65Mn, and 64Zn has been used to image metal fluxes within a plant via a real-time and non-destructive technique called Positron-Emitting Tracer Imaging System (Kume et al., 1997; Tsukamoto et al., 2006; Tsukamoto et al., 2009). Non-radioactive isotopes have been used for pulse labeling on specific organs. Application of 65Cu to one individual leaf of rice allowed to study Cu redistribution between the different leaves during vegetative stage (Zheng et al., 2012). Non-radioactive isotopes can be also added in the nutrient solution for labeling plants early during development in order to monitor nutrient movement during vegetative stages or later at reproductive stage to study remobilization and seed filling. Using Zn isotopes, this pulse-chase approach has been used to quantify the effect of nutrient limitation on Zn fluxes between organs in rice and wheat (Wu et al., 2010; Erenoglu et al., 2011). Moreover, 65Zn pulse-chase labeling combined with laser ablation-inductively coupled plasma-mass spectrometry has provided a spatial distribution of Zn within wheat seeds revealing zinc transport barriers during grain filling in wheat (Wang et al., 2010).

Long term labeling in nutrient solution may be performed to address the contribution of uptake from soil to organs during a specific developmental stage, with respect to the contribution of endogenous remobilization. Continuous application of 64Zn provided evidence that Zn uptake before anthesis contributes to...
more than 50% to the total Zn grain content in rice (Wu et al., 2010). Shorter continuous labeling can also be used to determine the uptake capacity by measuring isotopic accumulation in roots (Heggelund et al., 2012) or isotope depletion in the nutrient solution (Erenoglu et al., 2011).

Isotopic labeling is an essential tool to study metal fluxes within the plant but require the availability of enriched isotopes and adequate analytical tools. Initially, isotopic labeling was mainly performed using radioactive isotopese despite the risk for humans. Nowadays, enriched stable isotopes are more and more accessible at least for Fe, Ni, Cu, Zn, and Mo. They represent a healthier and less restrictive alternative but their analysis requires the use of mass spectrometry, such as inductively coupled plasma-mass spectrometry.

THE COUPLING BETWEEN SENERSCENCE AND MICRONUTRIENT REMOBILIZATION

CONTROL OF SENESCENCE AND REMOBILIZATION AT THE WHOLE PLANT LEVEL

Senescence is an active process controlled by age whereby sink tissues performing photosynthesis and anabolism become source tissues undergoing catabolism (Figure 2). Senescence makes nutrients available for further plant organs (Hörtensteiner and Feller, 2002), contributing to nutrient use efficiency. Optimal remobilization requires close synchronization between sink formation and source organ senescence (Figure 1). It was observed that the removal of sink tissues delays senescence in oilseed rape, soybean and wheat and decrease nitrogen remobilization in oilseed rape and soybean (Patterson and Brun, 1980; Crafts-Brandner et al., 1999). Pigment degradation directly takes place in chloroplasts (Patterson and Brun, 1980; Crafts-Brandner and Ehl, 1987; Noquet et al., 2004; Htwe et al., 2011). However, senescence and remobilization are also controlled by other parameters such as nutrient availability (Figure 1). In Arabidopsis, nitrogen limitation triggers leaf senescence (Lemaitre et al., 2008).

In wheat, remobilization of Fe and Zn from flag leaves to seeds is increased under nutrient-limiting conditions (Waters et al., 2009; Wu et al., 2010; S perpetr oto et al., 2012b). Conversely continuous nutrient uptake during seed formation may account for low nutrient remobilization in some species (Masclaux-Daubresse and Chardon, 2011; Waters and Sankaran, 2011). However, an opposite behavior was observed in barley plants for which remobilization increased upon high Zn supply. This illustrates the diversity of Zn management at the whole plant level (Heggelund et al., 2012). Moreover, other abiotic and biotic stresses such as pathogen attack, high salinity, drought, low temperature, modifications of light intensity, and quality can also cause premature senescence and remobilization (Nooden et al., 1996; Buchanan-Wollaston, 1997; Gan and Amasino, 1997). Because they are sessile, plants developed high plasticity to respond to environment conditions, triggering cell death and remobilization in order to save nutrients and produce more adapted organs and tissues.

CONTROL OF SENESCENCE AND REMOBILIZATION AT THE MOLECULAR LEVEL

Transcript analysis, comparing green and senescing leaves, led to the identification of senescence-associated genes (SAG) in different species (Hensel et al., 1993; Buchanan-Wollaston, 1994; Smart et al., 1995; Guo et al., 2004; Buchanan-Wollaston et al., 2005; van der Graaff et al., 2006; Breeze et al., 2011). Irreversibly, the expression of genes encoding cysteine proteases is strongly induced in senescent leaves (Hensel et al., 1993; Smart et al., 1995; Bhale raon et al., 2003; Andersson et al., 2004; Guo et al., 2004; Park et al., 2007). However, stromal proteins are degraded into the central vacuole through rubisco containing body (RCB) autophagosome or into senescence-associated vacuoles (SAV) through an ATG-independent route which is not well understood yet (Hörtensteiner and Feller, 2002; Ishida et al., 2006; Ishida et al., 2007). These dismantling mechanisms decrease chloroplast seize enabling whole chloroplast degradation via chlorophagy (Ishida et al., 2007). Peroxisomes are modified to glyoxysomes, which produce energy and soluble sugars from lipid catabolism (Buchanan-Wollaston, 1997; del Rio et al., 1998). Mitochondria that remain intact until late after senescence onset are in turn degraded when the energy demand decreases (Ishida, 2003). Finally, membrane permeabilization causes loss of cytosome that finally leads to death. ROS, reactive oxygen species; SAV, senescence-associated vacuoles; RCB, rubisco containing body; N, nucleus.
et al., 2004; Breeze et al., 2011). As expected, these analyses confirmed induction of genes involved in hormonal pathways (Andersson et al., 2004; van der Graaff et al., 2006; Breeze et al., 2011). Indeed, senescence is regulated by the balance between senescence promoting hormones, namely jasmonic acid, abscisic acid, salicylic acid, and ethylene, and senescence repressing hormones such as cytokinins, auxins, and gibberellins (van der Graaff et al., 2006). As hormones, sugars are known to act as signaling molecules and several lines of evidence indicate that they also contribute to senescence regulation. Sugar concentrations rise in senescent leaves. Moreover, overexpression of hexokinase, a sugar sensor, accelerates senescence whereas antisense expression delays senescence in Arabidopsis (Nooden et al., 1997; Masclaux et al., 2000; Xiao et al., 2000; Watanel et al., 2013).

Genes coding metal ion binding proteins such as metallothioneins, ferritins, zinc-finger proteins, metalloproteases (Fts) and metal transporters were also frequently found to be upregulated in senescent leaves (Buchanan-Wollaston, 1994; Bhalerao et al., 2005; Andersson et al., 2004; Guo et al., 2004; Zelisko et al., 2005). This may illustrate the involvement of metals in degradation mechanisms and/or the importance of their remobilization (Breeze et al., 2011). Furthermore, these transcriptomic analyses highlighted the significant induction of autophagy related genes (ATG genes) and genes encoding NAC and WRKY transcription factors (Andersson et al., 2004; Guo et al., 2004; van der Graaff et al., 2006; Breeze et al., 2011). Whereas NAC have already been demonstrated to be involved in micronutrient remobilization during senescence (Olmos et al., 2003; Guo and Gan, 2006; Uasy et al., 2006; Sperotto et al., 2009, 2010; Waters et al., 2009), nothing is known about the implication of ATG genes in this process.

**ROLE OF AUTOPHAGY IN NUTRIENT RECYCLING AND REMOBILIZATION**

**INVOLEMENT OF AUTOPHAGY IN NUTRIENT RECYCLING**

Autophagy catalyzes cytoplasmic components that are no longer useful. It eliminates aberrant proteins and damaged organelles for the maintenance of essential cellular function by vacuole internalization mediated by double membrane vesicles called autophagosomes (Yoshimoto, 2012). Genes involved in autophagy (ATG) were first defined by a genetic screen in yeast (Matsumoto et al., 1997), thereby molecular mechanisms have been well described on this organism (for reviews see Thompson and Vierstra, 2005). Most of these genes turned out to have conserved functions in all eukaryotic cells. They encode proteins involved in the induction of autophagy, membrane delivery for autophagosome formation, nucleation, expansion, and enclosure of autophagosomes (Thompson and Vierstra, 2005).

Autophagy can be triggered upon nutrient starvation and stress leading to intracellular remodeling, which allows plants to respond to environmental constraints (Yoshimoto, 2012). Accordingly, mutants impaired in ATG genes exhibit decreased growth associated with premature senescence when they develop under carbon or nitrogen starvation (Doelling et al., 2002; Hanaoka et al., 2002; Yoshimoto et al., 2004; Phillips et al., 2008; Chung et al., 2010; Suttangkakul et al., 2011). Plants defective in autophagy are thus unable to cope with nutrient starvation suggesting that autophagy is an important mechanism for nutrient use efficiency and cellular homeostasis.

**AUTOPHAGY CONTROLS NUTRIENT REMOBILIZATION DURING SENESCENCE**

During senescence, cytoplasmic components such as organelles are gradually dismantled and degraded. Autophagy is an essential degradation process for nutrient recycling and remobilization. Accordingly, up-regulation of ATG genes is observed during leaf senescence in Arabidopsis (Doelling et al., 2002; van der Graaff et al., 2006; Chung et al., 2010; Breeze et al., 2011) and the decrease of chloroplast number and chloroplast size during senescence is affected in Arabidopsis atg4a-b1 mutant (Wada et al., 2009).

Because of its key role in the degradation of cellular components during nutrient recycling and its up-regulation and involvement during senescence, it was hypothesized that autophagy could play a role in nutrient remobilization. During senescence, autophagy was shown to be involved in the degradation of chloroplasts and specifically of RuBisCO which is the most abundant leaf protein containing about 80% of the cellular nitrogen (Figure 2; Chiba et al., 2003; Ishida et al., 2008; Wada et al., 2009; Gaiboia et al., 2012; Ishida et al., 2013). In addition, pulse-chase experiments in which 15N labeling was applied in nutrient solution during vegetative stage revealed a significant decrease of nitrogen remobilization from vegetative tissues to seeds in atg mutants. These results demonstrated that autophagy is required for nitrogen remobilization and seed filling (Gaiboia et al., 2012).

Chloroplast is the organelle where metals are most intensively used. Thereby about 80% of the cellular Fe is localized in chloroplasts (Nouret et al., 2011). Because autophagy is involved in the degradation of organelles, including chloroplasts, the role of autophagy in metal recycling in source tissues for remobilization to the seeds has to be considered. In plants, autophagy leads to the degradation of autophagosome cargo within the vacuole. Hence, tonoplast metal efflux transporters are needed to retrieve metals from the vacuole. Interestingly, transcriptomic analyses that highlight autophagy induction during senescence in Arabidopsis leaf also show specific up-regulation of NRAMP3, a gene encoding a transporter involved in metal mobilization from vacuoles (Thomine et al., 2003; Lanquar et al., 2005, 2010; Breeze et al., 2011). Availability of metals in source tissues may therefore also be dependent on autophagy and subsequent mobilization from vacuole during senescence.

**REMOBILIZATION AND AUTOPHAGY IN THE CONTEXT OF BIOFORTIFICATION**

**BIOFORTIFICATION TO IMPROVE HUMAN DIET**

Key micronutrients are often not sufficiently available in human diet (Kennedy et al., 2003). Over 60% of the world population are Fe deficient and over 30% are Zn deficient (White and Broady, 2009). Staple food crops such as cereal grains are poor sources of some mineral nutrients, including Fe and Zn. Thus, the importance of cereals in human diet accounts
Another option to increase seed micronutrient content could be to introduce transgenes conferring strong sink strength in seeds, high metal translocation and enhancing phloem unloading during seed maturation, it was possible to increase Fe concentration by 4.4 in rice seeds (Masuda et al., 2012).

**ACKNOWLEDGMENTS**

The authors thank Dr Sylvain Merlot and Sara Martins for critical reading of the manuscript. This work was supported by grants from Région Ile-de-France. Research in the CMD and ST laboratories is supported by INRA and CNRS funding and grants from the Agence Nationale de la Recherche (ANR 2011 BSV6 004 01).

**REFERENCES**

Aggarwal, A., Sharma, I., Tiwari, B. N., Murajik, A. K., Bhandari, M., and Sharma, V. (2012). “Metal toxicity and phytochelatins,” in Plant Biotechnology: Overview on Recent Progress and Future Perspectives, eds S. Bish, P. Maley, and K. N. Garapoud (New Delhi: III International Publishing House Pvt Limited).

Allsopp, B. J. (2009). Soil factors associated with zinc deficiency in crops and humans. Environ. Geochem. Health 31, 537–548. doi: 10.1007/s10655-009-9255-4

Andersson, A., Kokkelak, I., Sydän, S., Blähers, R., Sterley, F., Wissel, K., et al. (2004). A transcriptional timetable of autumn senescence. Genome Biol. 5, R24. doi: 10.1186/gb-2004-5-4-r24

Badger, M. K., and Price, G. D. (1994). The role of carbonic anhydrase in photosynthesis. Annu. Rev. Plant Biol. 45, 369–392. doi: 10.1146/annurev.arplant.45.1.369

Bleackley, M. R., and Macgillivray, R. T. A. (2011). Transition metal homeostasis: from yeast to human disease. Biochem. J. 434, 785–809. doi: 10.1042/BJ20101122

Bleda, M. R., and Maugard, R. T. A. (2011). Transition metal homeostasis: from yeast to human disease. Biochem. J. 434, 785–809. doi: 10.1042/BJ20101122

Boschap, D. C. (2007). Plant autophagy more than a starvation response. Curr. Opin. Plant Biol. 10, 587–593. doi: 10.1016/j.pbi.2007.06.006

Bhalerao, R., Kokkelak, I., Sterley, F., Erdmann, B., Broydulka, H., Birve, S. I., et al. (2005). Gene expression in autumn leaves. Plant Physiol. 135, 830–842. doi: 10.1104/pp.105.064475

Buchanan-Wollaston, V. (1994). Isolation of cDNA clones for genes that are differentially expressed during senescence in Arabidopsis. Plant Physiol. 105, 829–846. doi: 10.1104/pp.105.5.829

Buchanan-Wollaston, V. (1997). The molecular biology of leaf senescence. J. Exp. Bot. 48, 131–139. doi: 10.1016/j.ydbio.2011.01.012

Buchanan-Wollaston, V., Page, T., Harrison, E., Broum, E., Lim, O. P., Nau, H. G., et al. (2003). Comparative transcriptome analysis reveals significant differences in gene expression and signaling pathways between development and dark illuminated induced senescence in Arabidopsis. Plant J. 34, 587–595. doi: 10.1046/j.1365-313X.2003.02596.x

Chen, Y., and Barak, F. (2002). Iron nutrition of plants in calcareous soils. Adv. Agron. 75, 217–240. doi: 10.1198/006521105X56225

Chiba, A., Ishida, H., Nakamura, N. K., Makino, A., and Mac, T. (2003). Exclusion of ribulose-1,5-bisphosphate carboxylase/oxygenase from chloroplasts by specific bodies in naturally senescing leaves of wheat. Plant Cell Physiol. 44, 814–821. doi: 10.1093/pcp/pcw018

Chung, T., Phillips, A. B., and Vissera, R. D. (2010). ATP7B and ATP8-mediated autophagy in Arabidopsis require ATPG21 expressed from the differentially controlled ATPG12A AND ATPG12B loci. Plant J. 62, 483–493. doi: 10.1111/j.1365-313X.2010.04166.x

Crasto-Brandsen, S. J., and Eijl, D. B. (1987). Sink removal and leaf senescence in sorghum: cultivar effects. Plant Physiol. 85, 662–666. doi: 10.1104/pp.85.3.662

Da Silva, I. A., Paterns, G. M., Palms, J. M., Sandal, L., and Cleva, C. J. (2008). The activated oxygen role of peroxisomes in senescence. Plant Physiol. 146, 1195–1203. doi: 10.1104/pp.107.11395

Diaz-Troya, S., Pérez-Pérez, M. F., Remon, F. J., and Crespo, J. L. (2008). The role of TOR in autophagy regulation from yeast to plants and mammals. Autophagy 4, 861–865.

Dordjevic, J., Helfenwerth, J. M., Riederl, E. M., Thompson, A. B., and Visser, R. D. (2002). The ATP13A2-activating enzyme APG7 is required for proper nutrient recycling and senescence in Arabidopsis thaliana. J. Biol. Chem. 277, 33105–33114. doi: 10.1074/jbc.M204902020

Enomoto, K., Ueno, K., Uchida, Y., Yada, H., and Numakuma, S. (2011). Improved nitrogen nutrition enhances root uptake, root-to-shoot translocation and remobilization of zinc (65Zn) in wheat. New Phytol. 190, 438–448. doi: 10.1111/j.1469-8137.2010.04488.x

Funke, F., Doole, M., Le Gos, L., Gombert, J., Boomsma, J., Maurel, K., et al. (2007). N protein mobilisation associated with leaf senescence process in oilseed rape is consonant with the disappearance of trypan inhibitor activity. Front. Plant Sci. 8, 893–900. doi: 10.1074/ f100188
Kennedy, G., Nantel, G., and Shetty, P. (2003). The scourge of "hidden hunger":

Karamanos, R. E., Kruger, G. A., and Stewart, J. W. B. (1986). Copper deficiency in

Kamada, Y., Funakoshi, T., Shintani, T., Nagano, K., Ohsumi, M., and Ohsumi, Nooden, L. D., Guiamet, J. J., and John, I. (1997). Senescence mechanisms.

Grusak, M. A. (1994). Iron transport to developing ovules of

Graham R. D. (1988). “Genotypic diferences in tolerance to manganese deficiency, ”

Guiboileau, A., Yoshimoto, K., Soulay, F., Bataillé, M.-P., Avice, J.-C., et al. (2012). Autophagy machinery controls nitrogen remobilization at the whole-plant level under both limiting and ample nitrogen conditions in Arabidopsis. New Phytol. 194, 752–760. doi: 10.1111/j.1469-8137.2012.04084.x

Guo, C., Zai, C., and Gan, S. (2004). Transcriptomes of Arabidopsis leaf senescence: Plant Cell Environ. 27, 521–537. doi: 10.1111/j.1365-3040.2003.01156.x

Guo, Y., and Gan, S. (2006). ANAP, a NAC family transcription factor, has an important role in leaf senescence. Plant J. 46, 601–612. doi: 10.1111/j.1365-313X.2006.02073.x

Hanaoka, H., Noda, T., Shirano, Y., Kato, T., Hayashi, H., Shibata, D., et al. (2002). Leaf senescence and starvation-induced chlorosis are accelerated by the disruption of an Arabidopsis autophagy gene. Plant Cell 129, 1105–1119. doi: 10.1105/tpc.010754

Hegelund, J. N., Polej, P., Hamel, S., Schleh, M., and Schiering, J. K. (2012). Zinc fluxes into developing barley grain: use of stable Zn isotopes to separate root uptake from remobilization in plants with contrasting Zn status. Plant Soil 361, 241–258. doi: 10.1007/s11104-011-1272-x

Hosokawa, H., Sato, M., Baumgartner, D. A., and Bocek, A. (1995). Developmental and age-related processes that influence the longevity and senescence of photosynthetic tissues in Arabidopsis. Plant Cell 7, 553–564. doi: 10.1105/tpc.011024

Hörtensteiner, S., and Feller, U. (2002). Nitrogen metabolism and remobilization under both limiting and ample nitrate conditions in

Htwe, N. M. P. S., Yuasa, T., Ishibashi, Y., Tanigawa, H., Okuda, M., Zheng, S.-X. et al. (2006). Leaf senescence and starvation-induced chlorosis are accelerated by the dis-

Hsiao, R. L. C., Yeung, K. P., Fang, M. J., and Clouse, D. W. (2012). Iron import characteristics and phloem iron-loading capacity of source regions in

Huang, C. (2009). Enzymatic and metabolic diagnostic of nitrogen deficiency in

Huang, Q. Y., Zheng, J., Zhang, L., Li, L., and Zhang, S. (2008). Characterization of the sink/source transition in tobacco (Nicotiana tabacum L.) shoots in relation to nitrogen management and leaf senescence. Plant Physiol. 148, 510–519. doi: 10.1104/pp.108.120000510

Huang, W., Ishimaru, Y., Jung, M. S., Kobayashi, T., Kakei, Y., Dakekawa, M., et al. (2012). Iron biofortification in rice by the introduction of multiple genes involved in iron nutrition. Sci. Rep. 2, 543. doi: 10.1038/srep00543

Imamura, A., Tsukada, M., Wada, T., and Ohsumi, Y. (1997). Autophagic system in plants: an emerging concept. Autophagy 4, 141–147. doi: 10.1625/aut.4.141

Ishikawa, H., Izumi, M., Woda, S., and Makino, A. (2013). Roles of autophagy in chloroplast recycling. Biochem. Biophys. Acta 1828, 674–682. doi: 10.1016/j.bbadis.2013.08.009

Ishikawa, H., Yoshimoto, K., Izumi, M., Resen, D., Yano, M., and Makino, A. (2008). Mobilization of rubisco and atpase localized fluorescent proteins of chloroplast to the vacuole by an ATG gene-dependent autophagic process. Plant Cell Physiol. 49, 142–155. doi: 10.1093/pcp/pcn127

Iuliano, B. (1995). Rice to Human Nutrition. Rome: International Rice Research Institute & FAO.

Iwadomi, T., Shintani, T., Nagano, K., Ohsumi, M., and Ohsumi, Y. (2000). Time-mated induction of autophagy via an Atg protein kinase complex. J. Cell Biol. 150, 1307–1315. doi: 10.1083/jcb.150.6.1307

Karamanos, R. E., Kruger, G. A., and Stewart, J. W. B. (1986). Copper deficiency in cereal and oilseed crops in northern Canadian prairie soils. Agron. J. 78, 317–323. doi: 10.2134/agronj1986.00021962007800020021x

Kawano, T., Matsuoka, S., Shemara, M., Ito, H., Fujimura, T., Aishi, K., et al. (1997). Uptake and transport of pyrethrin-smearing tracer (18 F) in plants. Appl. Radiat. Isot. 46, 1005–1014. doi: 10.1016/0969-8043(97)00117-6

Kerepesi, I., Herzeit, D., van Montagu, M., and Inze, D. (1997). Differential expres-

Kern, T., Matsushita, S., Shemara, M., Ito, H., Fujimura, T., Aishi, K., et al. (1997). Uptake and transport of pyrethrin-smearing tracer (18 F) in plants. Appl. Radiat. Isot. 46, 1005–1014. doi: 10.1016/0969-8043(97)00117-6

Kennedy, G., Nantel, G., and Shetty, P. (2003). The scourge of “hidden hunger”:
Autophagy and metal remobilization in leaves

Yoshimoto, K. (2012). Beginning to understand autophagy, an intracellular self-degradation system in plants. Plant Cell Physiol. 53, 1355–1365. doi: 10.1093/pcp/pcs099

Yoshimoto, K., Hanaoka, H., Sato, S., Kato, T., Tabita, S., Noda, T., et al. (2004). Processing of ATG8s, ubiquitin-like proteins, and their degradation by ATG4s are essential for plant autophagy. Plant Cell 16, 2967–2983. doi: 10.1105/tpc.104.025595

Yoshimoto, K., Ishimaru, Y., Kamiya, Y., Kasuno, M., Genornoi, C., Pantrenga, R., et al. (2009). Autophagy negatively regulates cell death by controlling NFR1-dependent salicylic acid signaling during senescence and the innate immune response in Arabidopsis. Plant Cell 21, 2914–2927. doi: 10.1105/tpc.109.086351

Ynada, I. (2008). Copper in plant acquisition, transport and interactions. Funct. Plant Biol. 35, 409–430. doi: 10.1071/FP07286

Ynada, I. (2013). Transition metals in plant photosynthesis. Metalomics 5, 1080–1109. doi: 10.1039/C3MT00006A

Zardetto-Manera, H., Franklin, K., Ogilvie, H., Thomas, H., and Scott, I. (1999). Regreening of senescent Nicotiana leaves. II. Redifferentiation of plastids. J. Exp. Bot. 50, 1683–1698. doi: 10.1093/jxb/50.340.1683

Zelisko, A., Garcia-Lorenzo, M., Jackowski, G., Jansson, S., and Funk, C. (2005). AtFtsH6 is involved in the degradation of the light-harvesting complex II during high-light acclimation and senescence. Proc. Natl. Acad. Sci. U.S.A. 102, 13699–13704. doi: 10.1073/pnas.0505472102

Zheng, L., Yamaji, N., Yokohori, K., and Ma, J. F. (2012). YSL16 is a phloem-localized transporter of the copper-nicotianamine complex that is responsible for copper distribution in rice. Plant Cell 24, 3767–3782. doi: 10.1105/tpc.112.103321

Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Received: 30 October 2013; accepted: 08 January 2014; published online: 24 January 2014.

Citation: Pottier M, Masclaux-Daubresse C, Yoshimoto K and Thomine S (2014) Autophagy as a possible mechanism for micronutrient remobilization from leaves to seeds. Front. Plant Sci. 5:11. doi: 10.3389/fpls.2014.00011

This article was submitted to Plant Nutrition, a section of the journal Frontiers in Plant Science.

Copyright © 2014 Pottier, Masclaux-Daubresse, Yoshimoto and Thomine. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) or licensor are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.