

We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,900

Open access books available

186,000

International authors and editors

200M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities



WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com



Regulation Effect of Different Water Supply to the Nitrogen and Carbon Metabolism

Szilvia Veres, László Zsombik and Csaba Juhász

Abstract

Drought stress and flood result in the generation and accumulation of active oxygen species, the peroxidation of membrane lipids, and reduction of nitrogen metabolism, photosynthesis, growth, and development, causing a significant decline in the qualitative and quantitative production. The water availability influences the different component of NUE and photosynthetic system and its connections. The goal of this chapter is to summarize the effect of water supply to the nitrogen and carbon metabolisms. Knowing about the value of nitrogen use efficiency and photosynthetic parameters is really a useful essential for selecting and growing the best genotypes. But what will happen with these two crucial characteristics of plants, if the environment for growing is not ideal?.

Keywords: nitrogen, carbon, drought, water

1. Introduction

The most widely discussed projections—*World Population Prospects* every 2 years—are those published by the United Nations from 1951. From this year they have published knowledge about the world population that increased more than 400% over the twentieth century [1]. Expanding populations, income growth, and urbanization have brought about quantitative and qualitative changes in the demand for food. Agriculture faces multiple challenges: it has to produce more food to feed a growing population and more feedstocks for a potentially huge bioenergy market, adopt more efficient and sustainable production methods, and adapt to climate change. Although all of the challenges are more or less hang together, thus if we will be able to find a good point to step in, it can mean a medicine for all function. Climatic change is the middle of this complex problem; it is the reason and the solution as well. According to the most recent assessment report of the Intergovernmental Panel on Climate Change (IPCC), published in 2014, levels of anthropogenic emissions of greenhouse gases are now at their highest in history [2]. Agricultural production and its effect on land use are major sources of these emissions, by sharing methane and nitrous oxide gases. As more greenhouse gas emissions are released into the air, causing air temperatures to increase, more moisture evaporates from land and water bodies. Warmer temperatures also increase evaporation and evapotranspiration in plants and soils, which affects plant life and can reduce rainfall even more.

Plant growth and productivity are adversely affected by water deficiency and/or drought. Moreover, they are not able to solve their serious problem in a short way. Responses of plants to water stress may be assigned as either injurious change or tolerance index. Short-term acclimatization skills are not always enough mainly if any other loads are also presented. Therefore the development of plants with increased survivability and growth during water stress is a major objective in the breeding crops. All of the skills and traits of what the different plant genotypes are able to use need to be known to cope with water deficiency as single or under multiplied stress conditions.

2. Plant response to drought stress

Drought stress is one of the most common abiotic stresses for terrestrial plants [3, 4]. Drought adaptability of plants was defined as comprehensive capacity for adaptation to the drought stress and the re-watering cycle. Drought resistance and recovery determine drought adaptation of plants. Plants can increase the drought resistance through three strategies, namely, “drought escape,” “drought avoidance,” and “drought tolerance” (**Figure 1**). The “drought escape” strategy plants reduce life span and induce vegetative dormancy to escape severe drought stress [5]. Drought avoidance includes increasing water uptake ability and water use efficiency: stomatal closure, root systems, high capacity for water transport from roots to leaves, and high leaf mass per leaf area [6]. Behind the strategy of drought tolerance, the plant cells improve osmotic adjustment ability, increase cell wall elasticity to maintain tissue turgidity, elevate antioxidant metabolism, and enhance the resistance to xylem cavitation [7].

It is possible to categorize plant responses to drought stress in accordance with the organizational level of study: from whole plant to molecular level. At molecular level: epigenomics, which affect DNA activity without modifying the gene sequence; transcriptomics, which are changes in gene expression; proteomics, referring to changes in proteins; and finally metabolomics, which are changes in metabolites [9]. Epigenetic mechanisms regulate chromatin structure, gene expression, transposon mobility, and DNA recombination [10]. Several authors have reported the differential regulation of genes encoding epigenetic regulators [11–13] as well as local chromatin and DNA methylation changes in response to a variety of abiotic stresses

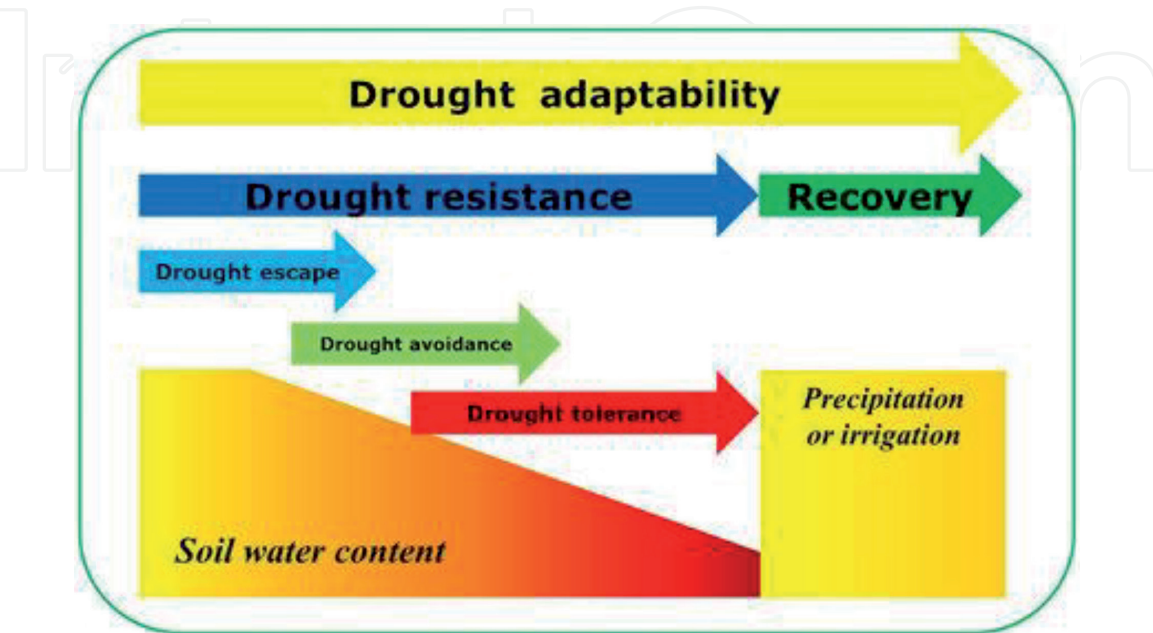


Figure 1.
Diagram about drought-adaptive capabilities during drought and re-watering cycle [8].

[14–16] including drought [17–19]. Recent studies had been performed to investigate drought responses in plants using transcriptomic approaches [20, 21]. The differentially expressed transcripts help for identifying the key genes in stress response and performing functional analysis to reveal their roles in stress adaptation in plants. High-throughput proteomics has proved to be a powerful tool for the comprehensive identification of drought-responsive proteins in plants [22]. In previous investigations, more than 2200 drought-responsive protein species have been identified in leaves [23]; these drought-responsive protein species are defined as 440 unique proteins on the basis of their protein sequence homology and functional domain similarity. Further progress in plant performance under stresses is expected by combining marker-assisted breeding with metabolite markers. The most dramatic effect on the metabolite composition was experienced in leaves compared with other organs [24]. Drought stress evoked the accumulation of many amino acids (glycine, serine) including isoleucine, valine, threonine, and 4-aminobutanoate, which has been reported in both field and greenhouse experiments in many plant species [25].

Plants can adapt to water deficiency by a wide range of alterations in their morphology, anatomy, and physiology that have been the focus of many studies [26, 27]. Plant's strategies on the whole plant level can lead to stomatal closure, reductions in photosynthesis and transpiration, growth inhibition, antioxidant production, and changes in hormonal composition [28–30]. Plants have evolved several strategies to cope with drought stress, including drought escape via a short life cycle or developmental plasticity, drought avoidance via enhanced water uptake and reduced water loss, as well as drought tolerance via osmotic adjustment, antioxidant capacity, and desiccation tolerance [31]. Plant responses to drought stress also vary at different growth stages of the crop [32]. The decrease in yield varies from 13 to 94% in the investigated crops that were under drought stress [33].

3. Interaction between C and N metabolism

Nitrogen is an essential macronutrient for plants, and it can affect many aspects of plant growth and metabolic pathways [34–36]. Nitrate is a primary nitrogen source for photosynthetic organisms. The assimilation of nitrate-N into amino group of amino acids contains at least three main steps: nitrate uptake, reduction of nitrate to ammonium, and incorporation of ammonium to carbon skeleton. One of the main connections is that all assimilatory power utilized by plant metabolism originates from photosynthesis. In plant leaves nitrate assimilation is a direct photosynthetic process that increases the capacity of the photosynthetic apparatus for non-cycling electron flow, overcoming the limitation imposed by CO₂ fixation through the Calvin cycle [37]. Nitrogen assimilation has an impact on the efficiency of CO₂ fixation and the distribution of just fixed carbon among metabolite fractions. Under limiting light intensity condition, there is a strong competition for reducing equivalents between CO₂ and nitrate assimilation [38]. When the available nitrogen source is ammonium, there is no reduction in CO₂ fixation under low light intensity; moreover ammonium has a positive effect on it [39]. Photosynthetic reactions are involved in the synthesis, regulation, and maintenance of the enzymes of nitrate assimilation pathway. Photorespiratory nitrogen metabolism is one of the important aspects of the interactions of carbon and nitrogen.

High carbohydrate content of grain (in maize, wheat) versus low nitrogen content indicates the crucial role of photosynthesis in attaining maximum yield. With the increased use of fertilizer N being closely associated with enhanced crop yields, it seems reasonable that both carbon and nitrogen metabolisms should be considered when attempting to identify factors that limit productivity [40].

4. Water supply and nitrogen nutrition

Water and nitrogen are the most limiting factors in agricultural production in most parts of the world, which are able to determine and influence the carbon metabolism. Nitrogen is a vital structural component of proteins, ribulose-1,5-bisphosphate carboxylase/oxygenase (Rubisco), nucleic acids, chlorophylls, as well as some hormones, and nitrogen fertilization is an essential agronomic management practice to enhance the crop productivity [41]. Primary carbon metabolism is dependent on nitrogen assimilation, because much of the nitrogen pool of the plant is invested in the proteins (structural and enzymes) and chlorophyll of the photosynthetic apparatus. Leaf chlorophyll provides the platform for photosynthetic system [42], whereas Rubisco is the key enzyme involved in the process of photosynthesis [43]. A major part of plant nitrogen is stored in the enzymes participating in the photosynthesis especially Rubisco, which is a key source of N recycling [44]. The limitations in the photosynthetic process as a consequence of intensified drought stress not only impose direct drought stress-induced damages to plants but also result in light-induced oxidative stress. The lower efficiency of photosynthetic system under drought stress leads to the imbalance between absorbed light energy and its utilization in the carbon assimilation process, which in turn spares more electrons triggering the production of reactive oxygen species. Conversely, nitrogen assimilation requires a continuous supply of energy and carbon skeletons. Interconnected metabolic processes make the effect of water deficit on plant nitrogen nutrition status difficult to predict. An adequate assessment of the impacts of drought stress under different nitrogen levels on the physiological activities and yield attributes can provide the valuable insights for wheat cultivation under drought stress [45]. Efficient nitrogen nutrition has been reported to have the potential to alleviate the drought stress damages by maintaining metabolic activities even at low tissue water potential [31]. Abid et al. [46] published that higher N nutrition contributed to drought tolerance in wheat by maintaining higher photosynthetic activities and antioxidative defense system during vegetative growth periods. N-fertilized wheat plants responded more rapidly to increasing drought stress by closing stomata and reducing net photosynthesis [7].

The nitrogen form and the levels of nitrogen available affect root water uptake [47–49]. Synergetic transport has been found between nitrate and water uptake in roots. In plants supplied with nitrogen in both ammonium and nitrate forms, the high nitrogen supply also increased root hydraulic conductance in plants [50, 51]. The radial water transport also can be influenced by nitrogen nutrition. The water flow in apoplastic pathway is blocked by apoplastic barriers at the endodermis, and water flow continues through the symplastic pathway. The deposition of lignin and suberin in the endodermis may affect root hydraulic conductance; Ranathunge et al. [52] demonstrated that high ammonium supply increased this deposition and thus decrease root hydraulic conductance. Drought stress may induce the alkalinization of leaf apoplast, in tomato [53] and hop [54], and especially in plants supplied with high nitrate [55].

5. Conclusion

Nitrogen is an essential nutrient for plants, and it can affect dry matter production by influencing photosynthetic process in several direct and indirect ways. Drought is also a crucial abiotic factor in terms of photosynthesis and also means control for the nutrient nutrition of plants. The effect of water deficit on nitrogen nutrition has been the subject of considerable research on several plants [7, 56, 57]. The interconnected metabolic processes make it difficult to predict the effect of

water deficit on plant nitrogen nutrition status and the exact regulation point in the carbon metabolism. In the future we need to know more skills and traits what the different plant genotypes are able to use to cope with water deficiency as single or under multiplied stress conditions.

Acknowledgements

The work was financed by the Higher Education Institutional Excellence Programme (20428-3/2018/FEKUTSTRAT) of the Ministry of Human Capacities in Hungary, within the framework of the 4th thematic programme of the University of Debrecen. The authors thank the support of the “Kiváló malomipari paraméterekkel rendelkező adaptív őszi búza vonalak előállítása” (AGR_PIAAC_13-1-2013-0002) grant and the Arid Land Research Center of the Faculty of Agricultural and Food Sciences and Environmental Management at University of Debrecen.

Conflict of interest

We have no “conflict of interest” to declare.

Author details

Szilvia Veres^{1*}, László Zsombik² and Csaba Juhász³


¹ Department of Agriculture Botany, Crop Physiology and Biotechnology, Faculty of Agricultural and Food Sciences and Environmental Management, Institute of Crop Sciences, University of Debrecen, Debrecen, Hungary

² Institutes for Agricultural Research and Educational Farm, Research Institute of Nyíregyháza, University of Debrecen, Nyíregyháza, Hungary

³ Faculty of Agricultural and Food Sciences and Environmental Management, Institute of Water and Environmental Management, University of Debrecen, Debrecen, Hungary

*Address all correspondence to: szveres@agr.unideb.hu

IntechOpen

© 2019 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/3.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. 

References

- [1] Roser M. Future Population Growth. Published online at OurWorldInData.org. Retrieved from: <https://ourworldindata.org/future-population-growth/2017> [Online Resource]
- [2] Porter JR, Xie L, Challinor AJ, Cochrane K, Howden SM, Iqbal MM, et al. Food security and food production systems. In: IPCC. 2014. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK/New York, USA: Cambridge University Press; 2014. pp. 485-533
- [3] Yordanov I, Velikova V, Tsonev T. Plant response to drought stress. *Photosynthetica*. 2000;**38**(1):171-186
- [4] Xiong L, Wang RG, Mao G, Koczan MJ. Identification of drought tolerance determinants by genetic analysis of root response to drought stress and abscisic acid. *Plant Physiology*. 2006;**142**:1065-1074. DOI: 10.1104/pp.106.084632
- [5] Geber MA, Dawson TE. Genetic variation in and covariation between leaf gas exchange, morphology, and development in *Polygonum arenastrum*, an annual plant. *Oecologia*. 1990;**85**: 153-158. DOI: 10.1007/BF00319396
- [6] Jackson RB, Sperry JS, Dawson TE. Root water uptake and transport: Using physiological processes in global predictions. *Trends in Plant Science*. 2000;**5**:482-488. DOI: 10.1016/S1360-1385(00)01766-0
- [7] Morgan JM. Osmoregulation and water stress in higher plants. *Annual Review of Plant Physiology*. 1984;**35**:299-319. DOI: 10.1146/annurev.pp.35.060184.001503
- [8] Chen D, Wang S, Cao B, Cao D, Leng G, Li H, et al. Genotypic variation in growth and physiological response to drought stress and re-watering reveals the critical role of recovery in drought adaptation in maize seedlings. *Frontiers in Plant Science*; 2016;**6**:1241. DOI: 10.3389/fpls.2015.01241
- [9] Singh S, Parihar P, Singh R, Singh VP, Prasad SM. Heavy metal tolerance in plants: Role of transcriptomics, proteomics, metabolomics, and ionomics. *Frontiers in Plant Sciences*. 2015;**6**:1143. DOI: 10.3389/fpls.2015.01143
- [10] He G, Elling AA, Deng XW. The epigenome and plant development. *Annual Review of Plant Biology*. 2011;**62**:411-435
- [11] Fang H, Liu X, Thorn G, Duan J, Tian L. Biochemical and biophysical research communications expression analysis of histone acetyltransferases in rice under drought stress. *Biochemical and Biophysical Research Communication*. 2014;**443**:400-405
- [12] Li H, Yan S, Zhao L, Tan J, Zhang Q, Gao F. Histone acetylation associated up-regulation of the cell wall related genes is involved in salt stress induced maize root swelling. *BMC Plant Biology*. 2014;**14**:105. DOI: 10.1186/1471-2229-14-105
- [13] Su LC, Deng B, Liu S, Li LM, Hu B, Zhong YT. Isolation and characterization of an osmotic stress and ABA induced histone deacetylase in *Arachis hypogaea*. *Frontiers in Plant Science*. 2015;**6**:512. DOI: 10.3389/fpls.2015.00512
- [14] Chen L, Luo M, Wang Y, Wu K. Involvement of Arabidopsis histone deacetylase HDA6 in ABA and salt stress response. *Journal of Experimental Botany*. 2010;**61**:3345-3353

- [15] Luo M, Liu X, Singh P, Cui Y, Zimmerli L, Wu K. Chromatin modifications and remodeling in plant abiotic stress responses. *Biochimica et Biophysica Acta*. 2012;**1819**:129-136
- [16] Bocchini M, Bartucca ML, Ciancaleoni S, Mimmo T, Cesco S, Pii Y. Iron deficiency in barley plants: Phytosiderophore release, iron translocation, and DNA methylation. *Frontiers in Plant Science*. 2015;**6**:514. DOI: 10.3389/fpls.2015.00514
- [17] González RM, Ricardi MM, Iusem ND. Epigenetic marks in an adaptive water stress-responsive gene in tomato roots under normal and drought conditions. *Epigenetics*. 2013;**8**:864-872
- [18] Kim JM, Sasaki T, Ueda M, Sako K, Seki M. Chromatin changes in response to drought, salinity, heat, and cold stresses in plants. *Frontiers in Plant Science*. 2015;**6**:114. DOI: 10.3389/fpls.2015.00114
- [19] Fortes AM, Gallusci P. Plant stress responses and phenotypic plasticity in the epigenomics era: Perspectives on the grapevine scenario, a model for perennial crop plants. *Frontiers in Plant Science*. 2017;**8**:82. DOI: 10.3389/fpls.2017.00082
- [20] Zhou J, Wang X, Jiao Y, Qin Y, Liu X, He K. Global genome expression analysis of rice in response to drought and high-salinity stresses in shoot, flag leaf, and panicle. *Plant Molecular Biology*. 2007;**63**:591-608
- [21] Gao F, Wang J, Wei S, Li Z, Wang N, Li H, et al. Transcriptomic analysis of drought stress responses in *Ammopiptanthus mongolicus* leaves using the RNA-seq technique. *PLoS One*. 2015;**10**(4):e0124382
- [22] Mohammadi PP, Moieni A, Komatsu S. Comparative proteome analysis of drought-sensitive and drought-tolerant rapeseed roots and their F1 line under drought stress. *Amino Acids*. 2012;**43**(5):2137-2152. DOI: 10.1007/s00726-012-1299-6
- [23] Wang X, Cai X, Xu C, Wang Q, Dai S. Drought-responsive mechanisms in plant leaves revealed by proteomics. *International Journal of Molecular Sciences*. 2016;**17**(10):1706
- [24] Witt S, Galicia L, Lisec J, Cairns J, Tiessen A, Araus JL, et al. Metabolic and phenotypic responses of greenhouse grown maize hybrids to experimentally controlled drought stress. *Molecular Plant*. 2012;**5**:401-417
- [25] Obata T, Witt S, Lisec J, Palacios-Rojas N, Florez-Sarasa I, Yousfi S, et al. Metabolite profiles of maize leaves in drought, heat, and combined stress field trials reveal the relationship between metabolism and grain yield. *Plant Physiology*. 2015;**169**:2665-2683
- [26] Nagy Z, Tuba Z, Zsoldos F, Erdei L. CO₂-exchange and water relation responses of sorghum and maize during water and salt stress. *Journal of Plant Physiology*. 1995;**145**:539-544
- [27] Gratani L, Bombelli A. Leaf anatomy, inclination, and gas exchange relationships in evergreen sclerophyllous and drought semideciduous shrub species. *Photosynthetica*. 1999;**37**:573-585. DOI: 10.1023/A:1007171525298
- [28] Szegletes ZS, Erdei L, Tari I, Cseuz L. Accumulation of osmoprotectants in wheat cultivars of different drought tolerance. *Cereal Research Communications*. 2000;**28**:403-410. Available from: <http://www.jstor.org/stable/23787271>
- [29] Lawlor DW, Cornic G. Photosynthetic carbon assimilation and associated metabolism in relation to water deficits in higher plants. *Plant, Cell and Environment*. 2002;**25**:275-294. DOI: 10.1046/j.0016-8025.2001.00814.x

- [30] Zhu JK. Salt and drought stress signal transduction in plants. *Annual Review of Plant Biology*. 2002;**53**:247-273. DOI: 10.1146/annurev.arplant.53.091401.143329
- [31] Zhang LX, Li SX, Zhang H, Liang ZS. Nitrogen rates and drought stress effects on production, lipid peroxidation and antioxidative enzyme activities in two maize (*Zea mays* L.) genotypes. *Journal of Agronomy and Crop Science*. 2007;**193**:387-397. DOI: 10.1111/j.1439-037X.2007.00276.x
- [32] Shi J, Yasuor H, Yermiyahu U, Zuo Q, Ben-Gal A. Dynamic responses of wheat to drought and nitrogen stresses during re-watering cycles. *Agricultural Water Management*. 2014;**146**:163-172. DOI: 10.1016/j.agwat.2014.08.006
- [33] Farooq M, Wahid A, Kobayashi N, Fujita D, Basra S. *Plant Drought Stress: Effects, Mechanisms and Management Sustainable Agriculture*. Berlin: Springer; 2009. pp. 153-188
- [34] Guo S, Kaldenhoff R, Uehlein N, Sattelmacher B, Brueck H. Relationship between water and nitrogen uptake in nitrate- and ammonium-supplied *Phaseolus vulgaris* L. plants. *Journal of Plant Nutrition and Soil Science*. 2007;**170**:73-80. DOI: 10.1002/jpln.200625073
- [35] Wang M, Shen QR, Xu GH, Guo SW. New insight into the strategy for nitrogen metabolism in plant cells. *International Review of Cell and Molecular Biology*. 2014;**310**:1-37. DOI: 10.1016/B978-0-12-800180-6.00001-3
- [36] Ding L, Lu Z, Gao L, Guo S, Shen Q. Is nitrogen a key determinant of water transport and photosynthesis in higher plants upon drought stress? *Frontier in Plant Science*. 2018;**9**:1143. DOI: 10.3389/fpls.2018.01143
- [37] Lara C. Interaction between nitrogen and carbon assimilation in green cells. In: Srivastava HS, Singh RP, editors. *Nitrogen Nutrition in Higher Plants*. New Delhi, India: Associated Publishing Co.; 1995. pp. 323-336. ISBN: 978 81 85211 38
- [38] Rathnam CKM. Malate and dihydroxyacetone phosphate-dependent nitrate reduction in spinach leaf chloroplast. *Plant Physiology*. 1978;**62**(2). DOI: 10.1104/pp.62.2.220
- [39] Woo KC, Canvin DT. Effect of ammonia on photosynthetic carbon fixation in isolated spinach leaf. *Canadian Journal of Botany*. 1980;**48**:389. DOI: 10.1007/s11099-010-0051-2
- [40] Swank JC, Below FE, Lambert RJ, Hageman RH. Interaction of carbon and nitrogen metabolism in the productivity of mize. *Plant Physiology*. 1982;**70**:1185-1190. DOI: 10.1104/pp.70.4.1185
- [41] Ata-Ul-Karim ST, Liu X, Lu Z, Yuan Z, Zhu Y, Cao W. In-season estimation of rice grain yield using critical nitrogen dilution curve. *Field Crops Research*. 2016;**195C**:1-8. DOI: 10.1016/j.fcr.2016.04.027
- [42] Murchie EH, Pinto M, Horton P. Agriculture and the new challenges for photosynthesis research. *The New Phytologist*. 2009;**181**:532-552. DOI: 10.1111/j.1469-8137.2008.02705.x
- [43] Makino A. Photosynthesis, grain yield, and nitrogen utilization in rice and wheat. *Plant Physiology*. 2011;**155**:125-129. DOI: 10.1104/pp.110.165076
- [44] Gonzalez-Real MM, Baille A. Changes in leaf photosynthetic parameters with leaf position and nitrogen content within a rose plant canopy (*Rosa hybrida*). *Plant, Cell and Environment*. 2000;**23**:351-363. DOI: 10.1046/j.1365-3040.2000.00559.x
- [45] Teixeira EI, George M, Herreman T, Brown H, Fletcher A, Chakwizira E. The

impact of water and nitrogen limitation on maize biomass and resource-use efficiencies for radiation, water and nitrogen. *Field Crops Research*. 2014;**168**:109-118. DOI: 10.1016/j.fcr.2014.08.002

[46] Abid M, Tian Z, Ata-Ul-Karim ST, Cui Y, Liu Y, Zahoor R, et al. Nitrogen nutrition improves the potential of wheat (*Triticum aestivum* L.) to alleviate the effects of drought stress during vegetative growth periods. *Frontier in Plant Science*. 2016;**7**:981. DOI: 10.3389/fpls.2016.00981

[47] Gorska A, Ye Q, Holbrook NM, Zwieniecki MA. Nitrate control of root hydraulic properties in plants: Translating local information to whole plant response. *Plant Physiology*. 2008;**148**:1159-1167. DOI: 10.1104/pp.108.122499

[48] Gorska A, Lazor JW, Zwieniecka AK, Benway C, Zwieniecki MA. The capacity for nitrate regulation of root hydraulic properties correlates with species' nitrate uptake rates. *Plant and Soil*. 2010;**337**:447-455. DOI: 10.1007/s11104-010-0540-x

[49] Tyerman SD, Wignes JA, Kaiser BN. Root hydraulic and aquaporin responses to N availability. In: Chaumont F, Tyerman S, editors. *Plant Aquaporins*. Cham: Springer; 2017. pp. 207-236

[50] Ren B, Wang M, Chen Y, Sun G, Li Y, Shen Q. Water absorption is affected by the nitrogen supply to rice plants. *Plant and Soil*. 2015;**396**:397-410. DOI: 10.1007/s11104-015-2603-5

[51] Li G, Tillard P, Gojon A, Maurel C. Dual regulation of root hydraulic conductivity and plasma membrane aquaporins by plant nitrate accumulation and high-affinity nitrate transporter NRT2. 1. *Plant and Cell Physiology*. 2016;**57**:733-742. DOI: 10.1093/pcp/pcw022

[52] Ranathunge K, Schreiber L, Bi Y-M, Rothstein SJ. Ammonium-induced architectural and anatomical changes with altered suberin and lignin levels significantly change water and solute permeabilities of rice (*Oryza sativa* L.) roots. *Planta*. 2016;**243**:231-249. DOI: 10.1007/s00425-015-2406-1

[53] Jia W, Davies WJ. Modification of leaf apoplastic pH in relation to stomatal sensitivity to root-sourced abscisic acid signals. *Plant Physiology*. 2007;**143**:68-77. DOI: 10.1104/pp.106.089110

[54] Korovetska H, Novák O, Jùza O, Gloser V. Signalling mechanisms involved in the response of two varieties of *Humulus lupulus* L. to soil drying: I. Changes in xylem sap pH and the concentrations of abscisic acid and anions. *Plant and Soil*. 2014;**380**:375-387. DOI: 10.1007/s11104-014-2101-1

[55] Wilkinson S, Bacon MA, Davies WJ. Nitrate signalling to stomata and growing leaves: Interactions with soil drying, ABA, and xylem sap pH in maize. *Journal of Experimental Botany*. 2007;**58**:1705-1716. DOI: 10.1093/jxb/erm021

[56] Gonzales-Dugo V, Durand JL, Gastal F. Water deficit and nitrogen nutrition of crops—A review. *Agronomy for Sustainable Development*, Springer Verlag/EDP Sciences/INRA. 2010;**30**(3):529-544. DOI: 10.1051/agro/2009059

[57] Veres SZ, Petek M, Makleit P, Kiss L, Gáspár S, Frommer D, et al. Physiological detection of water and nitrogen deprivation. *Annals, Series on Agriculture, Silviculture and Veterinary Medicine Sciences*. 2017;**6**(1):152-158. ISSN 2069-1149