Water use efficiency in the production of crops: a review of current and potential applications in the context of climate change

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Abstract. The concern with the efficient use of water in the production of crops is centuries old and civilization, as we know it, is based on the ability to grow crops and manage their needs for water. Water, like air or soil, is of global interest and it is crucial to understand the risks posed by the ongoing climate change, the slowing down of agricultural productivity, the changes in demography and diet trends or the depletion of resources and energy. The threats to global well-being or food safety, security, quality and affordability drove to research and innovations in reformulating successfully adapted agriculture and farming management practices. Water use efficiency (WUE), described as the aboveground biomass production per unit area per unit of water used by the crop, is linked to the plants' response mechanisms to moderate-severe soil water deficits and was used as a selection criterion in improving fodder plant species and varieties. Another application is related to the potential of reducing the risk of the groundwater resources depletion due to irrigation practices. This review focuses on both environmental and agricultural considerations regarding the latest implications of WUE and processes information that has led to innovations in crop production during the last ten years. However, the future of the weather on Earth is still uncertain and thus the need to drive improved and adapted changes in the ways of managing climate change difficulties in agriculture. The aim of this paper was to reveal plant stress response mechanisms, through integrated approach, in order to understand the complex interactions with potential favorable impact on the environment. Specifically, apart from creating a manuscript of scientific value, the objectives are: (1) to understand the current and future risks posed by climate change to agroecosystems from the point of view of crop production; (2) to reveal the complexity of the water movement direction in the soil-plant-atmosphere system in order to use WUE traits for conservation agriculture purposes.
Key Words: perennial fodder legumes, *Medicago sativa*, improved fodder varieties, yield, plant biomass, plant productivity.

Introduction. Water use efficiency (WUE), described about 100 years ago as the aboveground biomass production (usually determined as dry matter) per unit area per unit of water used by the crop, is linked to the plants' response mechanisms to moderate-severe soil water deficits (Hatfield 2019). Therefore, in case of an increased WUE the question arises about the opposition between the processes of increased yield production and decreased transpirational water loss. The desired effect in forage and fodder crop production would be the transpired water rates to be lower under water deficit stress, without reducing photosynthesis, thus biomass production.

The second goal of the 17 Sustainable Development Goals adopted by the United Nations in 2015 aiming to improve the quality of human life on Earth by 2030, is to end hunger, achieve food security, improve nutrition and promote sustainable agriculture (www.un.org). This initiative strives to help rethink our global food infrastructure, as a whole, from production and processing to consumer because there is a need to implement innovative, sustainable practices in order to ensure food access. Therefore, providing the market with healthy plant and animal products is one of the most important objectives for agricultural producers, while obtaining healthy animal products depends on the fodder. A vital substance on Earth, covering three-quarters of the planet's surface, water is practically present everywhere on the planet, in all its forms - solid, liquid, gaseous - and throughout human history, has set the Earth apart from the other planets in our solar system. Water is therefore an issue as well, in terms of both quantity and quality. On the one hand, the availability of water, especially freshwater reserves, is determined by climate change, and on the other hand, water is itself an element that also changes the weather and climate of the Earth by moving around the globe, carrying latent heat in the form of strong greenhouse gases, as NASA experts consider water vapor (Graham et al 2010).

The Earth's water content is about 1.39 billion km^3, most of it, about 96.5%, being in the global oceans. As for the rest, about 1.7% is stored in polar ice, glaciers and permanent snow, and another 1.7% is stored in groundwater, lakes, rivers, streams and soil. Only one thousandth of 1% of the Earth's water exists as water vapor in the atmosphere (Graham et al 2010).

The aim of the present paper was to reveal plant stress response mechanisms, through integrated approach, in order to understand the complex interactions with potential favorable impact on the environment. Specifically, the objectives were: (1) to understand the current and future risks posed by climate change to agroecosystems from the point of view of crop production; (2) to reveal the complexity of the water movement direction in the soil-plant-atmosphere system in order to use WUE traits for conservation agriculture purposes.

Water cycle observations. In its hydrological cycle, powered by energy from the Sun, water is in a permanent transition between oceans, atmosphere and land. Around 495,000 km^3 of water are cycled through the atmosphere every year. Water continually evaporates, condenses, and precipitates and on a global basis, evaporation approximately equals precipitation. Oceans are being replenished largely through runoff from the land areas. However, over the past 100 years, sea level around the globe has risen approximately 17 cm over the course of the twentieth century. As shown in studies, the process of evaporation from oceans, seas, and other water bodies (lakes, rivers, streams) provides nearly 90% of the water vapor in the atmosphere and that most of the remaining 10% is released by plants through transpiration, which is also significant - for example, a 0.5 ha cornfield can release through transpiration up to 15 m^3 (15,000 L) of water every day (Graham et al 2010). Precipitation (including rain, snow, sleet, freezing rain, hail) is the most important mechanism for transporting water from the atmosphere back to the land surface, following various routes (flowing into the oceans or other water bodies), then the cycle continues. At different stages of the cycle, some of the water is intercepted by humans or other life forms for drinking, washing, irrigating or other uses, while most of human activities adversely affect the quality of freshwater resources (Graham et al 2010).

Water and climate change. Global warming affects plants, not by the gradually increasing temperatures, but mostly by the increase in extreme events like heatwaves and droughts, torrential downpours, hail, more powerful storms, hurricanes and typhoons (Elias 2019). Water and its movements within or between atmosphere, land and ocean define the global water cycle and is central to the climate system. Almost all weather and climate phenomena are in some way tied to the water cycle. Examples include extreme rainfall during thunderstorms, hurricanes and tropical cyclones, flooding, droughts, and sea level rise. Now, the water cycle is changing in important ways as the climate changes. Theory and models suggest that as the Earth is warming, the global water cycle is amplified. This means that more water is evaporated from the ocean, and consequently, precipitation is increasing, as well. There is strong new evidence that the global water cycle has amplified substantially in the past 50 years (Cheng et al 2020). Ocean salinity change can be used to estimate water cycle change because it reveals the modification of global surface freshwater exchanges - evaporation takes freshwater from the ocean into the atmosphere and increases the ocean salinity; precipitation puts more freshwater into the ocean and reduces the salinity. Consequently, salinity changes integrate effects over broad areas and provide an excellent indicator for water cycle change. The new data demonstrate 'the fresh gets fresher, and the salty gets saltier' in much of the ocean. It can be shown that this increase is due to human influence - the water cycle has been already amplified by 2 to 4% per degree Celsius since 1960, meaning that the global water cycle has been intensified with global warming, In a world warmed by +2°C (the upper limit of the Paris Agreement target), the water cycle will amplify by 4~8%. This amplification will be even stronger if the aerosol impacts are smaller in the future than today (i.e., if the air pollution can be controlled). Consequently, there will be stronger evaporation: the drier regions will get even drier and further increase the odds of worsening drought. Droughts affect livestock and crops and increase risk of sometimes deadly wildfire in many regions, posing severe risks to food safety and human health (Cheng et al 2020).

Water and agriculture. Water provides a crucial input for agricultural production and plays an important role in food security. Irrigated agriculture accounts for 20% of all cultivated land and contributes 40% to all food produced worldwide (www.unesco.org). Irrigated agriculture is, on average, at least twice as productive per unit of land as rain fed agriculture, thus allowing for greater production intensification and crop diversification. Soil moisture decreases during periods of poor rainfall, so irrigation is the most widely used way to combat water scarcity in the soil and therefore by far the predominant use of water in agriculture (DG ENV project ClimWatAdapt 2012; EEA 2019). Samaniego et al (2018) predicted that Europe will face increases in soil moisture drought and the need for adaptation measures. Also, according to UNESCO WWAP, predictions show an average increase of 0.6% a year in irrigated land until 2030. Even if the surface of irrigated agriculture increased during the last 50 years, the expected climate change impacts on agriculture and the competing demand between agriculture and other sectors (energy, human use) will lead to a moderate increase in the demand of water as shown in 2015 by the European Climate Adaptation Platform (Climate-ADAPT).

Adaptation options to water scarcity due to climate change. The Romanian Climate Change Strategy proposes, for the Agriculture sector, measures such as the introduction of modern agricultural technologies in the use of drought, disease and pest resistant plant varieties, for which less agrotechnical work is required, their purpose being (1) to reduce greenhouse gas (GHG) emissions and (2) the adaptation to the effects of climate change. The three principles can be applied to all agricultural cropping systems, provided that they are adapted to the specific requirements of the crop and to local/regional factors (www.mmediu.ro). These three principles are also found in the measures promoted and supported by the EU and by the National Rural Development Plans 2014-2020 (www.madr.ro). In Romania, farmers are encouraged to grow alfalfa by providing financial support, under Commitments, to apply sustainable agricultural practices on farms, in accordance with the specific management requirements of some Packages such as Package 4 (P4) - Green Crops; Package 5 (P5) - Adaptation to the effects of climate change - Measure 10 and Package 1 respectively - Agricultural crops on arable land (including fodder plants) in conversion to organic farming - Measure 11 - Organic farming (apia.org.ro).

Vegetation response to water deficit in Europe. As a consequence of climate change, there will be a stronger evaporation: drier regions will become even drier and the chances of a worsening drought will continue to increase. Drought affects animals and crops and increases the risk of fires in many regions, including the US, China, Australia, Brazil and other countries, with severe risks to food safety and human health, with an increased risk of heavy rainfall and other extreme events. Monitoring vegetation response to water deficit due to droughts is necessary to be able to introduce effective measures to increase the resilience of ecosystems. Between 2000 and 2016, Europe was affected by severe droughts, causing average yearly vegetation productivity losses covering around 121,000 km^2. This was particularly notable in 2003, when drought affected most parts of Europe, covering an estimated 330,000 km^2 of forests, non-irrigated arable land and pastures. Drought impact was also relatively severe in 2005 and 2012 (EEA 2019).

Water Use Efficiency (WUE) - current applications in agriculture/crop production. Water use efficiency refers to the ratio of water used in plant metabolism to water lost by the plant through transpiration and soil evaporation (evapotranspiration) (Lelievre et al 2011; Hadebe et al 2017; Sima 2017). Photosynthetic water use efficiency (also called instantaneous water-use efficiency), which is defined as the ratio of the rate of carbon assimilation (photosynthesis) to the rate of transpiration, and water use efficiency of productivity (also called integrated water-use efficiency), which is typically defined as the ratio of biomass produced to the rate of transpiration (Saliendra et al 2018; Sean 2018; Schauer et al 2019). Measuring the performance/productivity of fodder crops under abiotic stress conditions. Trying to explain the carbon isotopic composition of plants, Farquhar et al (1982) developed a simple method to assess WUE of C3 plants and showed that as isotopic discrimination decreases (Zhu et al 2018), the value of WUE increases, thus increasing productivity in crops containing those species (Farquhar et al 1982; Sima et al 2011).

Studies have shown that mild water stress leads to an increase in WUE due to stomatal closure, causing a reduction in transpiration (Erice et al 2011; Zhu et al 2018), also valid in case of drought-resistant cultivars, which in addition are better able to extract water from drying soil (Kirkham 1978). Furthermore, at high concentration of carbon dioxide in the atmosphere, the water-use efficiency increases as well (Chaudhury et al 1990; Souza et al 2019), therefore growth is directly related to stomatal opening (Kirkham 2008). Because soil carbon, nitrogen and phosphorus concentrations generally decreased with water addition in manipulative experiments (Suriyagoda et al 2011), but increased with annual precipitation along environmental gradients, it is important that ecosystem models consequently incorporate both experimental and observational data to properly assess the impacts of climate change on nutrient cycling (Sima et al 2011; Yuan et al 2017).

Assessing the need for irrigation in temporary pastures. According to Potters et al (2007) and Wang et al (2018), irrigation is a key factor in maintaining and promoting WUE and temporary pastures' productivity. Soil moisture, also referred to as 'green water', is the component of the water cycle that is accessible by the roots of plants, enabling them to grow. Soil moisture drops in periods of deficient precipitation. Irrigation is the most widely used way to combat the soil water deficiency and, accordingly, by far the prevalent water use in agriculture. Differences in stomatal response to water limitation may cause differences in the effect of drought on WUE. Mild water deficit may improve WUE due to stomatal closure, leading to a reduction in transpiration (Erice et al 2011). Experimental trials have shown that the highest WUE rate might be related to mild water stress. According to Zhu et al (2018), 10 different alfalfa genotypes, cultivated in Ningxia central desert steppe conditions, received three water treatments corresponding to drought stress: severe (total amount of irrigated water during the whole growth period=230 mm), intermediate (total amount of irrigated water during the whole growth period=460 mm) and mild (total amount of irrigated water during the whole growth period=700 mm) and the results showed that the highest WUE occurred when alfalfa grew under intermediate water stress.

Improvement of irrigation efficiency. Centre pivot irrigation, a method widely used in agriculture in the USA, has a reputation for spilling water and exhausting groundwater supplies (https://www.circularlandscapes.nl/en/springfields). However, the opposite can be achieved by using soil sensors and satellite information to carefully match the water supply to the exact needs of the crop without extracting more water in dry periods than can be replenished when it rains. In addition, if necessary, measured quantities of nutrients can also be added to the irrigation water, resulting in high yields and substantial water and energy savings (www.circularlandscapes.nl/en/springfields).

Assessment of the sustainable use of irrigation in fodder crops. Long-term cultivation (minimum seven years) of alfalfa as a perennial forage plant causes water shortage in the soil locally, the degree of drying of the soil layer at the roots will be intensified and soil compaction will be difficult to recover. Therefore, the timely rotation of crops will help restore soil quality and maintain the stability of local groundwater (Sun et al 2018).

Determining the most suitable crop system for temporary pastures. Water productivity increases under deficit or regulated deficit irrigation. According to Kirda (2002), this is irrigation below full crop-water requirements, such as partial root zone irrigation (PRI) or conventional deficit irrigation (CDI), meaning that the crop is exposed to a certain level of water stress either during a particular period or throughout the whole growing season. In geographical areas where water resources are limited, it can be more advantageous and economically profitable to maximize WUE instead of maximizing the harvest per unit land. However, the application of this technique requires adjustments in the agricultural systems, imposing changes at different levels. A shift from the gravity irrigation to modern pressurized systems (e.g. drip and sprinkler irrigation) and improved conveyance efficiency provide an opportunity for reduced water demand in irrigation, but at a cost and with possible negative side effects (impacts on soil quality, such as the acceleration of mineral weathering, the transport and leach of soluble and colloidal material, the change in soil structure, the raise of the local water table, the risk to reverse soil preparation measures such as the tillage which precedes planting, all depending on the intensity of irrigation and the quality of water) (Murray & Grant 2007).

Selecting fodder crop species/varieties that use water more efficiently in biomass production - Drought-tolerant crops. Growing species that are appropriate to the region’s climate is another way that farmers are obtaining safe production (https://eur-lex.europa.eu/eli/reg/2021/2115). Species that are native to arid regions are naturally drought-resistant while other species and varieties have been selected over time for their low water needs. It is important to note the advantage of early growth of species/varieties (early varieties) characterized by a short period of vegetation (precocity) during the spring, thus being sheltered from the drought period in their first stage of development. As reported by FAO in 2019 (www.fao.org), the plant breeding efforts usually aim at species’/varieties’ adaptation to local conditions and mitigation of the stress effects of the factors that influence production. The newly developed crop varieties/species must be resistant to climatic stress and efficiently use available resources. Depending on the region, one of the most commonly researched climate-related traits in crops is drought resistance to extreme temperatures. Using biotechnologies in the improvement of alfalfa crops and the application of breeding programs lead to the development of alfalfa varieties with higher pest resistance, greater local adaptability, higher perenniality and yield, as well as better tolerance to graze, drought and tolerance of acid pH, aluminum toxicity soils (Brejea et al 2021).

Choosing the optimal time to set up the fodder crop. It is useful to understand how the onset of precipitation, the amount and distribution throughout the different phenophases influence the efficiency of water use in agricultural crops and the harvest , to determine the optimal time of establishment of crops and the selection of the most suitable varieties (within a species) for local conditions (Dincă 2017; Sima 2017). Thus, the responses of different genotypes regarding water use are different depending on the variations of the time of establishment of the culture (Hadebe et al 2017).

Mitigating climate change. Climate change is weakening plants’ ability to mitigate further climate change over large areas of the planet. Terrestrial ecosystems are becoming less reliable as a temporary climate change mitigator (Wang et al 2020). Some studies highlight the possibility of extending alfalfa (*Medicago sativa*) to tropical and subtropical production systems. Land ecosystems currently play a key role in mitigating climate change. The more carbon dioxide (CO_2) plants and trees absorb during photosynthesis, the process they use to make food, the less CO_2 remains trapped in the atmosphere where it can cause temperatures to rise. But scientists have identified an unsettling trend – as levels of CO_2 in the atmosphere increase, 86% of land ecosystems globally are becoming progressively less efficient at absorbing it. Because CO_2 is a main ‘ingredient’ that plants need to grow, elevated concentrations of it cause an increase in photosynthesis, and consequently, plant growth – a phenomenon aptly referred to as the CO_2 fertilization effect, or CFE. CFE is considered a key factor in the response of vegetation to rising atmospheric CO_2 as well as an important mechanism for removing this potent greenhouse gas from our atmosphere – but that may be changing (Wang et al 2020).

Conservation agriculture. According to the United Nations’ Food and Agriculture Organization (FAO 2019), conservation agriculture is a farming system that promotes (1) the maintenance of a permanent soil cover, (2) minimum soil disturbance and (3) diversification of plant species. The three principles can be applied to all agricultural cropping systems, provided they are adapted to the specific crop requirements and the local/regional factors. The result of sustainable land management is visible in improved and sustained crop production as a consequence of the increased water and nutrient use efficiency, which are determined by the enhancing biodiversity and natural biological processes above and below the ground surface (EEA 2019). In other words, soil is protected from erosion and degradation, its quality and biodiversity improved, natural resources preserved and efficiently used, resulting in increased crop yields.

Future trends in WUE applications in agriculture/crop production. Characterizing climate change variability and its effect on forage crops, depending on the region and the season of year is key to understanding how changes in the future climate will affect life on Earth in terms of food supply. Besides this, adapting water conservation and drought management plans provides environmental and economic benefits, including some diseases prevention or treatment.

In terms of climate, the major trends of changes are common to all regions: the increase in temperatures, especially the maximums and especially in summer, as well as a decrease in precipitation, more obvious in the distant future. As a result, a high increase in temperature, the negative effect of lower rainfall, might trigger a global decrease in crop production and the increase in evapotranspiration, which the positive effect of higher CO_2 levels may not manage to compensate (Ruget et al 2013). Moreover, the changes are different depending on the region, so the cumulative annual production decreases will occur at a certain moment in time – crop production schedules are to suffer from changes, the required solution being the constitution of stocks for the summer, because yield decreases are already occurring in summer. However, prognosis for the distant future state that, due to the difference in behavior between alfalfa and grasses, the climate would be more favorable for alfalfa, than for grasses (Ruget et al 2013). The absence of nitrogen stress in alfalfa (a consequence of the symbiotic fixation) during spring time, a potentially very productive period, generally without drought stress, would explain the increased yield for legumes like alfalfa (Ruget et al 2013). Using existing water supplies more efficiently can diminish water demand. For this reason, the use of a drought management plan presents possible opportunities to reduce risks associated with the effects of climate change and therefore their economic, social and environmental impacts. Water conservation plans aim to (1) limit water consumption by improving the WUE, with no negative effects reflected upon crop production, (2) to reduce loss or waste of water, (3) to extend the life of current water supplies by reducing water demand and (4) to document the level of recycling and reuse of water.

Sustainable management policies are necessary to secure the different water uses over the years (Lijzen et al 2014; Klaas et al 2019; Thomann et al 2020), which in turn depend on a thorough understanding of the aquifer functioning, especially the groundwater recharge processes (de Vries & Simmers 2002; Scanlon et al 2006; Cuthbert et al 2019). Including WUE calculations in the promotion of adaptive groundwater management strategies is of significant importance. Depending on the diversity of agricultural systems, crop species with traits enhancing their productivity under drought stress will be favorable from both economic and environmental point of view.

Access to adequate supplies of water is central to a sustainable future and climate change is expected to exacerbate water scarcity problems in several European regions. Recycling of water is here considered as an adaptation measure to save resources through reuse for not-for-drinking uses. Domestic water from baths, showers and sinks (grey water) can be re-used for various purposes, including toilet flushing, laundry and garden irrigation. Waste water can be used also in agriculture for irrigation. Glasshouses and industrial processes can be designed to use water in closed circuits for temperature control. Wastewater reuse can therefore be a valuable option for water supply in areas where water is limited. Over 200 water reuse projects in Europe have been identified by the AQUAREC project (Wintgens et al 2005). Treated wastewater can serve as a more dependable water source, contributing to a more sustainable resource utilisation and sound demand management. The measure can reduce overall water consumption and treatment needs, resulting in cost savings. Further, the use of nutrient-rich treated waste water for agriculture may lead to a reduction (or elimination) of fertilizer application or increased productivity and can therefore also contribute to food security. Looking at the environment, the reuse of treated water allows for the conservation and allocation of freshwater and can enhance the restoration of streams, wetlands and ponds.

Conservation agriculture, as a long-term adaptation measure to the effects of climate change has therefore the potential for future application and practicability during generally a long lifetime (decades). However, in order to become an accepted and integrated practice, studies should be conducted in different locations on different crops with different agricultural technology.

Conclusions. In conclusion, global policies that impose adaptations to a changing climate and the reduction of the greenhouse gas emissions, along with the rising concerns among the population about the negative effects of intensive agriculture and the ecological damages caused by it, led to numerous research in the field of plant science, with applications in crop production. Innovations in rethinking food production are based on the introduction of sustainability principles in the agricultural field, for example by calculating the WUE of the crops. Species and varieties bred to resist changing regional and local climatic conditions could be the most efficient adaptation strategy to cope with climate change. Modern technology use as a method of data gathering and analysis for crop species requirements and productivity parameters, topography, climate and soil results in a complex study of the crop culture area and can highlight the levels of favorability and restriction determined by the environmental factors or even predict some potential effects in the context of climate change. Therefore, there is a great need to further exploit the impact of different WUE parameters specific to different crops, and also to promote among farmers the benefits of local bred varieties usage, as well as the perennial legume crop benefits and their favorable impact on the environment.

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