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Review

Towards sustainable use of water in rainfed and irrigated cropping systems: review of some technical and policy issues

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Abstract: Water sustainability in agriculture is the main topic of this review. However, moving from studies carried out at worldwide level, the main focus of the paper is the Mediterranean farm which practices irrigated and/or rainfed cropping systems. On the basis of the state of the art on this matter, a lack of knowledge in some areas has come to light that calls for new policies and further research. Basically, the review provides feasible agro-technical solutions for using water in the most efficient and productive way. Alternative ways to use water resources rationally in growing crops are discussed. They are based mainly on progress due to agronomy (No-Till Conservation Agriculture), information technology (Decision Support System and Precision Irrigation) and genetics. Agronomic options are analysed taking into account recent European agricultural and environmental trends of policies which conjugate the issues related to sustainability and production intensification. In perspective, the review encourages discussion on how to relocate farming systems within natural cycles, specifically those of the water cycle, based on No-Till Conservation Agriculture principles and practices which apply to all land-based agro-ecologies in all continents where agriculture is practiced.

Keywords: irrigation; water policy; crop intensification; Mediterranean climate; Conservation Agriculture; Decision Support Systems

1. Introduction

The one of final goals of "sustainable" agriculture is assumed to be the rational management and protection of renewable resources of the biosphere [1,2]. This definition fits well with that of water sustainability. The fact is that the rational and efficient management of water is aimed for in agriculture in order to preserve and perpetuate uses in the non-agriculture sectors [3,4]. Water is used not only for agriculture for the production of a wide range of commercial goods, from food to energy, but also for domestic, industrial and environmental purposes [5]. In the future sustainable (or rational) agriculture will play an increasingly important role in the conservation of water and, in general, of many other natural resources. The primary objective of any cropping system continues to be the increase in productivity and profitability of crops, particularly through sustainable intensification. This provides opportunities for optimizing crop production per unit area, taking into consideration the range of sustainability aspects including potential and real social, political, economic and environmental impacts [6,7]. Available good practices and scientific knowledge can allow the achievement of intensification of irrigated crops without neglecting sustainability principles.

Aware of the aforementioned, in recent years European Union (EU) [8] legislation has been moving towards the development of a bio-economy strategy. The European Commission Communication "Innovating for Sustainable Growth: A Bio-economy for Europe" identifies as a priority the improvement of basic knowledge and innovation in order to achieve higher productivity, ensuring sustainable use of natural resources and reducing stress on environment. Bio-economy strategy proposes to be synergetic and complementary with other instruments, sources of funding and sectors that share the same priority. For water, these objectives are included in the European Commission Communication "A Blueprint to Safeguard Europe's Water Resources" which identifies with: efficiency incentive water pricing, metering take up, efficient water use in agriculture, maximization of the use of natural water retention measures, maximization of water reuse and the use of Decision Support Systems (DSS), all of which are the necessary elements for sustainable water use. Finally, the development of bio-economy to sustainable growth addresses the commitments made by EU on the international part of the Agenda 2030 of the United Nations for Sustainable Development and for the G7 Alliance that provides 17 Sustainable Development Goals to combat poverty, protect the planet and achieve prosperity.

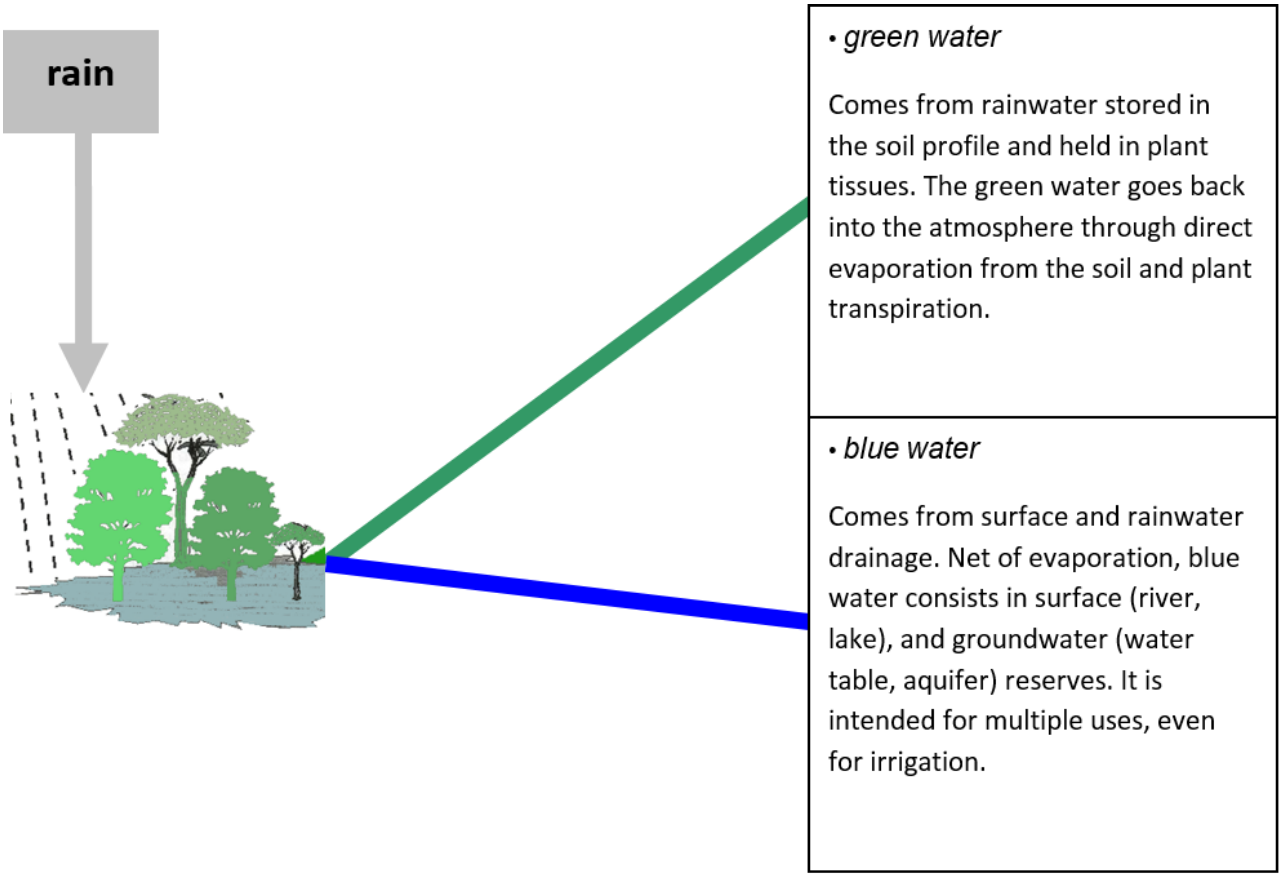
In this review two different parts are presented. In the first (sections 2–6) the issue of water scarcity and water use by agricultural systems are depicted, focusing mainly on the Mediterranean area. In the second (section 7), three major issues are briefly presented for improving water use efficiency from a hydrological and farm point of view: DSS, precision irrigation and genetics.

2. Green and blue water to meet crop water requirements

Water required by a cropping system is the volume of water used during the whole cropping cycle and is usually split into three categories: green water (GW), blue water (BW) and grey water (GW). GW which represents the water infiltrating into the unsaturated part of the soil to be used for crop growth, while the BW is fresh surface and groundwater, and which accumulates in water bodies (natural or artificial), superficial or even underground (Figure 1). The polluted water is the grey water, quantified as the volume of fresh water needed to dilute the pollution load, and lower the concentration of contaminants, to environmental quality standards.

For planning the use of water resources for crop production on a territorial scale, it is necessary to quantify how much GW a given environment can make available for crop growth, and how much BW (with the use of irrigation) is required to meet the evapotranspiration needs of the crops grown.

From an agronomic point of view, knowledge of both GW and BW is necessary to identify the highest level of water use efficiency that can be managed for each cropping system [10]. In addition, the division between GW and BW proves to be useful in comparing various agricultural options for identifying those that allow a better exploitation of GW, while reducing the amount of BW to be supplied to the cropping systems through irrigation [11]. This approach is also of help in using water resources in agriculture, according to sustainability principles.



Comes from rainwater stored in the soil profile and held in plant tissues. The green water goes back into the atmosphere through direct evaporation from the soil and plant transpiration.

Comes from surface and rainwater drainage. Net of evaporation, blue water consists in surface (river, lake), and groundwater (water table, aquifer) reserves. It is intended for multiple uses, even for irrigation.

Figure 1. According to a scheme proposed by FAO [9], the water cycle originates from rain and has two pathways of two different colours.

3. Water sustainability begins from agronomic practices

Sustainability today has become a must for agriculture and therefore for Agronomic Studies [12]. As for water, they are evolving in the direction of sustainability, interacting with other scientific disciplines and with the support of technologies that become gradually available [5,13,14]. Agronomic practices cover wide range of issues in the use of water: i) from the interception of rain to the protection of water resources; ii) from the control of the excess water to crop water supply; iii) from the determination of the crop water requirements to reduction in the wastage of water; iv) from the efficiency of water used by crops to landscape conservations [15]. Comparing the different agronomic options for sustainable land management, the Conservation Agriculture approach appears to be the most cost-effective way of soil, land and production management to improve water availability at the farm and landscape level.

All the above agronomic and water features assume the existence of systems for measuring the water volumes. Given the importance of this issue for a sustainable use of water resources, EU Commission [16] has linked to it the funds supplied for the rural development. Thus, Member States have to start building systems for quantifying water volumes and, over time, to implement pricing policies able to provide an incentive to use water efficiently. For the EU Commission, pricing is a powerful awareness-raising tool for consumers and combines environmental with economic benefits, while stimulating innovation, with metering being a pre-condition (*ex-ante* conditionality) for any incentive pricing policy.

When validated by farmers directly dealing with cropping systems, and accompanied by the shared consent of the community, the agronomic innovations automatically become current agricultural practice. The process of generation and uptake of innovations could be speeded up if agronomy were recognized not only as a function of producing foods and raw materials for agro-industries, but also for generating a number of vital services for ecology and for society. The consequences of these policies are immediately evident in terms of landscape conservation. Farmers who, through best practice, continue to take care of their own land, indirectly protect the places where they are living and, at the same time, provide the community with control and safety of the territory, as well as job and other livelihood opportunities [17]. Maintenance of the environment, which results from the application of rational agricultural practices, deserves the greatest interest from society. Sustainable agronomy should be “culturally” recognized as the point of convergence of different interests, ranging from the legacy of historical landscapes, to today’s health of the planet, to the green economy of tomorrow [18]. For all functions and positive externalities associated with environmental friendly agricultural practices, agricultural policies are finally starting to recognize a remuneration, or other form of benefit, to the farmer. However, environmental functions of the agricultural sector are not all completely recognized and remunerated. Research and innovation can help to unearth and analyse those important issues.

Rice cultivation is the paradigm of water-demanding crops threatened by climate change. It is a crop of fundamental importance for food security, but it consumes 50% of all fresh water used in agriculture. When researchers, decision makers and farmers are in constant touch, continuous progress is possible to achieve from the scientific, economic and social issues of importance to rice production. The System of Rice Intensification (SRI) is a programme of research and co-operation, first assembled by Fr. Henri de Laulanié in Madagascar some three decades ago and promoted globally by the College of Agriculture and Life Sciences of the University Carnell (Http://sri.ciifad.cornell.edu/research/JournalArticles.html). SRI has demonstrated in more than 50 countries how it is possible to continue to increase yields, consistently with much reduced water requirement and with increased sustainability of the environment. The SRI project at Cornell, as well as the monitoring of scientific publications on sustainability in rice cultivation, connects field operators to researchers in a continuous exchange of information and actions. This exchange feeds mutual interests and, above all, produces socio-economic and environmental effects of the utmost importance. As a result, farmers adopting SRI agro-technologies use 40–50% less water, and produce 70–100% more rice [19].

Conservation Agriculture and soil water capacity

Usually, Conservation Agriculture (CA) is known to store carbon from the atmosphere in the soil and achieves a soil richer in biological fertility and biodiversity [20]. The same should be done for water: the conservation agro-techniques in irrigated or rainfed cropping systems, are set up to store natural water in cultivated fields for the benefit of the crops. If, at farm level, the soil is managed according to Conservation Agriculture principles and practices, water availability improves because of the greater water infiltration and increased water retention capacity of soil under CA system, and, in turn, it results an improved crop water productivity while sustainability principles are respected.

Water availability improvement through CA, whether rainfed or irrigated, aims at the reduction of loss (mainly runoff and evaporation) and the enhancement of the amount of water stored in the soil. The practice of zero tillage and soil mulch cover in CA systems is widely used globally to reduce the loss of unproductive water, and also to allow roots to access deeper soil layers. CA aims at improving the potential infiltration rate in a technically feasible and cost-effective way. Infiltration of water on the surface of the soil can be improved by either increasing its rate (due to presence of good soil structure and continuous macroporosity, mainly biopores created by macrofauna activity and former root channels), or by extending the time that water has to infiltrate (soil surface roughness and the overall slope of the plot are the main factors affecting the infiltration time). Since in CA soils the surface tends to be permanently covered, and the soils have good pore volume, the infiltration rate is higher. The presence of crop residues on the soil surface and cover crops increase the soil roughness and dissipates the energy load of raindrops before they hit the soil surface. Moreover CA develops and protects the soil's aggregate stability, reducing or avoiding the kinetic impact of raindrops (or of sprinkler irrigation systems) that would otherwise lead to the breakdown of aggregates, surface sealing, runoff and soil erosion. Same can be said about the negative effects on the soil structure due to the mechanical impact through tillage equipment or wheeling. A consequence of soil structure damage is soil particle detachment. Consequently, the soil surface tends to seal and form a crust, difficult to infiltrate. A sealed soil does not capture water to store within, and tillage drastically reduces soil pore volume, leading to surface waterlogging and runoff (Figure 2).

Figure 2. Foggia (CREA "Podere 124"), southern Italy: comparison between Conservation and Conventional Agriculture techniques. After a summer storm, the rain infiltrates the soil in the case of "Zero tillage" (Conservation Agriculture); while the crust on the soil surface prevents water infiltration in the case of "Conventional" Agriculture.

In synthesis, CA contributes to improving water infiltration through field care aiming at: avoiding or minimizing mechanical soil disturbance (to avoid aggregate disruption); increasing organic matter content in the soil (which allows for aggregate formation and subsequent stability); maintaining crop residues on the soil surface (and growing cover crops which reduce the impact of raindrops). As a long term strategy, since CA does not disturb the soil, the development of vertically oriented macropores is promoted (through the activity of earthworms and other soil micro-fauna, and the maintenance of former root channels) and, in turn, the percolation rate is improved. Moreover, after infiltrating the soil, vertical water movement is mainly influenced by gravity forces and the drainage process is not hindered in CA soils. On the contrary, conventional soil tillage disturbs soil and contributes to a reduction in the volume of mesopores. Further, under conventional tillage agriculture the effective deep percolation is reduced because of the presence of compact layers or hard pans originating from repeated intensive tillage operations by heavy machines.

In semi-arid regions, CA systems have shown to improve soil water availability considerably both through higher infiltration rates and reduced evaporation losses [21]. Moreover the soil water holding capacity is enhanced as a result of the increased percentage of mesopores and of soil organic matter content which ensure their stability in time. In other words, in the Mediterranean climate, CA becomes a feasible tool to intensify crop productivity in a sustainable way [22].

4. Water between agricultural and environmental issues

The sustainable management of water resources is closely connected with the implementation of rational agricultural systems [16]. Where landscape agronomy (the farming systems which deal with the agricultural landscape dynamics) is practiced with conventional tillage system, landslides and floods are phenomena that can be predicted and controlled [23,24]. Where there is no monitoring of the environment nor agronomic care of the land, consequences are quantified in terms of human life: in Italy from 1968 to 2012 landslides have caused 5192 victims, and floods 1563 victims (CNR-IRPI, Research Institute for hydro-geological Protection). These facts, at least in part, can be predicted and have been repeatedly reported to governmental authorities by experts, but have been inadequately and thoughtlessly tackled.

The new frontier of agronomy leaves the boundaries of farms to address the ecological and functional relationship between cultivated areas and surrounding environment and resources. Emblematic is the case of water: cropping systems together with forestry and pastoral systems are planned in order to intercept and distribute rainwater. With the adoption of rational cultivation practices such as CA, the hydrological cycle is not interrupted, leaving unchanged the quality of drained or runoff waters.

Despite its simple molecular, water poses to science difficult challenges [25]. Water is considered one of the most precious natural resources, so much so that it determines economic and social development [26]. Nonetheless, every part of the Earth will continue to collect fresh water and to return it to the environment when it is no longer pure (it becomes grey water). In many areas, it goes so far as to pollute the water resource through carelessness, even before using it. Water is wasted and defiled because the correct value is not given to it. Beyond the symbolic value, linked to purity, soul, maternity, life, health and youth, water has a socio-economic value. In addition, water is associated with an undisputed environmental value. However, with the depletion and degradation of water and the collapse of the environment collapses, existing forms of life become incompatible.

5. The management of water resources

Water reserves are disputed between the basic needs of man (starting from drinking), economic development and environmental protection. The proper allocation of water resources remains a complicated problem, unless the rules of "shared management" and of ecological sustainability are adopted. Consensus and ecology pave the way for sustainable development [27,28]. Population growth makes sustainable water management an urgent challenge. Earth was inhabited by two and a half billion people in the 1950s, which became six billion in 2000 and will become 9.2 billion in 2050 [29]. Forecasts are easy to guess (Figure 3). OECD [30] estimates that in the near future (2030) the number of those living in conditions of severe water restrictions will increase at a faster rate than the population growth. The 2030 Water Resources Group [31] retains that agriculture will continue to be the productive sector consuming most water (Figure 4).

To add complexity to water management, the climate is changing. As a result of global warming, the water cycle will undergo an acceleration. From this information, it follows that in the future, the differences between lands without water (arid and semi-arid areas) and lands with water (humid and sub-humid areas) will be accentuated. Moreover, the amount of water per capita will become less and less [32], at all latitudes of the planet until stable population is reached at the end of this century. For 30% of the world there is not enough drinking water, with easily imaginable consequences on health and infant mortality. To the problem of water scarcity, we also have a cost issue: since 1960 the cost of water has doubled [33].

By analysing water users' data on a spatial scale with greater resolution, particularly critical situations can be found, such as in the Mediterranean region. Here, water resources have always been chronically scarce, but the population is growing, especially the southern Mediterranean Sea shoreline is concerned.

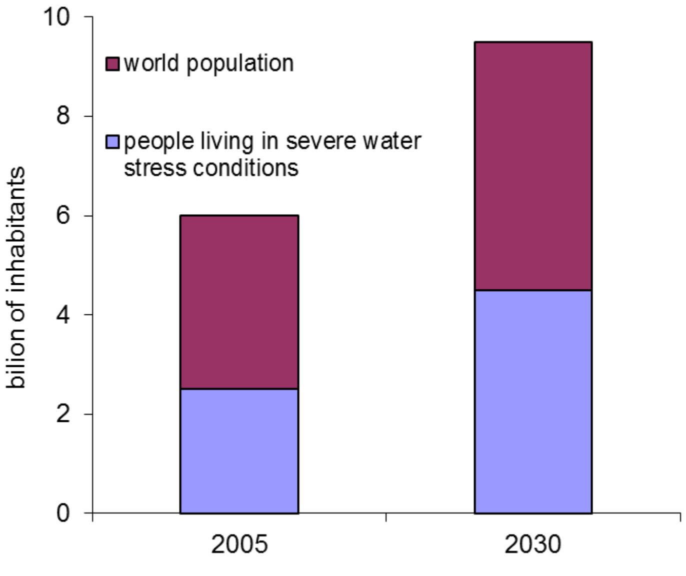


Figure 3. World population and the population that lives in water limiting conditions [30]. The estimate of 2030 is compared with the data in 2005.

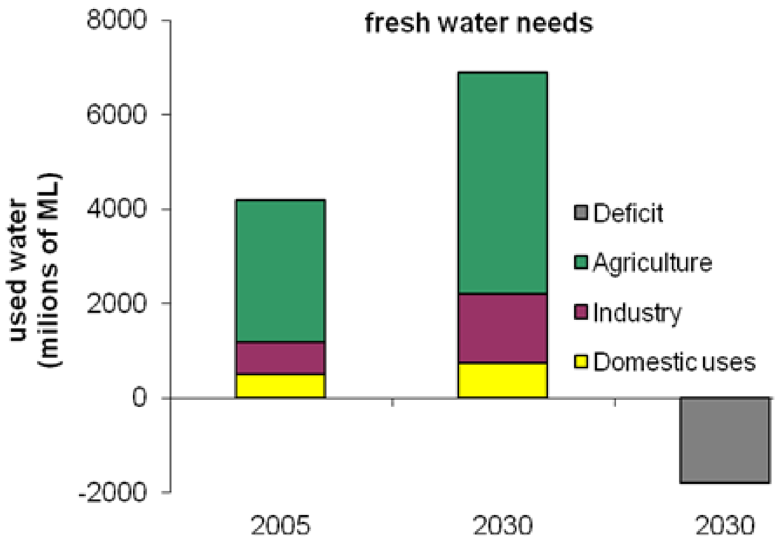


Figure 4. Requirements of fresh water in the near future (2030) and in 2005 [31].

6. Agriculture and sustainable water management

Agriculture is fully involved in water management because it is supposed to provide food and raw materials, social welfare (employment, income and development) and protect the environment which is often not the case with conventional tillage agriculture. Sustainable management of water means to seek a new balance between water resources, basic needs of humans, development and environment. It can be stated that the sustainable management of water resources is mainly an agricultural issue. In fact, most of the water is used in agriculture. In the developing countries of arid areas, more than 90% of water withdrawals are used for irrigation [34]. However, in semi-arid areas, satisfactory production is not achievable without irrigation [35].

Currently only 18% of cultivated land on the planet is irrigated [36] and from here 40% of agricultural production is obtained [37]. Increasing the irrigated area does not seem possible, as it is impossible that water resources will increase. However unconventional waters may contribute to the waters potentially available for irrigation: after treatment, low quality water, municipal waste water or even sea water could be used for irrigation. For water desalination, the major issue is energy, and if future energy will be cheap, and environmentally friendly, water resources could be certainly increased. At the moment it is likely to reduce the waste of water in irrigation management and to assume an increase in yield per unit of cultivated surface, if appropriate agronomic innovations, particularly CA, are heeded, aiming at increasing the efficiency of the water used by crops [38] and reducing degradation. It is also plausible to assume that unconventional waters (brackish water or reclaimed wastewater) are integrated with conventional ones to be used within irrigation in a sustainable way [39].

Sustainable water management is an example of how the interests of society are meeting with those of agriculture. The agriculture and forestry systems regulate the distribution of natural flows of water (Figure 5) and determine how much water goes back into the atmosphere (evapotranspiration), how much flows on the ground (surface runoff into the reservoirs or water courses) or is stored in the soil profile or drains into the deeper soil layers (recharge of water tables). Transpiration from cropped surfaces, as well as determining the levels of biomass produced, helps to mitigate the climate and changes the microclimate. However transpiration is also a cause of stress for crops when the climatic evapotranspiration demand exceeds actual crop evapotranspiration. Surface runoff and drainage alter the quality of water supplies if the water also carries chemicals or undesirable microbes.

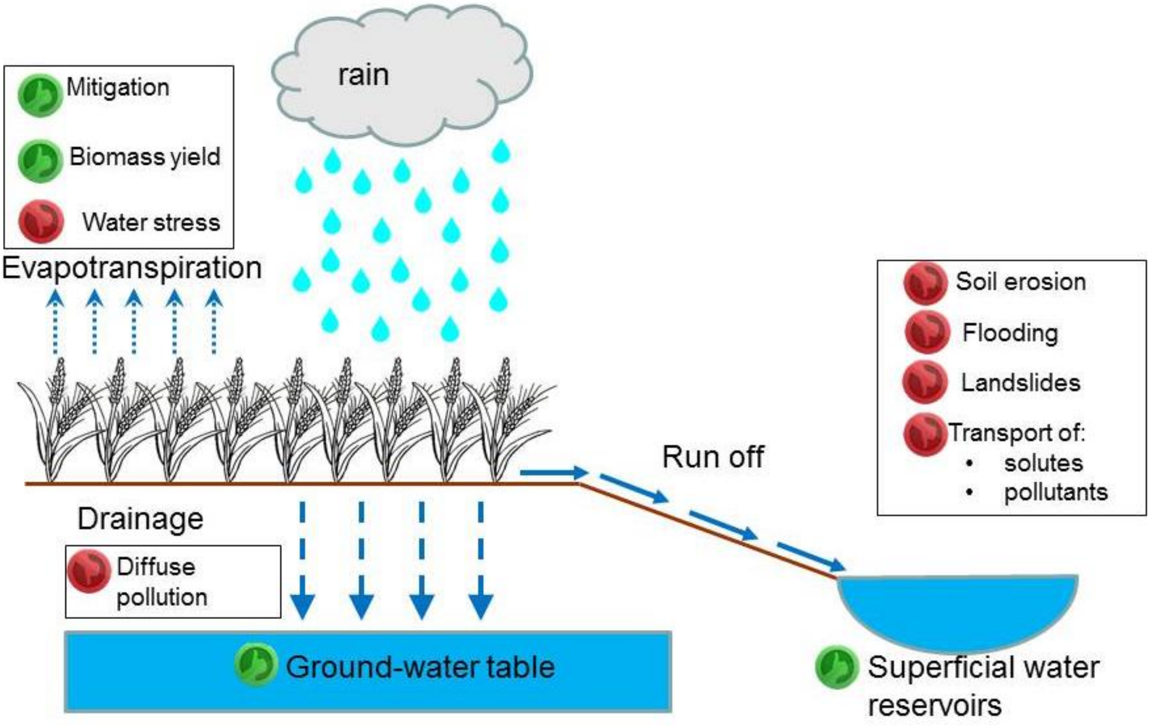


Figure 5. Breakdown (evapotranspiration, run off and drainage) of the natural flows of water (rain), modulated by cropping systems: the possible negative effects are covered by the thumbs down (in red), and the positive ones in green.

In other words, rational agriculture such as CA, by modulating and protecting the water cycle and water balance, offers undisputed benefits to society ranging from crop production to the formation of water resources of good quality, and climate mitigation. The negative consequences arise, primarily, from improper observance of agronomic principles such as the practice of tillage, poor soil health management and mono-cropping. Even in most orchards in the Mediterranean agriculture, intensive tillage is practiced leading to severe land degradation and erosion.

7. Optimizing water resources

Water scarcity is a difficult problem for humankind. Food security is closely dependent on water availability coupled with the access to technological tools. In fact, in economically advanced countries, cases of undernourished people are rare. Rainfall ensures the natural renewal of water resources, however strong differences of water availability may exist at local scales. To regions with abundant water resources there are others where, due to insufficient rainfall, the drought period extends for months. The need for water by crops corresponds to evapotranspiration, determined by weather conditions and the crop development stage but also whether the crops are part of the conventional tillage agriculture or part of CA. So far water withdrawals for agriculture concern rivers, lakes and groundwater.

However, the idea of using treated wastewaters should be seriously considered (with the advantage of lightening the pollution load of receiving water bodies), as well as water desalination. In fact, those practices are identified as important measures towards efficient and sustainable water management laid out both in the Blueprint to Safeguard Europe's Water Resources and the EU Action plan for the Circular Economy [40]. This EU communication shows that the reuse of treated wastewater in safe and cost-effective conditions is a valuable but under-used means of increasing the water supply and alleviating pressure on over-exploited water resources in the EU. So Member States have to incentive this practice taking a series of actions to promote it, also because it contributes to nutrients recycling by substitution of solid fertilisers; the European Commission is starting to work on common legislation with regards to the minimum requirements for reused water.

The main objective of the optimization of water use is the formation of sufficient water stocks for drinking, and for municipality, industry, environment and agriculture. The resources are built-up with new reservoirs and efficient distribution networks. The construction of new dams is opposed when adequate scientific information and local agreements are lacking, which represent crucial elements that give to the infrastructure the shared character of sustainability [41].

Water collected in reservoirs, checked for quality and then conveyed to the users has to have a cost. Agriculture should pay a political price, in view of the fact that, without rain and irrigation, land productivity decreases and yields are variable [42]. Proper water management is not easy in semi-arid environments. The complexity depends on geographical location, topography and fragile geomorphology. These aspects must be added to the irregular rainfall regime that recharges water resources. Apart from the geographical position of the area (latitude and altitude), rains vary over time. As an example, the temporal analysis of the water deficit index (WDI), calculated on the basis of agro-meteorological data measured over a long period, is given in Figure 6. These figures represent the typical Mediterranean climatic situation. In the second half of the temporal series, the WDI trend curve is always above the median value. High values of WDI have been calculated not only during the dry season. Moreover, from Figure 6 it is possible to argue that, in any period of the year, the risk of water stress has risen in the last 25-year period. The figure also shows that the inter-annual variability of WDI data is higher over the last decades. From this example, important agronomic conclusions can be made. The main conclusion is that in the Mediterranean region irrigation water requirements tend to increase. To avoid crop water stress for attaining convenient yields, more water amounts must be diverted by water reservoirs. Generally a link exists between quantity and quality of water: higher the amounts of pumped water, faster is deterioration of the water quality, due to sea intrusion or to lower salt (or contaminants) dilution [43].

The deterioration also concerns the soil. In the temporal intervals when the natural offer of water (precipitation amount) is lower than the climatic evaporative demand of atmosphere (positive values of WDI), saturation cannot be reached in the soil, and drainage does not occur. Moreover the fact that the groundwater tables are not recharged without drainage, salts accumulated at the soil surface during the growing season are not leached and the risks of soil salinization should be considered. In the Mediterranean region, a series of few consecutive winter seasons without a natural drainage could represent the start of desertification [44].

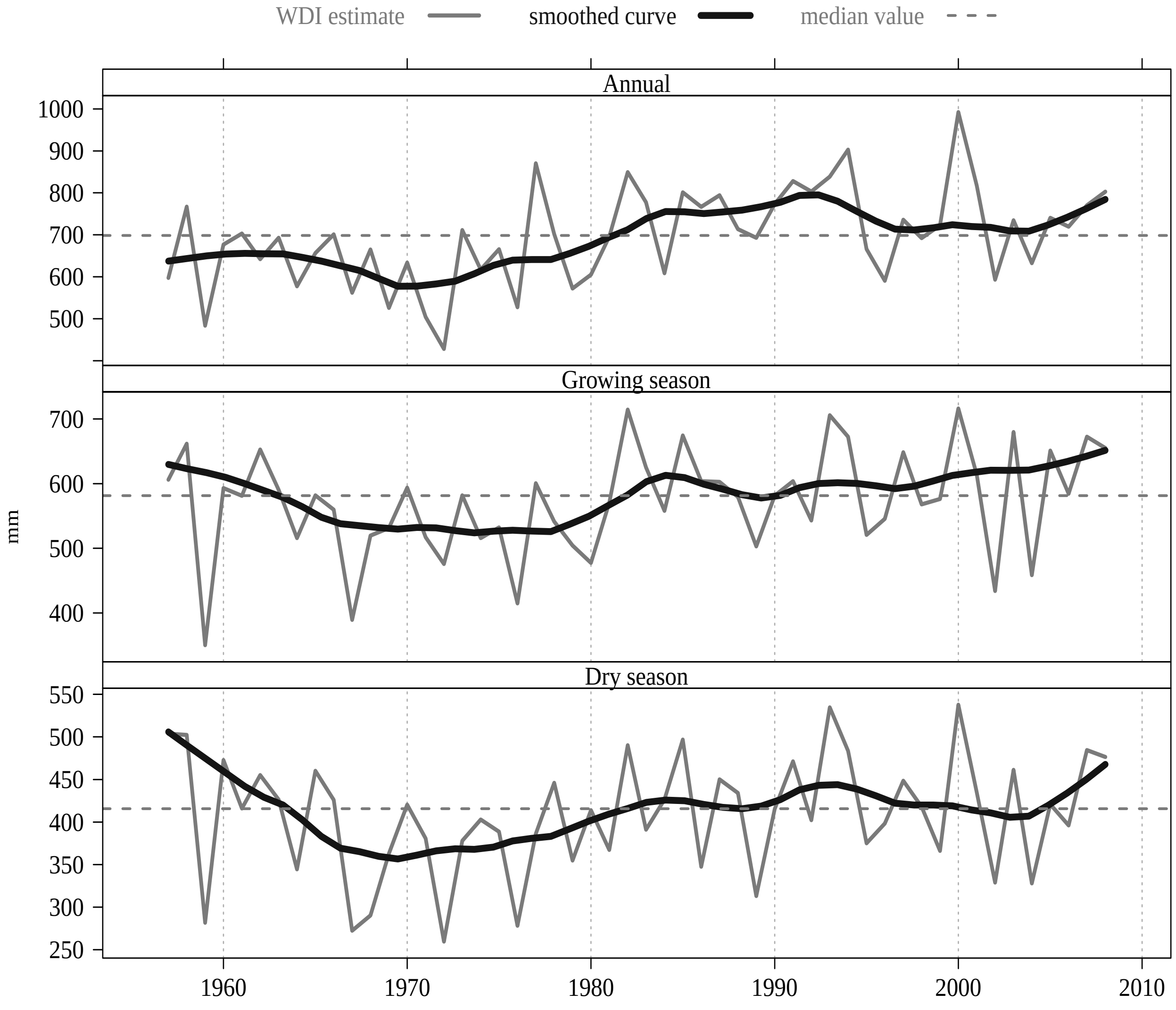


Figure 6. Changes over a long period (1957–2008) of climatic water deficit index (WDI), estimated as the difference between the reference evapotranspiration and the useful rainfall (in mm). Besides the estimates of WDI for each year, median values are reported along with simulation of the temporal trends (smoothed curves). WDI values were calculated for three time scales: annual, growing season of the tomato (April to August) and the "dry" season (June to August). The agro-meteorological data was recorded in southern Italy (at Foggia) [45].

In Italy the distribution of annual water consumption (42 km^3 or billion m^3 in total) in various sectors is: Civil = 8; Industrial = 8; Irrigation = 20; Energy = 6. Almost half of the total consumption of "Italian" water is destined for irrigation, even more in the Mediterranean Italy, with shares of 13.6 for South and 5.7 km^3 for the Islands. While, with reference only to irrigation (20.14 km^3 in all Italy), the South and the Islands, being 33% of the Italian surface, use a volume of water for irrigation that reaches 40% of the whole Italian consumption for irrigation. At a glance, a rough analysis of this data could indicate that irrigation in Mediterranean environments is an ecological scandal, since agriculture depletes most of the water reservoirs. On the contrary, from the Italian figures on irrigation, some general conclusions can be drawn.

However, when referring to irrigation, it should be considered a fact that part of the water supplied to the field crops returns in the environment. In fact, any excess water that is supplied with irrigation cannot be considered lost in an absolute sense because its final destination is in the aquifer, where water continues the hydrological cycle [46]. Without nitrogen (and other) leaching processes, over-irrigation by itself dismantles the harmlessness of an excess of water supplied to the crops. Moreover, the positive effect on the micro-climate due to the irrigated fields [47,48] should be also mentioned. Despite these considerations, water in agriculture continues to be perceived as a mere consumption. It is more correct to say that agriculture "uses" water for irrigation, or temporarily "rents" it from the natural resources.

It should be pointed out that in Mediterranean countries, during the last decade of the 20th century, there has been a reduction (22%) of irrigated farms and irrigated surfaces (9%). Reductions are expected in the future due to urban encroachment which further constrains availability of arable land. In this scenario, where there is less water available and an increasing demand for water from other sectors, agriculture is requested to reduce consumption. As for irrigation, this is possible thanks to the transfer of scientific research results. The benefits deriving from the applications of Information Communication Technologies (Decision Support Systems and Precision Irrigation) or Conservation Agriculture (discussed already) or genetics to the cropping systems are clear examples that it is feasible to save water under field conditions.

7.1. DSS

A Decision Support System (DSS) is an interactive software that can be used to define and solve a problem. In the case of cropping systems, DSS is an aid for people (the user) who, having personal skills and the access to information of different quality (environmental data, laboratory tests, field measurements, observations qualitative), wants to make a "rational" decision. With a DSS, the farmer can compare the possible solutions of the same problem. Moreover, users can get a better understanding of the processes and they will identify contingencies for saving in terms of investments (labour and external inputs) and of natural resources [49].

Several DSS applications concern water management and irrigation, at different spatial scales (plot, farm land, irrigation district). The structure of a DSS is essentially characterized by: 1. data-set input (soil, crop, weather conditions), preferably associated with a geographic information system (GIS); 2. simulation crop model; 3. interface with the user.

Those systems are strongly suggested by the EU Commission for an efficient and sustainable water management, and for water metering and monitoring. For this reason, within the new Rural Development Programming 2014–2020, with respect to the topic of water management for agriculture, Italy implemented a specific DSS called SIGRIAN (National Informative System for Water Management for Agriculture) for monitoring and metering volumes. Moreover SIGRIAN acts as technical support to the water and irrigation policies and investments.

7.1.1. Input data to DSS for irrigation scheduling

Soil data generally refers to chemical, physical and hydrological properties. More details, relating to the data spatial variability (horizontal and vertical), produce a better performance in the water balance calculation, allowing to switch from the simpler "cascade" approach (based on the Richard's equation), to the simulation of water dynamics in the soil at finer levels. A DSS user manually enters information about his cropped plot, or the whole farm. In case of applications on a larger spatial scale, the information relating to the soil is provided by the regional or national date-bases. Usually this data is geo-referenced and, through a GIS system, is easily accessible to the DSS.

The DSS requires meteorological data on a daily scale, at least for those climatic parameters that influence directly crop growth and phenology, and evapotranspiration. If DSS has to operate over a lengthy period, it could be satisfied with the information provided by national or regional meteorological networks and maps of land-use. Many DSS are built so that they can directly access the "meteorological information layer". For local applications, weather information input should be provided (manually or automatically) to the DSS, feeding the DSS with the outputs from agro-meteorological sensors installed directly on the farm. Finally if, in addition to the meteorological observed data, predictions for a short period (3–10 days) are provided to the DSS, irrigation scheduling will be much more effective.

GIS systems are used to connect a DSS at a large-scale. In the input phase, data with geographic coordinates will identify the points to be simulated, the fields, crops and climate. Data on land use, chemical and physical characteristics of the soil will be automatically uploads, as well as the connections to data-bases from nearby weather stations. In the output stage, through the GIS system, simulations made point by point will be returned to a map. On the contrary, for simulations on a lower scale, the DSS has to integrate GIS information (though geo-referenced systems) with a more detailed set of information. In this case, the spatial variability of soil properties, or distribution of crops within the farm, or of the micro-climate should be provided to DSS.

7.1.2. Crop models inside DSS

The DSS incorporates specific crop models to estimate on a daily basis increases in biomass and evapotranspiration (ET), as a function of intercepted solar radiation and assimilated CO_2. The modelling of the cultivated species is a study subject in agronomy. The crop models provide the dynamics of growth, water requirements and yield. Currently different models are available, especially for those crops that have a high economic value and for the most widespread. In practice, the range of model crops include cereals, legumes, but also vegetable crops and forestry.

Crop models can be designed for a single species or be "generic". In the second case, the models can be calibrated to any condition (environment and cropping system) and species (but also to the variety) with the appropriate parameterizations (tuning of the crop parameters). Depending on the model, the growth mechanism is driven by photosynthesis, from solar radiation or from the water.

In the case of the models based on photosynthesis [50,51], it is assumed that the architecture of the crop can be represented as a series of photosynthesizing layers. Knowing the leaf surface for each layer, and the distribution of the radiation inside the canopy, the assimilation of CO_2 (and increases in dry matter of the crop) is calculated. Starting from the top of the crop, the solar radiation is attenuated gradually through the layers of leaves. At each layer of the canopy, the radiation, in part, is transmitted to the next layer, partly reflected, partly intercepted and partly is absorbed by the leaves for photosynthesis.

Models driven by solar radiation [52,53] are founded on the assumption that, under optimal conditions, the biomass that accumulates during the crop growing season is linearly related to the intercepted radiation (photosynthetically active). This is a simplification that does not consider intermediate processes, but, even so, this approach is utilized in operative models of crop or cropping systems (CERES, EPIC, STICS, CropSyst) which simulate the effect of the limiting factors (usually abiotic), and their interactions, on the accumulation of potential biomass.

Models of the third type are driven by water [54]. The basic operative model was proposed by FAO in 1979 [55]. According to the FAO 33 handbook, the reduction in crop yield when crop stress is caused by soil water shortage can be given by:

$$\left(1-\frac{Y_a}{Y_m}\right)=Ky*\left(1-\frac{AET}{MET}\right)$$

Where Ky is a seasonal yield response factor. Ky seasonal values for 23 cultivated crops were reported in the FAO 33 handbook.

Actual water driven models are based on the concept of water productivity (WP) or on the concept that, in the absence of water and mineral restrictions in the soil, the biomass accumulated during the crop cycle is proportional to how much water the crop has transpired. The coefficient WP, if normalized to the evaporative demand of the environment, is a characteristic value of each species. The concept of WP has been introduced in some models (CropSyst or AquaCrop), proving to be useful mainly in environments without water deficiencies [56,57].

However it should be underlined that all the above models (driven by photosynthesis, radiation or water) are built upon crops being managed in conventional tillage agriculture, and generally for single crops as opposed to the whole cropping system in space and time. Moving from conventional to CA, the water related benefits (water use efficiency, water productivity, better production factor productivity, water savings, effective water cycles, less negative impact on the environment, less pollution) should be taken appropriately into consideration and incorporated in the crop models operating within the DSS, so that water use efficiency, crop water productivity and productivity in general can be modelled more comprehensively.

7.1.3. DSS interface

The interface allows for dialogue between the user and the DSS. Usually a successful DSS depends on how easy it is for the user to provide and receive information. The attribute that qualifies this feature is “friendly”. A good interface is not “boring” and gives the user satisfaction in using it. A friendly interface must treat the graphic line, the colours, the functions, the buttons and connected sounds, so as to attract the attention of the user and to provide outputs which are easy-to-use. To use the output of the DSS there are two possibilities. 1) The user can receive the information in several ways from the DSS, through SMS (short messaging service), MMS (multimedia messaging service), or maps displayed on smartphones and tablets. The DSS notifies that it is time for watering a plot and the specific water volume to supply. 2) The user is directed by the DSS to know the status of soils and crops, the growth stage, the potential risks of immediate stress or he is supported in planning the entire irrigation season.

Depending on the needs of the user, this information has different spatial scales. In the case of a river basin, or of an irrigation scheme, a DSS can be used to make decisions about the water policy, analysing costs and revenues, and involving the different stakeholders, including farmers. A DSS operating at large scale becomes a support when deciding how to use the water and the land, with the appropriate technologies and policies (such as pricing of the irrigation water, and environmental safeguard).

The spread of the DSS is connected with the development of computer technology and the familiarity of farmers with tablets and smartphones. Not unusual for applications in irrigation is the possibility that a DSS, has, connected in the field trough, wireless sensors, cameras and solenoid valves (to activate the irrigation), allowing the farmer to remotely control irrigation. In this way irrigation becomes easy and highly precise. This type of control is more frequent in the garden or in the greenhouse, but it is with the open-field crops that it becomes more economically and environmentally valuable.

7.2. Precision Irrigation (PI)

Irrigation aiming at “precision” requires an accurate estimation of the real water needs of the crop and “precise” application of this volume of water at the appropriate time. The common way to conceive precision irrigation is that water should meet the needs of the crop without delay, using efficient and uniform systems for supplying water to the plants in the fields. To reach such an objective high accuracy is required both in determining the time and the volume of water to be supplied, which entails the control of water delivery (only the amount of required water is applied: high volumetric efficiency) and the design of the irrigation system (each plant, or surface unit, receives the same amount of water: high spatial uniformity).

In synthesis, the irrigation aiming at “precision” is commonly perceived as an approach aiming to ensure the efficient and uniform distribution of water so as to satisfy the water requirements of the crops, in the hypothesis that canopy and soil were uniform. Irrigation aiming at “precision” consists in applying an exact amount of water at the right time, but uniformly over the entire field. The question is: does an average value of the field represent the whole spatial variability in the field?

On the contrary, the concept of Precision Irrigation (PI), in the context of PA (Precision Agriculture), differs significantly from the traditional irrigation since it takes into account the spatial variability inside fields and vegetation. PI uses a systemic approach to differentiate irrigation rates based on the space-time variability of the field (site specific irrigation).

In the literature PI has different definitions [58-62] which, however, share some elements:

- PI relates to the optimal management of spatial and temporal components of water and irrigation;
- PI requires a holistic approach: that optimizes the distribution system of irrigation, consistent with the management of water, fertilizer and agro-techniques;
- PI is not a specific technology, but a way of thinking that requires a systemic approach. You can optimize crop yields only through the collection and treatment of different types of data from different sources (data fusion), regarding both the plant and the field. The realization of a system of PI requires the use of different technologies for the management and application of irrigation, together with those of sensors (proximal and remote), modelling and control;
- PI is applicable to all crops and irrigation methods, with special emphasis to the appropriate spatial and temporal scales;

- PI systems can deeply change the way we manage the farm and pursue multiple objectives, such as increasing the efficiency of use of agronomic inputs, reducing environmental impacts, increasing profits of the farmer and the improvement of product quality;
- PI can be considered as a continuous learning system. The analysis of the performances (from the engineering, agronomic and economic points of view) provides a sort of feedback for the achievement of future improvements in water saving.

The above definitions of PI are sufficiently broad and inclusive and clearly show how the use of sophisticated technologies is not actually essential to its implementation. This does not exclude that the PI uses the most advanced technologies of management and water distribution, combined with those of sensing, modelling and control to achieve best performance.

An ideal system of PI should include Variable Rate Technology (VRT), Robotics, Automation, Information Technology and Communication (ICT); Real-time control.

7.3. Genetics

Apart from these two above examples (DSS and PI), the progress of genetics applied to cropping system agronomy should not be neglected, when breeding efforts accompany the cropping systems together with sustainability in the use of water and soil.

For the Mediterranean growers, breeders have made available a wide range of varieties having a shorter spring-summer cycle, which consume less irrigation water. Moreover, if made more hardy to resist cold weather, these varieties can be sown earlier in the winter season. In the first stages of their cycle, plants can profit from rains which falls at a high probability during the period between the end of winter and the beginning of spring seasons.

Generally in the semi-arid regions the choice of rainfed crops should be addressed to the species having an autumn-winter cycle, when it rains at a higher probability and the evapo-transpiration demand of the atmosphere is low. In case of water supply, farmers should choose cultivars compatible with agro-techniques expressly designed for reducing the evapo-transpired water in the environment [63,64], or tolerant to irrigation with low quality waters.

8. Perspective and conclusions

The above analysis provides an original role of agriculture within the frame of sustainability [65]. Sustainable water management in agriculture is the rational arrangement of different segments of knowledge covering three main issues: the environments of Agriculture, up-to-date technologies, functional agro-ecological relationships between water, soil, landscape and cropping systems.

An original perspective could derive from combining Conservation Agriculture (including System of Rice methods now applicable to other crops) and digital agriculture (DSS and Precision Irrigation) in order to achieve the highest water use efficiency and water productivity. Such a blend of agro-technologies, along with the progress from genetics, allow for the design of new cropping systems which are able to match and optimize their components to the water cycle, as well as to the cycles of nutrients and carbon.

However, agronomic research allows farmers and stakeholders to build countless interactions that exist when addressing the nexus Food-Water-Future. If motivated towards sustainable agriculture, each user of the research results can discover new possibilities, not yet evident to the researcher for intensifying the crop production through the better use of water. Innovations come from the operative application of agronomic science by farmers, rich in site-specific values, but perfectly in tune with the international scene, and ready to be used globally within agriculture.

The analysis suggested in the paper is in line with the approach proposed by UE Commission in the bio-economy Strategy Communication and can usefully contribute to the European debate on water efficiency for all uses. In fact, the Action Plan for bio-economy strategy aim to improve the knowledge base and foster innovation to achieve productivity increases while ensuring sustainable resource use and alleviating stress on the environment. In particular, Action Plane provides to ensure substantial EU and national funding, as well as private investments and partnering, for bio-economy researches and innovation.

The final goal is to increase the share of multi-disciplinary and cross-sector researches and innovations in order to address the complexity and inter-connection of society challenges by improving the existing knowledge-base and developing new technologies. In this context, the scientific advice is crucial for supporting informed policy decisions on benefits and trade-offs of bio-economy solutions. Sadly, most of our agriculture (some 90%) is based on the degrading tillage paradigm. This must change in the coming decades to Conservation Agriculture so that agriculture can intensify sustainably with maximum water use efficiency and maximum water productivity while delivering a full range of ecosystem services to society.

Conflict of interest

Both authors declare no conflicts of interest in this paper.

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