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Analysis of the current world biofuel production under a water–food–energy nexus perspective

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ABSTRACT

This paper assesses the sustainability of bioenergy production under a nexus perspective through a new efficiency type index. The index describes 1st generation biofuel production under the perspective of the implied consumption of natural resources. We consider the sustainability of energy production as a sequence of steps, each characterised by its efficiency, and propose an index which returns an overall efficiency value describing the adequacy or inadequacy of the considered processes under a nexus perspective. The direct application of the nexus index entails an indication of the possible improvements needed to move production towards most sustainable processes or places. Moreover, it allows evaluating the efficiency of the main crops currently used in biofuel production with respect to the water–food–energy nexus. The results depict countries presently capable of performing sustainable production of 1st generation biofuel from particular crops. Furthermore, the analysis of the single components of the nexus index allows understanding the effects of possible improvements (e.g. soil and water management, new generation biofuels) on the overall production efficiency under a nexus perspective.

1. Introduction

Some of the most debated topics for science in the 21st century are related to energy availability and production (IEA, 2014; Johansson, 2013). The need for more energy, due to population increase and global economic growth, is conflicting with the request of lower CO_2 emissions and decrease our reliance on fossil fuels (Edenhofer et al., 2011) The concern for food security, water scarcity and land consumption are becoming day by day more important and these aspects are far from being independent from energy production and use. The strict link among energy, food and water is generally referred to as the water–food–energy nexus (Sanders, 2015).

It is impossible to bound the analysis of energy production to a single limited sector because actions aimed to locally optimise the efficiency can, at the end, cause the settling of the global system to a condition worse than the initial one (Dubreuil et al., 2013).

In this context, the production of biofuels is a point of great debate amongst scholars. Recently, decision makers have given many incentives to the production of energy from renewable resources, finding in biofuels a good opportunity to decrease CO_2 emissions (EU parliament, 2009; EU commission, 2010; US Congress, 2005; US Congress, 2007; IEA, 2012). In fact, biofuels can decrease CO_2 emissions in energy production with respect to fossil fuels since they produce energy from a feedstock with lower life cycle time (Bentsen and Felby, 2012; Da Costa et al., 2010; Campbell et al., 2008; Dornburg et al., 2010) At the same time, they can increase the quote of self-produced energy for many countries (Amineh and Crijns-Graus, 2014; Thöne et al., 2009; Favero and Pettenella, 2014). Nevertheless, the use of edible crops as feedstock for energy conversion is in direct competition with food production (Harvey and Pilgrim, 2011), affecting water and land management. This is due to the higher request of crops caused by the simultaneous demand for food and feedstock for energy production (Gude, 2015). Moreover, the crop yield is often increased by massive irrigation, giving a higher food production, but accompanied by a low efficiency in the use of water resources.

The design of energy production systems, carried out taking into account all these aspects, is a challenging duty. A specific design method is far from being completely defined (Howells, 2013). The current energy, food and freshwater supply systems are optimised to give the maximum possible output in terms of the commodity or/and source they are designed to produce or deliver (Cosgrove and Louck, 2015; Hejazi et al., 2015), This leads to the creation of systems which are efficient in their own scope, but which are far away from the absolute optimal point in

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terms of sustainable use of water and energy resources under a food-energy-water (hereafter, FEW) nexus perspective.

Many authors have analysed the single subcomponents of water–food–energy nexus and many indicators exist to analyse the effect of 1st generation biofuel (as a definition, 1st generation biofuels are liquid fuels produced directly from crops otherwise used for food production. This distinguishes these products from the fuels obtained from conversion of waste (2nd generation) or non-food crops) production in terms of water use and depletion, competition with food and land consumption. For example, indicators of water and land use for biofuel production already assess the impact of bioenergy production of any single natural resource they are dealing with (Rulli et al., 2016). However, just few attempts of analysing the interlinks between food, energy and water in biofuel production have been done (D' Odorico et al., 2018). and at our knowledge no indicator does exist to take in bioenergy production under FEW nexus perspective. Historically, two different works set the basis to define and analyse the concept of water–food–energy nexus. In *'The limits to growth'* (Meadows et al., 1972) important insights in the problem were given, but these hints did not form a single tool suitable for policy makers. This study placed the first milestone for the sustainability assessment, but it did not address the WEF nexus as a whole. Few years later, the method WELMM (Grenon and Lapillonne, 1976) was developed, directly focusing on five connected resources: water, energy, land, materials and manpower. This methodology provided the first example of dataset used for sustainability assessment, but it did not involve an integrated analysis useful under a WEF perspective. Nowadays, the way is still open for the development of integrated assessment models (Tol, 2006). This study proposes a new methodology for the FEW description, considering all the aspects of this concept and summarising them in a single simple indicator. Most of the existing models consider the single relationships energy-land and energy-water use. However, most of the available tools do not address the problem as a whole. The commonly used methods for energy system analysis include MESSAGE (Messner and Strubegger, 1995), MARKAL (Zonooz et al., 2009), LEAP (Heaps, 2012) models; on the other side, the WEAP (Stockholm environment institute, 2011) model is often used for water system planning. These models, while providing useful information in their application field, lack the data and methodological components required to conduct an integrated policy assessment (Bazilian, 2011). A tool, which should be simple enough to be useful for policy makers, but precise enough to well describe the current energy production under a nexus perspective, is still missing.

Here we propose a new index, which resumes in one single output the effect of 1st generation biofuel energy production on sustainability under a FEW nexus perspective. The index is aimed to analyse the interrelationship among water, food and energy in 1st generation biofuel production at the global scale and to assess the sustainability of biofuel production from a specific crop in a single country. For this purpose, the various components of the FEW Nexus are studied in detail for biofuel production from any specific crop, and, in order to define an efficiency type index, the use of the resources (water, food and land) is compared to a reference value (i.e. the least impacting use of the specific resource). This new index does not substitute the existing tools used for the analysis of the single aspects of the FEW nexus, but it integrates and complements them giving a preliminary assessment of the complex interrelations between the components of the FEW nexus.

2. Methodological framework

The design of an index assessing the FEW nexus should follow the deep understanding of the punctual indicators characterising the single aspects of the nexus itself. For this reason, we recall here some literature resources useful to address the single facets of the problem.

2.1. Water

Since this paper is focused on biofuel production, it is necessary to have tools for analysing the water required to produce a reference quantity of energy from biofuels. Water is not only used in energy conversion, but it is virtually contained in crops used as feedstock, because they require large amounts of water to grow (Finley and Seiber, 2014). A concept of principal importance in this field is virtual water (Antonelli and Sartori, 2015). Virtual water is an indicator used to describe the quantity of water required to produce a specific industrial output (Allan, 1993). This indicator is widely used to describe the embedded water in traded goods, as shown in the example of virtual water trade (Antonelli and Sartori, 2015). However, the virtual water concept is designed to assess the water embedded only in physical goods. When a commodity is used to produce other goods (derived goods) in further processes, the virtual water concept results not sufficient (Antonelli and Sartori, 2015). To extend the concept to derived goods, the water footprint indicator was developed. Water footprint changes the perspective with reference to virtual water: The former indicator allows the determination of the quantity of water used in production of goods and services, while the latter allows the quantification of the amount of water used during the process of consuming the same goods and services (Chapagain and Hoeksrta et al. 2003).

Water footprint is a fundamental concept, since it allows defining in a precise way the amount of water required to produce bioenergy. Many studies are devoted to this topic (Grebens-Leenes et al., 2009; Velazquez et al., 2011) The results of these studies will be used as a starting point in defining our "water-efficiency" index (see Section 3), but they describe only a single aspect of a complex problem. They allow determining the quantity of water needed throughout the production chain of biofuels, but they allow neither to understand the renewability of the water used, nor to relate it to the resources effectively used during production.

The sustainability of the water use has been related to a sort of hierarchy in the typology of water sources, with some sources more valuable than others, also from an economic point of view (Chapagain and Hoekstra, 2004). To address this problem, the concepts of green and blue water were defined. Blue water refers to the liquid water above and below the ground (rivers, lakes, and groundwater). Green water is the soil water in the unsaturated zone derived from precipitations (Gerbens-Leenes et al., 2009). Only green water is usually considered a renewable resource in the strict sense (Mekonnen and Hoekstra, 2010). Both green and blue water are intensively used in agriculture, but blue water is used in direct competition with other human uses (e.g. industries, municipalities...) (Rulli and D'Odorico, 2013). We do not consider grey water in this analysis because of the scarce accuracy and spatial homogeneity of the available grey-water footprint estimators (Novo et al., 2009; Falkenmark, 1986; Mancosu et al., 2015).

The separation of blue and green water is therefore useful to understand the overall sustainability of the process under a water perspective, in particular because analysing the blue water footprint allows one to quantify the impact of biofuel production on renewable resources. The share of renewable resources used for biofuel production is therefore used as the main component of our "water-quality" indicator.

Also considering the separation between the blue and green water footprint, one is left with a water efficiency indicator which lacks information about the abundance (or scarcity) of water in the production place. Water availability is accounted for by considering the World data bank Water Withdrawal Index as a further determinant of the index (see Section 3).

2.2. Food

The second element to be discussed in a water–food–energy nexus analysis is the possible interaction of biofuel production with food production, including both commodities used for human and animal nutrition. We do not aim to consider, separately for each crop, the amount of food which is subtracted to human consumption by biofuel production, because this kind of analysis would involve dietary and nutritional facets which are beyond the scope of the paper. In contrast, we want to include in our index the simple concept that, at the country scale, human crop consumption should be favoured with respect to the crop use for energy-production when malnutrition affects a non-negligible portion of the country's population. The reference concept in this field is thus food security. Food security is defined as '*a situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life*' (FAO, 2003). While this definition is rather simple, it is difficult to turn this expression into a quantitative index, which states the effects of food insecurity worldwide. We therefore refer, in the definition of our "food efficiency" index in Section 3, to a very simple and well agreed concept to at least roughly characterise food security in a country: the prevalence of malnutrition, as defined by FAO in each country.

2.3. Land

The third element to be investigated in the analysis is land. Land is the basic resource needed in agriculture and the quantification of land required to produce a defined amount of crop is a point of capital importance. Models are required to have a good understanding of the efficiency in exploiting this resource for any purpose.

The key parameter in agriculture is crop yield, defined as the quantity of crop produced for ha of land used (Gebbers and Adamchuk, 2010). Crops yield depends on crop type, climate, cultivar, soil and terrain conditions, level of inputs (water and fertilizers) and management.

Yield data suffer similar problems as data of food security because they are mainly the results of statistical measurements. Only punctual data are precise, but the recovery of such data is hard and they are not always suitable for further studies. The use of average or country-based data gives less precise indications on land yield, but in many cases, these are the only data available or usable (Barret et al., 2002).

Another important feature to be considered in a sustainability assessment of land use is the quantity of land available and suitable for agriculture. Together with agricultural intensification and increased application of fertilisers and pesticides, the expansion in cultivated area is the key factor for the increase in food production observed over the last 50 years (Khan and Hanjra, 2008). The total global agricultural area has expanded by 11% to 5 billion ha, and the arable land area has expanded from 1.27 to 1.4 billion ha (FAOSTAT, 2014). More land has been converted to cropping in the 30 years after 1960 than in the 150 years between 1700 and 1850 (FAOSTAT, 2014). These data are fundamental to understand the possible further increase in agricultural production and if the use of land is compatible to a sustainable development and changing climate regimes.

3. Materials and methods

Table 1
List of crops considered during analysis.

Crops considered for analysis	
Bioethanol	*Biodiesel*
Maize Rice Rye Sorghum Sugar beet Wheat	Oil palm Soybean

In order to assess the effects of biofuel production on global sustainability under a water–food–energy nexus perspective the current production of biofuels is evaluated by means of a new index, which we call the nexus index (NI). We calculate the nexus index for the most important crops used in biofuel production. The list of considered crops is reported in Table 1. The index is designed to evaluate the resources required, in terms of water, food and land, to produce one unit of energy (Fig. 1).

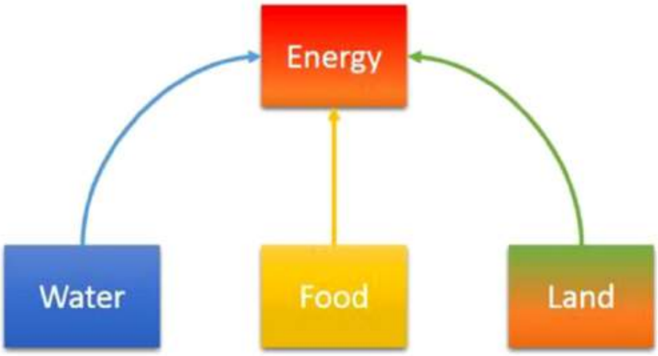

Fig. 1. Water–food–energy nexus under an energy perspective.

The formula of the nexus index is:

$$NI = \eta_{water} * \eta_{food} * \eta_{land} \tag{1}$$

which is the mathematical description of a system similar to the one shown in Fig. 1, where the use of three resources (water, food and land) is necessary to get the final output (energy). NI is the Nexus Index, η_{water} is the efficiency in water use, η_{food} the efficiency with respect to food production and η_{land} is the efficiency in the use of land. The first term (η_{water}) is linked to the water used for crop production, stating an efficiency with respect to the lowest quantity of water that is possible to use in a specific process. The second term (η_{food}) is country-related and describes the effects of the competition between biofuel and food production. The third term(η_{land}) takes into account the quantity of land required to produce one unit of product, again referring to the best attainable performance. This method allows comparing different systems, providing a result in the range between 0 and 1. In order to get a good score, a process must work with the best available technology, preventing the resources from being depleted and guarantee the water and food security and a rigorous use of land. The three parts have the same weight in the index, so that the inefficiency in a single step is directly translated into the result. The multiplication of 3 different factors is chosen in order to increase the influence the inefficiency of any single aspect of the index. In fact, thanks to the theory of limiting effects, if only one factor is not efficiently managed, the value of the index results strongly penalised. This form is preferred to other possible mathematical formulations (e.g.: additive form) to avoid the need of weighting factors, which would include more arbitrary choices in the index definition. The number of factors is limited to three to have a compromise between complexity in the data mining phase and precision of the index. The three factors determine the influence of biofuel production on the three most important elements that affects the water–food–energy nexus (water use, land consumption and food availability), giving a simple but precise indicator of efficiency.

In the following each component of the Nexus Index is described in detail.

3.1. Water efficiency

The water efficiency index is introduced for assessing the use of water related to biofuel production. To this aim this index considers both the amount of water and the source of water used for crop production (i.e. soil moisture due to precipitation, that is the so called green water or irrigation water, the so called blue water) required to produce a pre-defined amount of energy via biofuels.

The water efficiency is here expressed as the product of two terms:

$$\eta_{water} = \eta_{water.quant.} * \eta_{water.source} \tag{2}$$

The two terms are equally important and determine the efficiency of water use in biofuel production both for the quantity of water used and for the quality of this water.

The first part of this index refers to the quantity of water used in the steps required to produce the crop adopted for energetic purposes and to convert it into liquid fuel. In order to assess this quantity, the water footprint of energy from a selected crop has been calculated following the approach introduced by Gerben-Lenens et al. (2009). We then divide the bioenergy water footprint (in m^3/MJ) by the lowest global value of the bioenergy water footprint, which corresponds to the highest efficiency. The reverse of this ratio is an efficiency, lying in the desired range of values, [0,1]. The resulting formula is:

$$\eta_{water.quant.} = \left(\frac{WF_{min}}{WF_i}\right) \tag{3}$$

where $\eta_{water.\ quant.}$ is the quantitative part of water efficiency, WF_i is the water footprint of bioenergy (from selected crop) of the country *i*, WF_{min} is the minimum water footprint of bioenergy (for the selected crop) at the global scale. The hyperbolic form is chosen after a sensitivity analysis, which showed that this form provides the most realistic results. Other functional forms (e.g. exponential) would make the index more complicated, with an increased computational complexity not compensated by a higher accuracy.

This part of the index needs being complemented with some additional information on the water used. For this purpose, it is important to consider the effect of water footprint according to the availability of freshwater resources in a region. Moreover, there is a great difference if the water used in biofuel production comes from irrigation (blue water footprint) or from soil water (green water footprint). To quantify these aspects a specific index is defined.

The starting point to calculate this effect is the ratio between green water footprint of biofuel production according to (Gerben-Lenens et al., 2009) and the total water footprint. The maximum value (equal to 1) is reached if only green water (i.e. only a renewable resource) is used to produce biofuel. To penalise countries where water is less abundant, we consider the following definition

$$\eta_{water.source} = \left(\frac{WF_{green}}{WF_{tot}}\right)^{WWI} \tag{4}$$

where $\eta_{water.source}$ is the source-related part of water efficiency, WF_{green} is the green water footprint of biofuel production, WF_{tot} is the total water footprint of biofuel production and WWI is the calculated water withdrawals index. This exponent is calculated according to data on water withdrawals coming from the World Bank data (World bank, 2014). This index assumes increasing values according to the water withdrawal rate of a specific country. The water withdrawal index used here is defined as:

$$WWI = water\ withdrawals\ [\%] \tag{5}$$

3.2. Food efficiency

The *food efficiency* component of the nexus index aims to account for the potential competition for flexible crops (crops usable both for nutrition and energy purposes) between food and biofuel sectors in food insecure countries.

The data from FAOSTAT describing the prevalence of undernourishment (FAOSTAT, 2014) are used to assess food efficiency. This indicator (M.I) assumes values between 0 and 1 and expresses the percentage of population within a country that does not consume a sufficient amount of food. This value is then adjusted with an exponent (α) that aims at penalising the countries more affected by this phenomenon. This parameter (α) is set at 5, a value chosen after a sensitivity analysis showing that larger α values produce more sensible results, and for values of α greater then 5 η_{food} is stable. The resulting formula is:

$$\eta_{food} = (1 - M.I)^{\alpha} \tag{6}$$

where η_{food} is the food efficiency and M.I is the prevalence of malnutrition according to FAOSTAT (2014). Food efficiency as defined here is not crop based, but it considers the food security condition of a country, because we do not aim to consider the energy-food competition for each crop, but the overall nutritional picture for each country.

Table 2
List of countries available for each crop and location of the maximum in nexus index.

Item	No. of countries	Maximum country
Wheat	110	Belgium
Maize	140	Belgium
Rice	100	China
Rye	58	Denmark
Sorghum	32	Algeria
Sugar beet	57	Mexico
Soybean	100	Algeria
Oil palm	50	Peru

3.3. Land efficiency

The main aim of the land efficiency index is the evaluation of the impact of biofuel production on the availability of cultivable land in a specific country. To do so, similarly to the case of water efficiency, it is necessary to consider both the use of the resource (land) and its availability. The efficiency in using land for growing a certain crop is defined as the crop yield registered in the specific country divided by the maximum value of the crop yield reachable with the current technology (i.e., the maximum yield registered worldwide) (FAOSTAT, 2014). These data are provided by FAO (FAOSTAT).

In order to account for the country available land suitable for agriculture (not already used), a country specific land used index (LU) is developed. This index is the ratio between the land already used for agriculture (the arable land in FAOSTAT) and the total area suitable for agriculture in a specific country. We selected the extent of very suitable, suitable or moderately suitable land for mixed input under rain fed and/or irrigation conditions for all crops as reported by GAEZ (2014). Finally, the land component of the NI is:

$$\eta_{land} = \left(\frac{yield_i}{yield_{max}}\right)^{LU} \tag{7}$$

where η_{land} is the land efficiency, $yield_i$ is the yield for the considered crop in the country *i*, $yield_{max}$ is the maximum possible yield for the specific crop and LU is the land used index. Similarly to the case of source water efficiency, the hyperbolic form is chosen to have a right balance between the two contributions (use and availability of the resource).

4. Results and discussion

For applying the proposed methodology, the nexus index for various crops used in 1st generation biofuel production was calculated. In order to have a homogeneous and complete framework, avoiding the problems due to the differences in the used databases, the calculation was limited to 191 countries (eliminating incongruent data coming from countries with incomplete or unreliable statistical data). The number of available countries depends on the distribution of the crop in the world. The total number of countries with a calculated nexus index for each crop is shown in Table 2. The study is performed with the data referred to year 2014. Largely diffused crops like maize, rice, wheat and soybean have a large quantity of available data, because they are cultivated and used as feedstock for biofuels in most part of the considered countries. On the other hand, for less diffused cultivations, like Sorghum and Oil Palm, the

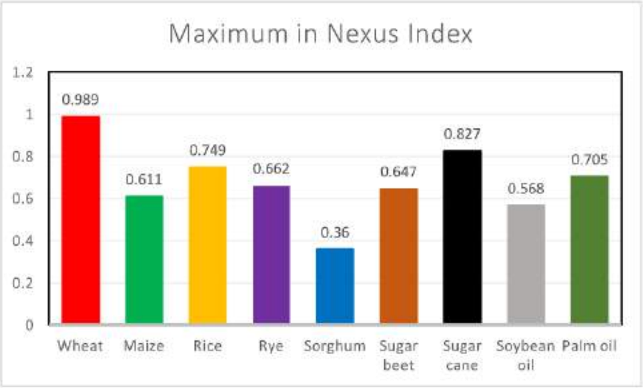

Fig. 2. Maximum Nexus Index values for the considered crops.

number of countries in which the Nexus Index can be calculated is quite low. Table 2 also reports the localisation of the highest score for each considered crop. This depends on the area where the climate is most suitable for cultivation, but also on the efficiency of cultivation techniques. The maximum values attainable have a great variability (Fig. 2), with crops characterised by high maximum efficiency (especially Wheat) and crops with low maximum efficiency (e.g. sorghum). The method is designed to give excellent results when one country is highly efficient in all of the steps composing Nexus Index. This means that crops cultivated with minimum water requirement, maximum agricultural yield and without competing with food production will give high scores; mismanagement of only one of these steps strongly decreases the overall performance.

The most produced crops have in general the highest maximal efficiency. This is a natural consequence of the intensive research performed in the past to improve agricultural yield for these species (Fisher et al., 2002). On the other hand, some crops with low diffusion (e.g., Palm Oil) also score good results. This is mainly due to the high specialisation in these cultivations that some countries were able to establish in some cases due to the high profitability of such cash crops. The maxima are only representative of the global capability to reach good scores in the nexus index; to have a complete understanding of the world performance it is necessary to discuss the results in detail for the selected crop. As an example, results for maize are discussed in the following section. The results for the other crops (limited to the cases with more than 50 countries available) are reported as maps in the supplementary material. The results of the single elements of the proposed index can be compared with the indicators representing the components of the FEW nexus available in literature to verify the consistency of the results.

4.1. Nexus index for maize

Maize is one of the most produced commodities in the world and it is widely used as a feedstock for biofuel production (Rulli et al., 2016). This makes maize an interesting crop to be analysed. As mentioned, the maximum value for the nexus index for maize is 0.611 and it is reached in Belgium. The maximum value is not high, stating the existence of inefficiencies in bioethanol production. The general analysis of the nexus index is displayed in Fig. 3 as a map and the values for top 10 countries are reported in Table 3. The number of countries with scores close to the highest values is not large. This means that, despite the large diffusion of Maize at the global scale, inefficiencies are widely present and, in many cases, the current bioethanol production does not fulfil the requirements of sustainability under a WFE nexus perspective. The geographical distribution of scores does not show specific areas where bioethanol production is particularly favourable or penalised. In all continents, there are countries with Nexus Index values close to the maximum. In

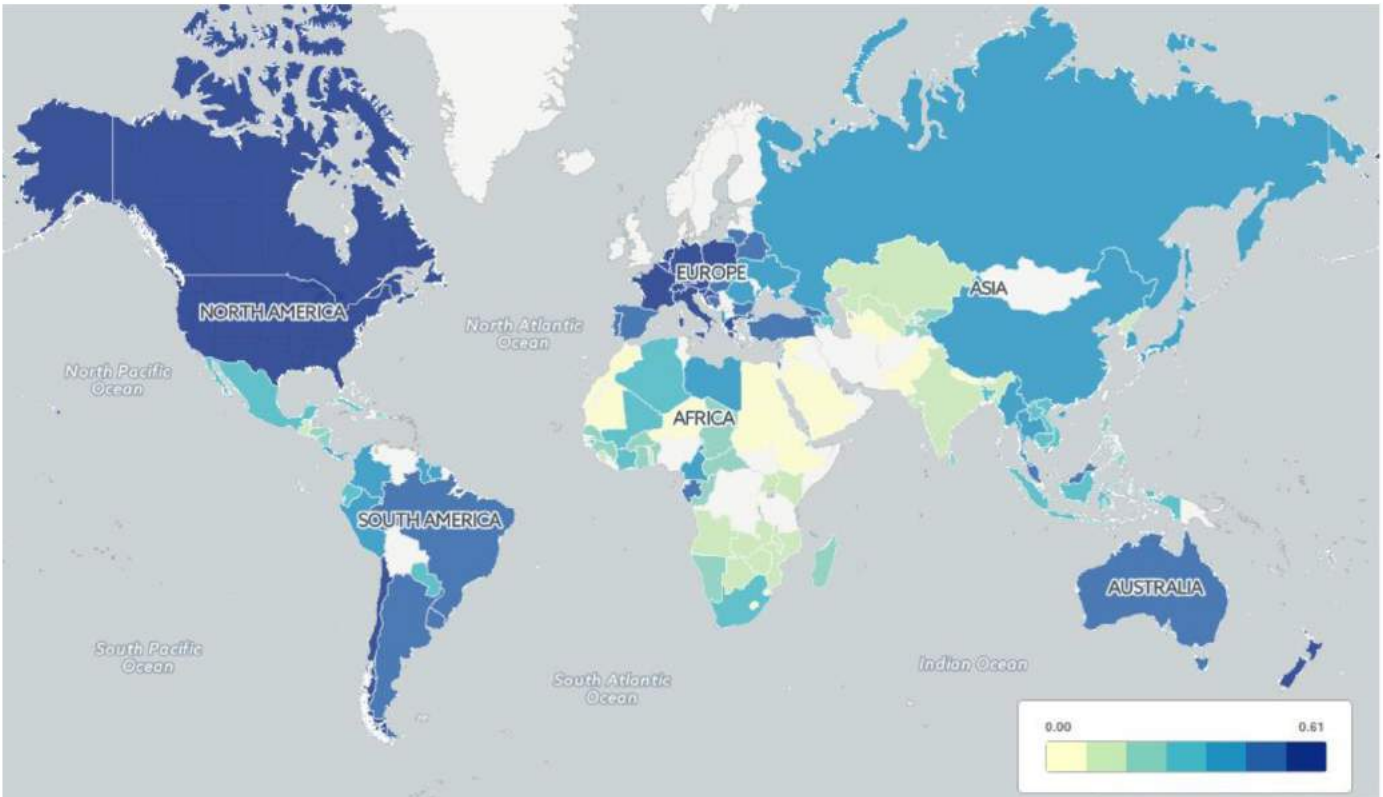

Fig. 3. Nexus index for maize.

Table 3
The top 10 countries in nexus index for maize.

	Nexus index	Quantitative water eff	Source water eff	Food efficiency	Land efficiency
Belgium	0,611	1,000	0,999	1,000	0,611
Luxembourg	0,565	0,625	1,000	1,000	0,905
Netherlands	0,475	0,858	0,995	1,000	0,557
New Zealand	0,445	0,503	0,992	1,000	0,892
Switzerland	0,366	0,700	1,000	1,000	0,523
Austria	0,362	0,749	1,000	1,000	0,483
Germany	0,353	0,699	0,999	1,000	0,505
Slovenia	0,351	0,503	1,000	1,000	0,699
Greece	0,310	0,558	0,913	1,000	0,608
Canada	0,307	0,622	1,000	1,000	0,494

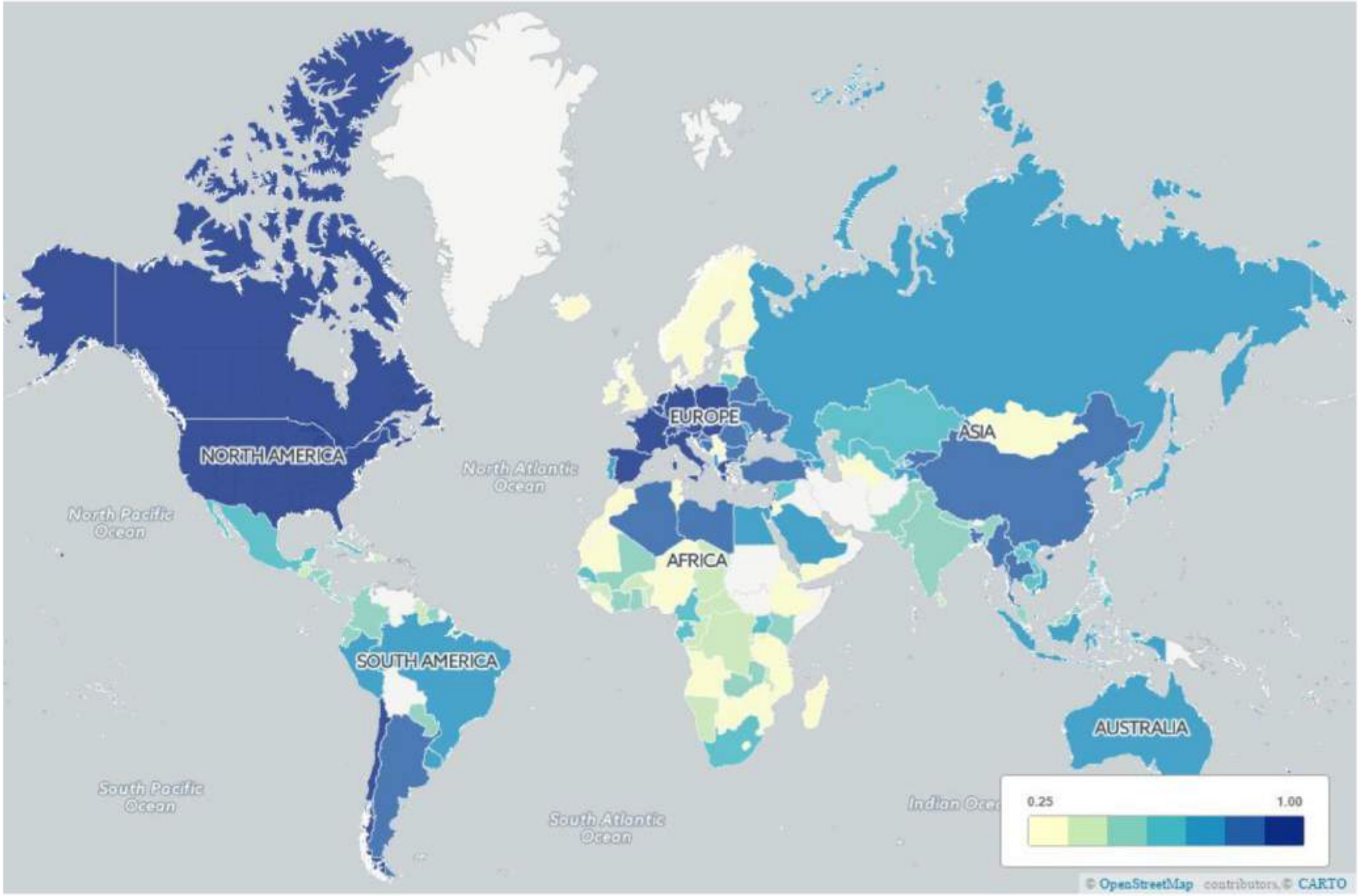

Fig. 4. Quantitative water efficiency for maize.

general, the largest values are found in industrialised countries. Most of the countries with low scores are in the sub-Saharan Africa; other inefficient countries are placed in the area comprised between the Middle East and the Indian subcontinent. The discussion of the single components of the nexus index will disentangle the problems that make some countries not efficient.

4.1.1. *Water efficiency*

Quantitative water efficiency strongly influences the index because it directly states the quantity of water needed to produce bioethanol in a specific country. Results are shown in Fig. 4. Maize is suitable to be grown in many climates, so that its cultivation is diffused in many areas of the world. The cultivation techniques have been refined in all the industrialised countries since long time ago. For this reason, in these places it is not possible to determine areas where the cultivation is particular efficient. This relative homogeneity of the results is because the quantity of water required for growing maize is quite similar. In almost all the industrialised countries, specific country water and soil management does not significantly change the crop water footprint. Conversely, other countries (such as most of the sub-Saharan African and south east Asian countries) are penalised in this index, because of the large quantity of water required to cultivate maize, both in term of crop water requirement and as crop water footprint. This large need of water can derive both from climate conditions that determine higher crop water requirement and from production inefficiency (low yield that results in low production per unit of water used). We will distinguish between the two phenomena, while discussing the quality-based water efficiency.

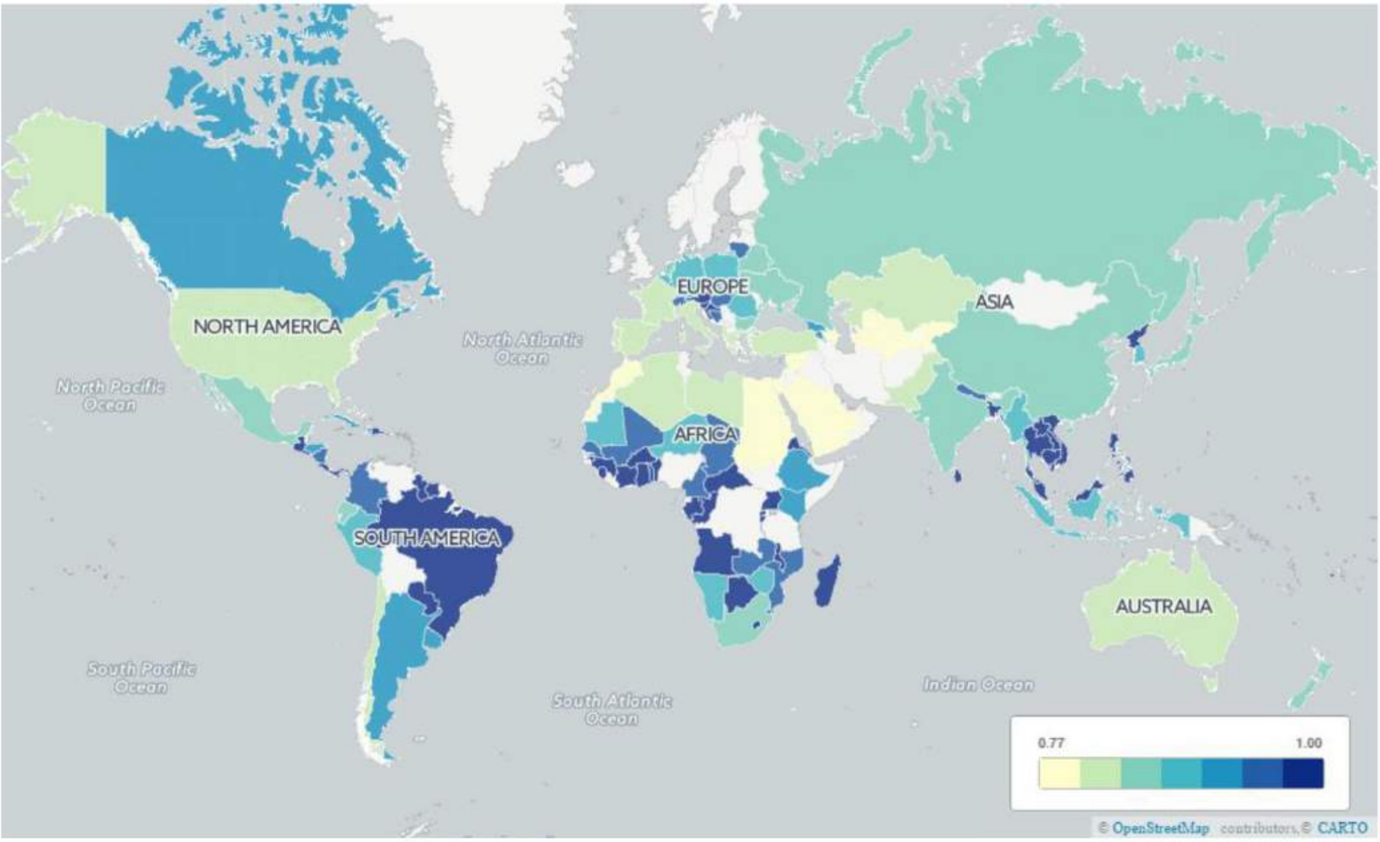

Fig. 5. Source water efficiency for maize.

The *source water* (green vs. blue water) efficiency completes the information on sustainable use of water in biofuel production. The situation described by the *source water* efficiency is largely different from the previous part of the index (Fig. 5). We notice that the scale of the results is extremely narrow: the lowest value is 0.77. This means that maize is produced in the great majority of countries using mainly green water resources. Interestingly, some of the countries with high level of *source water* efficiency have, at the same time, a low score in quantitative water efficiency. This is the case of Brazil, of many sub-Saharan African countries and of some countries of the Asian Southeast. This is a clear clue of the high crop water requirement of maize in these countries. Other countries have high quantitative water efficiency and relatively low *source water* efficiency. These countries (e.g., the USA, Western Europe and China) produce maize using low quantities of water (green + blue), but with a considerable contribution coming from irrigation.

4.1.2. *Food efficiency*

The second component of the nexus index is food efficiency. This index is, by definition, independent of the biomass considered. The results are displayed in Fig. 6. Most of the world's countries have the maximum score; but in Africa, South America and Southeastern Asia some countries are not efficient in providing food to their population.

4.1.3. *Land efficiency*

Land use efficiency characterises the last part of water–food–energy nexus, assessing the appropriate use of land in crop production. The results for maize are displayed in Fig. 7. This index is linked to quantitative water efficiency, but with some exceptions. In fact, agricultural yield, crop water requirements and irrigation are strictly connected. Usually, large use of irrigation can guarantee high agricultural yield, but this is not necessarily the case. Furthermore, agricultural yield is part of the definition of water footprint, so that a high yield can decrease the water footprint. These complex relationships highlight the need of a punctual analysis of the situation for every single crop. In the specific case of maize, we can notice that the distribution of scores for land efficiency is sensibly different from the quantitative water efficiency.

Most of the industrialised countries have low values of land efficiency, opposite to the high values of water efficiency. This is due to the focus in the rationalisation of use of water in cultivation. The use of water is adjusted to the optimal point, but this does not correspond to the highest level of crop yield. Furthermore, in these countries most of the suitable land is already dedicated to intensive cultivation, preventing the possibility of increasing the production. A case of particular interest is Belgium, leading country in nexus index ranking. In Belgium, water and food efficiency have the maximum value, while land efficiency results the bottleneck of the biofuel production process. In this country, land suitable to be cropped does exist, but the ratio between the maize crop yield in Belgium and the maximum yield in the world is low (0.5). Some other nations are characterised by low scores in water efficiency, but also by high crop yield. This is the case of some small countries (e.g., Israel) where the little land available for cultivation is exploited in a highly efficient way. The analysis of sub-Saharan countries gives some other interesting hints: most of the countries penalised in quantitative water efficiency have high land efficiency scores. This is due to the large quantity of land available for cultivation. In these countries, maize production can be increased without decreasing the nexus index. Measures to make these countries more efficient should first focus on the reduction of the water footprint. The good management of water is in general a key point to generate a sustainable biofuel production system.

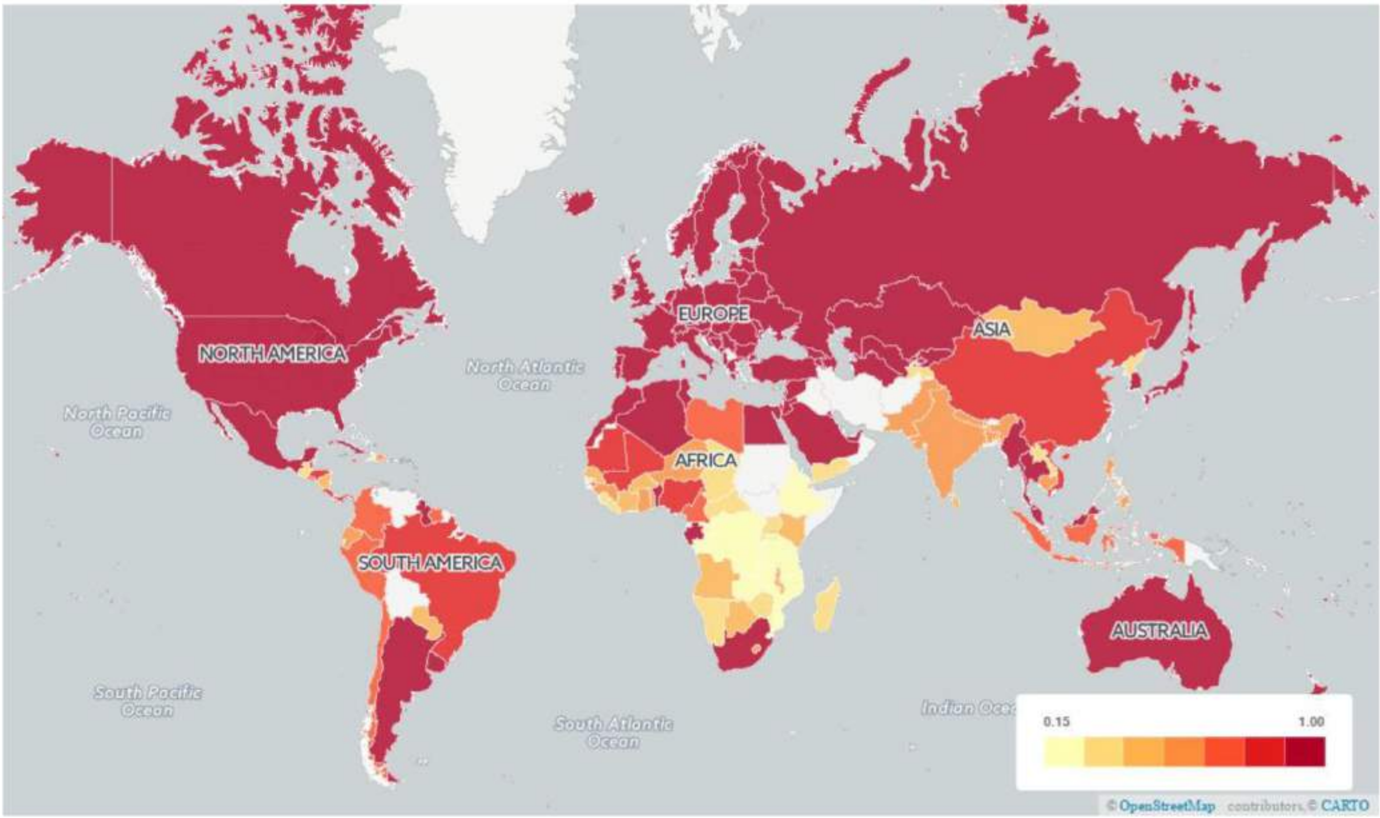

Fig. 6. Food efficiency.

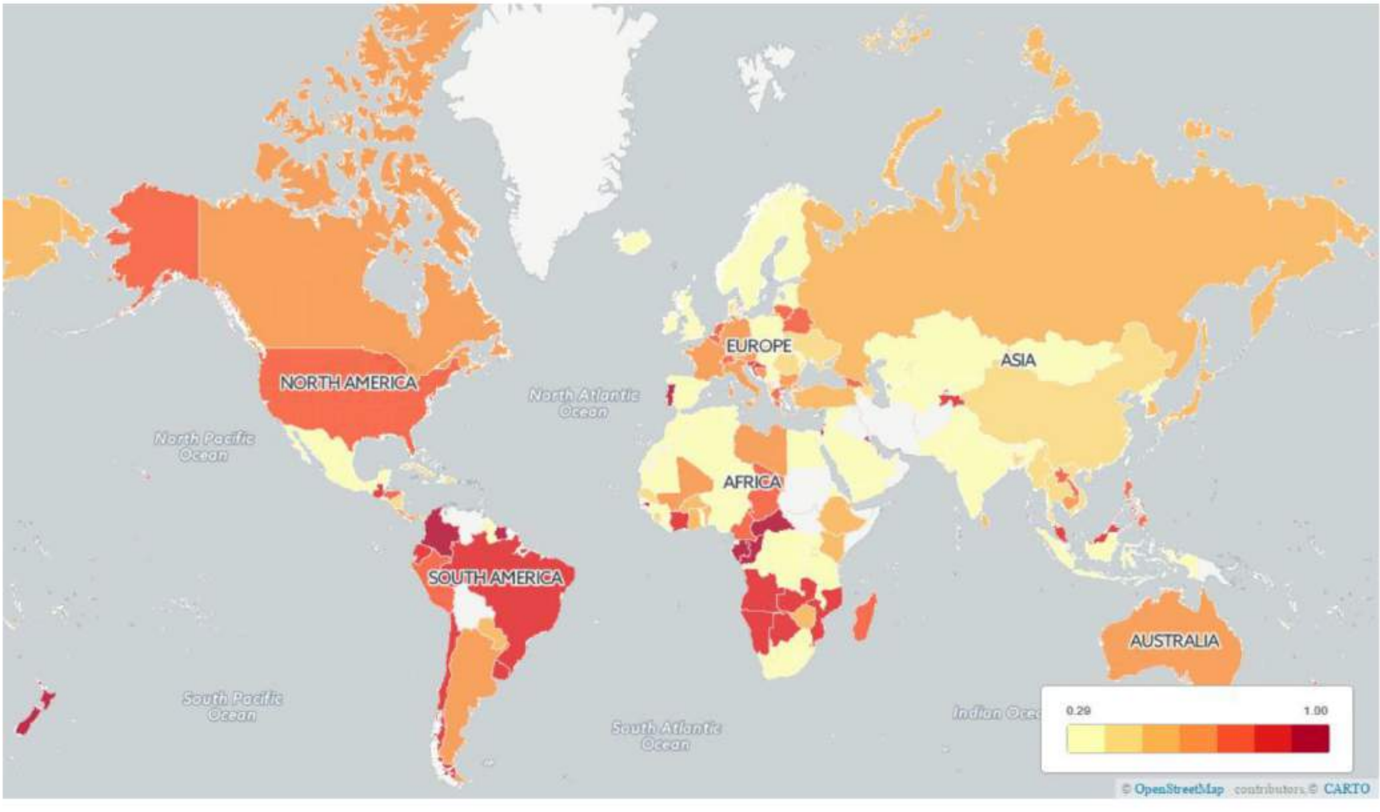

Fig. 7. Land efficiency for maize.

5. Conclusions

The sustainability of 1st generation biofuel production at the global scale is assessed through the definition of a new index, called the Nexus Index. The output of the method is a score, which defines the efficiency of the production of biofuels. The index is the product of three intermediate indexes that quantify all the key parameters in biofuel production. The Nexus Index determines if a country is efficiently managing biofuel production from a specific crop, defining the lowest attainable consumption of resources in this process.

The results of the analysis provide the starting point for considerations concerning geographic differences in biofuel production. Even if we acknowledge the sub country spatial variability of resources availability and demand, the country scale of analysis is chosen in order to have homogenous and reliable results because, often, only at country level all the required information (for water, food and land) is available.

Efficiency in Production of biofuels from the same crop can be very different from one country to another. This is due to differences in agricultural yield, but also to differences in resources deployment due to farming. In the case of maize, whose cultivation is optimised in most part of the world, the effect of farming techniques on global process sustainability is particularly evident. Some countries could be able to increase yield to optimal values, but only while increasing blue water consumption. On the other hand, also land is sometimes mismanaged. Nevertheless, in many situations, water management is the key parameter to design a sustainable energetic system.

The analysis of the nexus index makes it evident what the best cultivable crops in the country are, giving to decision makers an instrument to understand how to define an energy policy in biofuel production to exploit in the best way the country's resources. Furthermore, the inefficiencies present in the country become evident thanks to the Nexus Index, allowing one to design the best solutions to increase efficiency.

One of the main potentiality of the Nexus Index is the possibility to analyse in a simple and direct way the effects of corrective measures used to improve process efficiency and decrease the impact of biofuel production. To do so, the Nexus Index can be used in a dynamic way, considering the variability of the same over time, and comparing the expected effects of new technologies on the results of past changes. In this way, it is possible also to analyse the effects of climate change on the WEF nexus.

In addition to this, the nexus index is capable to determine the possible impact in terms of increased or decreased water and land consumption of important innovations in the field of bioenergy production, like a switch to 2nd generation biofuels. This is possible, because these changes are only modifying some parameters used to generate the nexus index, but not the general assumptions the method is relying on. Moreover, it is important to highlight that the Nexus index returns the sustainability of 1st generation biofuel in the current scenarios of soil and water technology management, climate and soil use and at country scale. Future improvements translating both in crop's yield increase and/or in more efficient water use can be taken into account by the Nexus index, so describing the effects of agriculture intensification on 1st generation biofuel production.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.advwatres.2018.07.007.

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