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Review

Water Footprint of Forest and Orchard Trees: A Review

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Abstract: The measurement of water consumption by trees is fundamental for detecting potential opportunities to mitigate water resource depletion. The water footprint (WF) is a tool to address the environmental effects related to water use, identifying ways to reduce overall water consumption. This work presents a review, updating the information on how WF is being addressed when applied to forest and orchard trees, identifying the methodological trends of the WF studies, and highlighting the main challenges that deserve further research for a consistent WF assessment of these trees. A sample with 43 publications selected based on keyword screening criteria was comprehensively reviewed, showing that most of the studies focus on orchard trees (mainly olive and citrus trees). The bulk of the studies only presented accounting or inventory results (i.e., water volumes consumed) and disregarded their sustainability or impact. This review highlights that a robust WF assessment of forest and orchard trees requires further research for harmonising the quantification of the green water scarcity footprint, and puts key challenges to the WF practitioners, such as the selection of the most adequate method to estimate ET considering trees specificities and climatic parameters, and the adoption of high spatial and temporal resolution for the WF assessment.

Keywords: life cycle assessment; water consumption; water nexus; water scarcity; sustainability

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1. Introduction

The current challenge of global water scarcity is addressed in Goal 6 of the 2030 Agenda for Sustainable Development ('Ensure availability and sustainable management of water and sanitation for all') aiming to increase global water use efficiency and guarantee sustainable freshwater withdrawals and supply [1], with a huge grade of interconnections with other Sustainable Development Goals such as Goals 7, 13 and 15 [2–4].

Forest and orchard trees play a relevant and fundamental role in human life, such as in providing raw materials and goods (e.g., wood, lumber, pulp, paper, fuel, firewood), food, and ecosystem services (e.g., habitat and biotic preservation, hydrological cycle regulation, watershed protection, erosion control, and climate change adaptation and mitigation) [5–7]. However, the agriculture and forestry sectors are highly dependent on the sustainable use and management of water resources, which can have different origins. Trees can be rainfed, use groundwater, or be irrigated. Blue water includes surface and groundwater, i.e., water in freshwater lakes, rivers, and aquifers, while green water corresponds to rainwater on land that does not run off or recharge the groundwater but is stored in the topsoil, incorporated into the vegetation, or temporarily stays on the top of the soil or vegetation and that is evaporated and transpired by plants [8]. Disturbances in tree management affect evapotranspiration (ET) and, consequently, atmospheric moisture transport and freshwater availability [9].

The increasing water demand from human activities exacerbated by current climate change trends (e.g., temperature rise, and changes in rainfall patterns), and the rapid depletion of groundwater will put further pressure on water supplies [10,11]. This can be an issue to sustain the capacity of producing enough food to feed a world population of 11 billion by the end of the century [12]. In regions that are already experiencing increasing water scarcity, such as South Africa, at least 90% of the orchard tree plantations are dependent on irrigation [13]. Tree water consumption is a complex issue that depends on tree type, soil characteristics, climate conditions, water availability, irrigation system, and land management practices, among other edaphoclimatic conditions [9,14,15]. The water consumption issue of trees widely researched and discussed and still attracts debate. Some authors state that trees use more water than shorter types of vegetation [9,16], but other studies state there is no evidence that trees have an impact on water availability (e.g., [17–19]).

Overall, trees consume more water than shorted vegetation mainly due to the interception of rainwater by their aerodynamically rougher canopies and deeper rooting that increases transpiration rates. Globally, evaporation from tree interception represents about 11% of ET [20]. Nonetheless, depending on environmental conditions and leaf area, interception can be greater such as in boreal forests, where interception gets around 40% of the total ET [21]. Nisbet [22] has found that, in the United Kingdom, the forest loses between 10 and 45% of annual rainfall by interception and 300–400 mm per year by transpiration. In addition, water use by trees varies greatly throughout the year. Nisbet [22] stated that the maximum daily transpiration loss for large individual trees can vary between 500 and 2000 L on a hot summer day. In addition, the effects of reforestation on water availability are still unclear [23,24]. The measurement and reporting of water consumption by trees are fundamental for detecting potential opportunities to reduce water consumption and consequently ease the pressure on water resources. In this context, the water footprint (WF) is a tool to quantify water consumption from a life cycle perspective that also evaluates the environmental burdens on natural resources. Thus, it allows the improvement of water resources management, identification of strategies to reduce overall water consumption, and reduction of water-related scarcity impacts associated with products [9,25,26]. It also allows to consider the effects of climate change on regional and local water availability [25,27–29] and, consequently, can support decision makers in establishing measures to fight against climate change effects on water resources. There are two main approaches for estimating the WF of a product: (1) the WF developed by the Water Footprint Network (WFN) [8] to quantitatively depict the volume of water use along the life cycle and to assess its relevance in water resources management, and (2) the WF approach based on Life Cycle Assessment (LCA), according to ISO 14046 [20] (from now on referred to as LCA-based WF).

The first approach has been applied for water management by quantifying the WF as the volume of water consumed via a Water Footprint Assessment, with the idea of optimizing water use and productivity at a global level, while considering different parameters such as total water available at the watershed and water scarcity when interpreting the sustainability assessment [8]. The LCA-based WF approach quantifies the potential environmental impacts related to water. Therefore, the water scarcity footprint addresses not only the volume of water consumed but also the quantification of water scarcity from an environmental impact perspective, including the identification of the potential contributions to water scarcity from blue and green water consumption [9,30–32]. Recently the WF has been also used to address the water node of a food or forest-energy-water nexus. A nexus approach can support a transition to agricultural and forestry sustainable systems and can be used to achieve stronger integrated management of the nexus nodes implicated (water-food/forest-energy resources) by cross-sector dialogue and coordination of stakeholders involved.

During the last decade, some literature reviews on WF have been published. Some of them were more focused on the methods to address water use in the LCA-based WF approach [9,32], whereas others were more focused on addressing the different water components for specific crops in specific geographical areas, following both WFN and LCA-based WF [33,34]. Lovarelli et al. [33] reviewed the volumetric WF of crop production, with a particular focus on crops for food and energy purposes in a global and local area. More recently, Deepa et al. [34] reviewed the WF of crops in a volumetric and impact-oriented assessment frame, including an analysis of freshwater ecotoxicity. Lovarelli et al. [33] and

Deepa et al. [34] did not focus on specific crop categories and do not explore the spatial location and resolution used by the reviewed studies. Ma et al. [35] conducted a review on virtual water and WF but only from a bibliometric perspective. In this context, this review advances this topic by addressing the WF of trees—forest and orchard trees—in particular by analysing publication trends, methodologies applied, and WF results. In addition, common challenges that still attract debate on how to calculate the WF of trees, and further developments in the WF field are addressed. This review is focused only on aspects related to water scarcity and, therefore, aspects related to water quality degradation are out of scope.

2. Materials and Methods

2.1. Literature Search Strategy and Inclusion Criteria

In this section, the procedure followed to conduct the literature review of published works about the WF of forest and orchard trees is described. The literature search was conducted in electronic databases (Web of Science, Scopus, and Google Scholar) focusing on relevant studies published in peer-reviewed journals until February 2022 (the last update of the review was on 15 February 2022). An initial year was not defined to allow to identify the first appearance of WF studies applied to forest and orchard trees.

Three groups of search terms on the title, abstract, and keywords were considered: (1) "water use" or "water consumption" and "water nexus"; (2) "forest", "wood" and "tree"; and (3) "water footprint", "life cycle assessment" or LCA, and "environmental impacts". The selection of articles was based on the definition of inclusion and exclusion criteria. The inclusion criteria consisted of articles published in peer-reviewed journals that have addressed simultaneously each search by combining simultaneously three search terms, one from each group (Figure 1). After removing duplicates, the exclusion criteria consisted firstly of non-English language publications and gray literature (books, book chapters, conference proceedings, editorials, errata, notes, and letters). Gray literature is generally not subject to a peer review process, so it was excluded to assure the quality, reliability, and bias of the final selected articles [36]. Moreover, articles out of scope, i.e., literature not related to WF of forest and orchard trees, were also excluded.

The literature search resulted in a total of 881 potentially relevant articles. A refinement was made by removing duplicates (360 articles) and excluding studies with the following criteria: publications not written in English (12 articles), gray literature (64 articles), and articles out of scope (405 articles). In addition, due to their relevance, 3 reports that do not appear in the search criteria were included. One focuses on the WF of crops, livestock, industrial products, and domestic water use in a river basin in Spain [37], while the other two are related to the WF of a forest product –paper– along its production chain, highlighting the importance of water consumed during forest growth [21,38]. Cumulatively, this search resulted in the selection of 43 WF studies for analysis, which were classified as a case study (35), overview (4), mixed approach (3), and review (1). "Case study" denotes a publication that applies a WF method in the assessment of a forest or orchard tree, "overview" designates a publication that focuses on key challenges and/or issues for development, "mixed approach" defines a publication that proposes a WF method and applies that method to a case study, while "review" indicates a publication that summarizes the state of understanding and operationalization of WF approaches.

2.2. WF Approaches

As mentioned in the Introduction section, there are two main approaches for calculating the WF of a product: the WFN [8] and the LCA-based WF [30]. They have a similar structure in terms of phases needed to carry out the assessment. The WFN approach considers the following phases: setting goals and scope, accounting, sustainability assessment, and response formulation. The LCA-based approach encompasses the goal and scope definition, inventory analysis, impact assessment, and interpretation phases. However, they present differences, mainly in the quantification of green water consumption in the accounting and inventory phases, and also in the development of regionalized scarcity indicators at the sustainability assessment and impact assessment phases. Given the specificities of the green water component and its interaction with the hydrological cycle and atmospheric moisture transport, the development of green water scarcity indicators is still a matter of ongoing research (e.g., [9,17,39]). The WF based on WFN and LCA-based approaches have been described [8,30,40] and widely reviewed [9,32,34], and their complementarities and pitfalls have been identified in previous studies [41–44]. Therefore, it is not a goal of this work to describe these approaches in detail. However, the issues that are still controversial and affect the WF results of forest and orchard trees are further discussed in this review in the Discussion section.

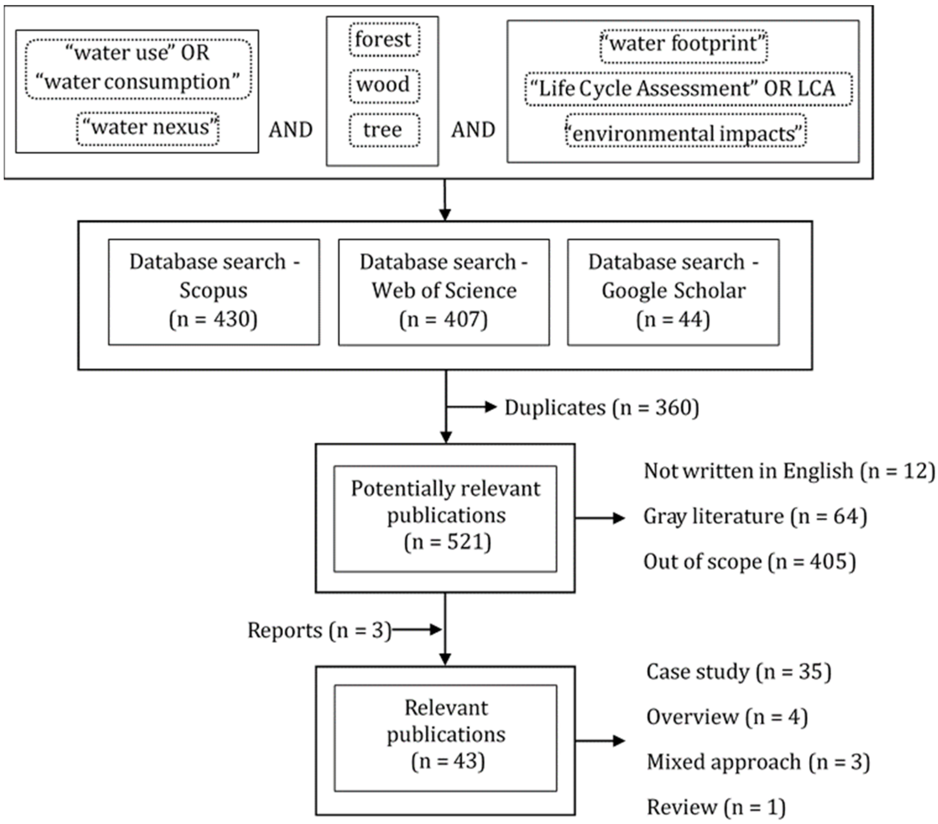

Figure 1. Flowchart of the review.

3. Results

3.1. General Overview

The main information arising from the WF studies of forest and orchard trees selected from the literature review is presented in Table 1. The following aspects were analysed: paper category, tree type, geographic coverage, spatial and temporal resolution, WF approach, WF component, and phase of the WF approach.

The column "paper category" indicates the type of studies considered in this review as defined in Section 2—case study, overview, mixed approach, and review. In the column "tree type", forest or orchards trees sub-categories were identified. The column "geographical coverage" indicates the specific geographic location of each study. The columns "spatial resolution" and "temporal resolution" indicates the specific spatial and temporal resolution of the WF studies, respectively. The column "WF approach" identifies the type of approach applied in the study, more specifically the WF from WFN [8] or the LCA-based WF [20]. In addition, given that some studies address a nexus concept [45], those studies were identified, as well as the WF approach used to calculate the water dimension. The column "WF component" identifies the water components considered in the study: blue water and/or green water. The column "phase" considers the following labels: "accounting", "inventory", "sustainability assessment" and "impact assessment", which refer to the phases included in the structure of the WFN and LCA-based WF approaches. Furthermore, the indication of the WF component in brackets after the "sustainability assessment" or impact assessment" label specifies the WF component that is assessed at those levels. "Accounting" and "inventory" refer to the phases where water use and consumption are estimated, respectively for the WFN and LCA-based approaches. "Sustainability assessment" is the phase in the WFN approach that follows the accounting phase, linking the reported volume of water used to water sustainability indicators to calculate the WF sustainability of a system. "Impact assessment" is the phase that follows the inventory phase in the LCA-based WF, linking the reported volume of water consumed to WF characterization factors to evaluate the impacts of a system.

Table 1. Key information of the literature reviewed.

Reference	Year	Paper Category	Tree Type	Geographic Coverage	Spatial Resolution	Temporal Resolution	WF Approach	Water Component	Phase
[6]	2019	Overview	Forest [a]	Global	5 arc-min	-	WFN	Green water	Accounting, Sustainability Assessment
[14]	2015	Mixed approach	Eucalyptus	Portugal	na	Yearly	LCA	Green water	Inventory, Impact Assessment
[17]	2014	Case study	Forest [a], rubber tree	China	5 arc-min	Monthly	WFN	Blue water, green water	Accounting, Sustainability Assessment (blue water)
[21]	2011	Overview	Pine, eucalyptus, spruce, broadleaves [a]	Finland	na	-	WFN	Blue water	Accounting
[37]	2008	Case study	Olive	Spain	na	Yearly	WFN	Blue water, green water	Accounting
[38]	2010	Mixed approach	Pine, eucalyptus, broadleaves [a]	Global	5 arc-min	-	WFN	Blue water, green water	Accounting
[39]	2014	Overview	Coniferous [a], deciduous [a]	Fennoscandia [b]	-	-	WFN	Blue water, green water	Accounting
[46]	2018	Case study	Olive	Spain	na	Yearly	WFN	Blue water, green water	Accounting
[47]	2022	Case study	Oil palm	Indonesia	na	Yearly	WFN	Blue water, green water	Accounting
[48]	2019	Case study	Date palm	United Arab Emirates	-	-	WFN	Blue water, green water	Accounting
[49]	2019	Case study	Almond	USA	8 km (ca. 5 arc-min)	Yearly	WFN-Nexus	Blue water	Accounting
[50]	2019	Case study	Citrus	Iran	na	Yearly	WFN	Blue water, green water	Accounting
[51]	2009	Case study	Lemon, orange	Italy	-	-	LCA	Blue water	Inventory
[52]	2019	Case study	Olive, peach	Italy	na	-	WFN	Blue water, green water	Accounting
[53]	2015	Case study	Almond, date palm, olive, orange	Tunisia	-	-	WFN	Blue water, green water	Accounting, Sustainability Assessment (blue water)
[54]	2021	Case study	Lemon	Argentina	na	-	LCA	Blue water	Inventory, Impact Assessment
[55]	2019	Case study	Almond	USA	na	Yearly	WFN	Blue water, green water	Accounting
[56]	2019	Case study	Apple	South Africa	na	Yearly	WFN	Blue water, green water	Accounting
[57]	2020	Case study	Oil palm	Indonesia	na	-	WFN-Nexus	Blue water, green water	Accounting

Table 1. *Cont.*

Reference	Year	Paper Category	Tree Type	Geographic Coverage	Spatial Resolution	Temporal Resolution	WF Approach	Water Component	Phase
[58]	2010	Case study	Almond	USA	na	-	LCA-Nexus	Blue water	Inventory, Impact Assessment
[59]	2012	Case study	Pine, eucalyptus	Australia	1 km (ca. 30 arc-second)	-	WFN	Green water	Accounting
[60]	2011	Case study	Almond, apple, date palm, lemon, orange, oil palm, olive, peach and nectarine, pear, walnut	Global	5 arc-min	-	WFN	Blue water, green water	Accounting
[61]	2020	Mixed approach	Almond, apple, date palm, lemon, orange, oil palm, olive, peach and nectarine, pear, walnut	Global	30 arc-min	-	WFN	Blue water	Accounting Sustainability Assessment
[62]	2019	Case study	Nectarine (peach)	Italy	na	-	LCA	Blue water	Inventory, Impact Assessment
[63]	2015	Case study	Oil palm	Thailand	na	-	LCA	Blue water, green water	Inventory, Impact Assessment (Blue water)
[64]	2016	Case study	Lemon, orange	South Africa	na	Yearly	WFN	Blue water, green water	Accounting, Sustainability Assessment (blue water)
[65]	2019	Case study	Almond, apple, olive, peach, pear, walnut	Turkey	na	-	WFN	Blue water, green water	Accounting, Sustainability Assessment (blue water)
[66]	2021	Review	Forest [a]	East Africa	-	-	WFN-Nexus	Blue water, green water	Accounting, Sustainability Assessment
[67]	2016	Case study	Olive	Italy	na	-	WFN	Blue water, green water	Accounting
[68]	2020	Case study	Olive	Italy	-	Yearly	WFN	Blue water, green water	Accounting
[69]	2018	Case study	Oil palm	Indonesia	na	-	WFN	Blue water, green water	Accounting
[70]	2019	Case study	Oil palm	Indonesia	na	-	WFN	Blue water, green water	Accounting
[71]	2011	Case study	Olive	Spain	na	Yearly	WFN	Blue water, green water	Accounting
[72]	2017	Case study	Oil palm	Indonesia	-	-	WFN	Blue water, green water	Accounting
[73]	2017	Case study	Coniferous [a], non-coniferous [a]	Global	30 arc-min	Yearly	WFN	Blue water, green water	Accounting
[74]	2019	Case study	Olive	Tunisia	na	-	WFN	Blue water, green water	Accounting
[75]	2018	Case study	Oil palm	Malaysia	-	-	LCA	Blue water	Inventory, Impact Assessment
[76]	2020	Case study	Oil palm	Malaysia	-	-	LCA	Blue water	Inventory, Impact Assessment

Table 1. *Cont.*

Reference	Year	Paper Category	Tree Type	Geographic Coverage	Spatial Resolution	Temporal Resolution	WF Approach	Water Component	Phase
[77]	2016	Case study	Oil palm	Thailand	na	-	LCA	Blue water, green water	Inventory, Impact Assessment (blue water)
[78]	2019	Case study	Citrus, olive	Greece	na	Yearly	WFN	Blue water, green water	Accounting
[79]	2016	Overview	Forest [a], orchard trees [a]	Global	-	-	WFN-Nexus	Blue water, green water	Accounting
[80]	2018	Case study	Peach	Italy	na	-	WFN	Blue water, green water	Accounting
[81]	2017	Case study	Almond, apple, lemon, olive, orange peach, pear	Greece	na	-	WFN	Blue water, green water	Accounting

Notes: na: spatial differentiation was considered but the resolution was not specified. [a] No tree species was specified. [b] Norway, Sweden, Finland (mainland), and Karelia (Russia).

Figure 2 provides further statistical data on the final set of articles reviewed, in terms of time evolution per paper category, and geographical coverage. Regarding the period of analysis, the first study was published in 2008 and a general increasing tendency is observed until 2019, with 67% of the studies published between 2016 and 2020. Concerning the region of the studies, all continents are represented, with articles from Europe and Asia displaying, respectively, 35% and 28% of the sample, 14% of reviewed articles performing a global analysis, 12% from Africa, and the remaining 9% and 2% come from America and Oceania, respectively. Within Europe, Italy is the country with more studies (14% of the total), while within Asia, Malaysia and Thailand present the highest number of WF articles (each 5% of the total). The majority of articles are case studies (81%), in which the WFN approach is the most widely used (74%). Overviews and mixed approaches correspond to 9% and 7%, respectively, and reviews account only for 2% of the sample.

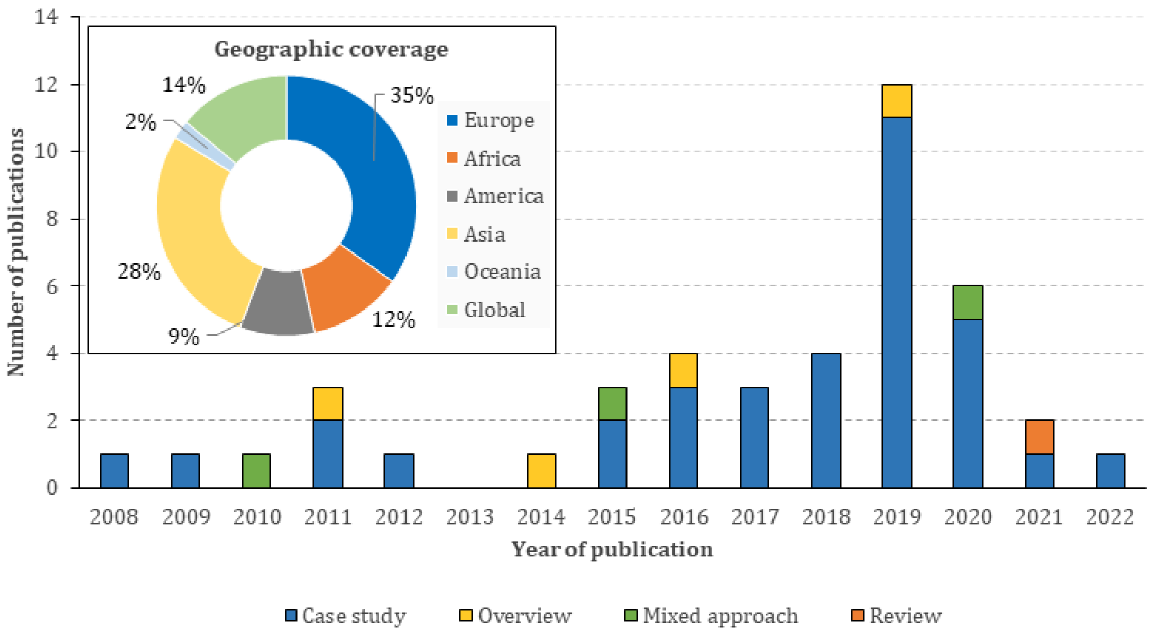

Figure 2. General outlook of the publications reviewed.

3.2. Methodological Trends

The analysis of the methodological trends for the 43 studies presented in Table 1 addresses five main aspects, as can be observed in Figure 3, as follows: (1) type of WF approach, (2) aspects related to the goal and scope, more specifically tree type, geographical coverage, and spatial and temporal resolutions, (3) aspects related with the accounting/inventory, in particular the assumptions and procedures on how to calculate the blue and green water components, and (4) aspects related with the sustainability/impact assessment, including the methods adopted.

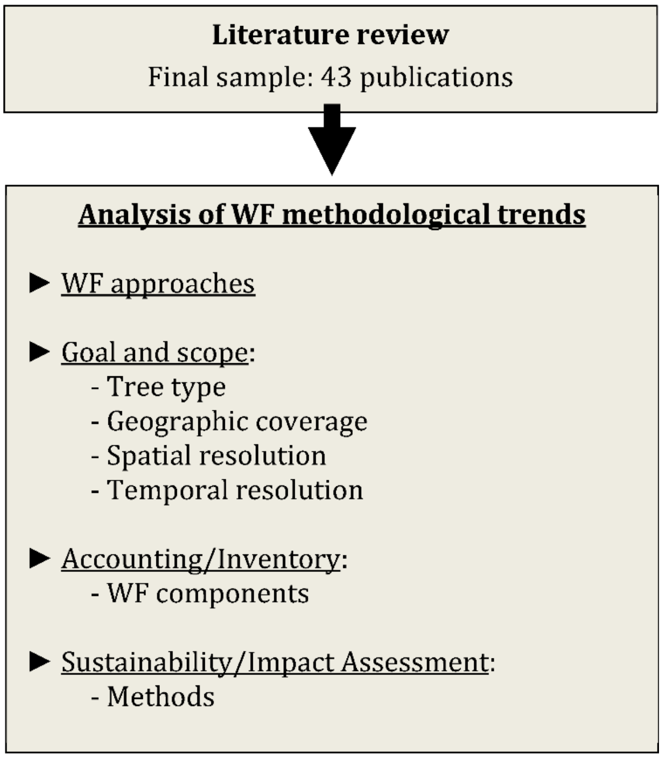

Figure 3. Methodological scheme followed in the present review.

3.2.1. WF Approaches

Figure 4 illustrates the distribution of the approaches used to calculate the WF of forest and orchard trees in the 35 case studies and 3 mixed approaches, showing that the WFN approach is the most used. This approach was applied in 26 case studies (74%), of which 2 address a nexus concept. The remaining 9 case studies (26%) applied the LCA-based WF approach, including one focusing on a nexus concept. Regarding the mixed approaches, 2 adopted the WFN approach and the other adopted the LCA-based WF approach.

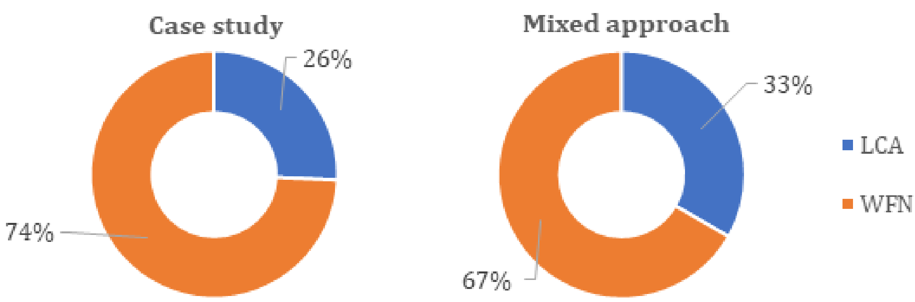

Figure 4. Approaches used in the case studies and mixed approaches reviewed.

3.2.2. Goal and Scope

An essential phase of a WF study is the definition of the goal and scope of the study. In general, the main goal of the reviewed studies is to analyse how forest and orchard trees relate to issues of water scarcity and to find out how they can become more environmentally sustainable from a water perspective. The product under study and its specificities, the geographical coverage, and spatial and temporal resolutions for evaluating water availability and consumption should be also defined in the goal and scope.

Regarding the tree type, each case study and mixed approach may involve several tree types (for instance, Chouchane et al. [53] considered almond, date palm, olive, and orange, which were expressed as "occurrences"). Therefore, case studies and mixed approaches encompass 64 and 12 occurrences, respectively, concerning tree type. Figure 5 presents the representativity of the analysed tree types (as occurrences). Olive (91%) was the most assessed tree in case studies, followed by citrus (19%) and oil palm (16%). In mixed approaches, the most assessed were citrus (17%) and forest and almonds (each 9%). Globally, citrus was the most assessed tree (18%), followed by olive (17%) and oil palm (14%).

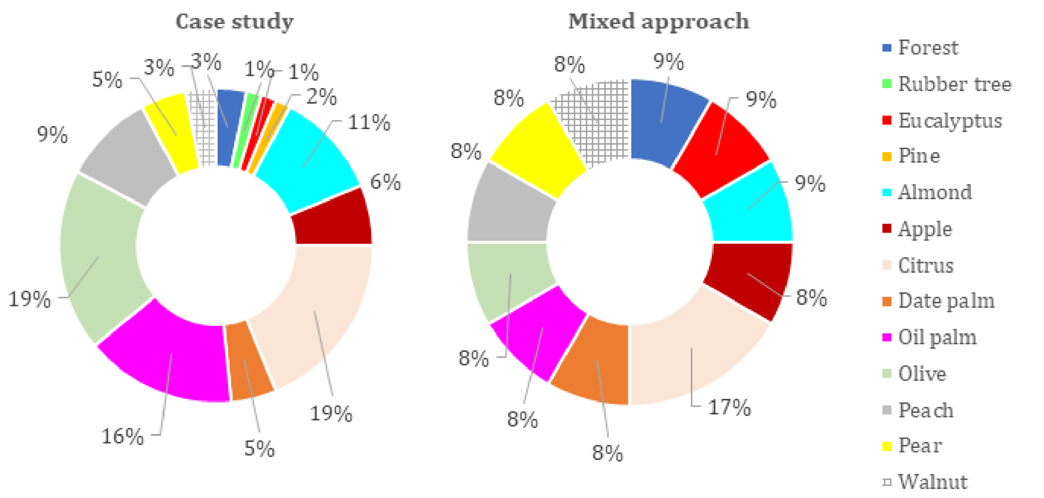

Figure 5. Distribution of tree type, expressed as a percentage of occurrences, in case studies and mixed approaches. The "citrus" label encompasses lemon and orange, and the "peach" label includes peach and nectarine.

The number of occurrences of each tree type according to the geographical coverage is represented in Figure 6 for the total case studies and mixed approaches. Most of the occurrences refer to the global scale (28%), followed by Greece (12%), Italy (12%), and Turkey (8%). The latter are countries from the Mediterranean area where water resources availability and management are important issues, which can explain the higher interest in WF studies. In such arid and semi-arid environments, the success of agricultural production largely depends on adequate irrigation [82,83]. Olive and citrus, which were the most evaluated trees, have been studied in 7 and 6 locations, respectively. Studies on olive were carried out mainly for the Mediterranean area where this tree type and water scarcity are relevant, with a higher number of occurrences from Italy and Spain. Studies for citrus cover a wider geographical area including not only countries from the Mediterranean area but also countries from Asia (Iran and China) and South America (Argentina). Studies on oil palm, which is the third most studied tree type, have been conducted in Asian countries.

Spatial differentiation was considered in 86% of case studies and mixed approaches, but only 18% clearly indicated the spatial resolution of WF results (Table 1). The temporal differentiation of the WF results was considered in only 33% of the case studies and mixed approaches. Most of these studies considered a yearly temporal resolution, i.e., they present WF results for different years. Only one case study, conducted by Chiarelli et al. [84], adopted a higher temporal resolution (monthly).

3.2.3. Accounting/Inventory

The accounting/inventory phase of a WF study involves the compilation and quantification of the blue and green water consumption of the trees under analysis. Figure 7 presents the representativeness (number of occurrences) of each WF component disaggregated by tree type. Given that some studies address several tree types and quantify both WF components, each tree type and the corresponding WF component were considered as one occurrence, resulting in a total of 131 occurrences (118 in case studies and 13 in mixed approaches). In the case studies, the blue water component was assessed in 53% of the occurrences, while the green water component corresponds to 47% of the occurrences. In the mixed approaches, 85% of the occurrences assessed the blue water component and only 15% assessed the green water component.

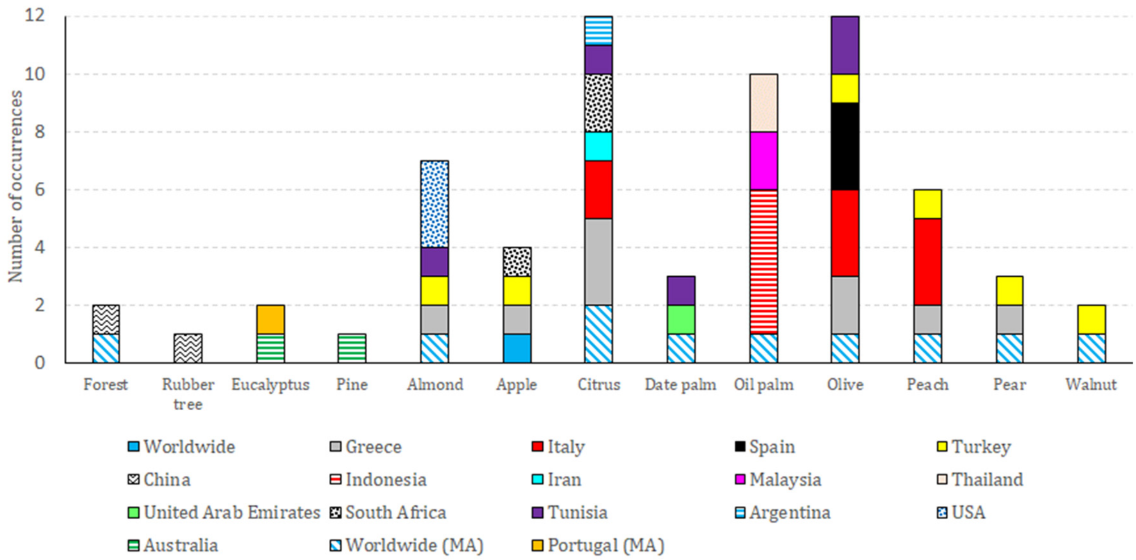

Figure 6. Tree type and geographical coverage are considered in case studies and mixed approaches. The "citrus" label encompasses lemon and orange, and the "peach" label includes peach and nectarine. MA refers to mixed approaches.

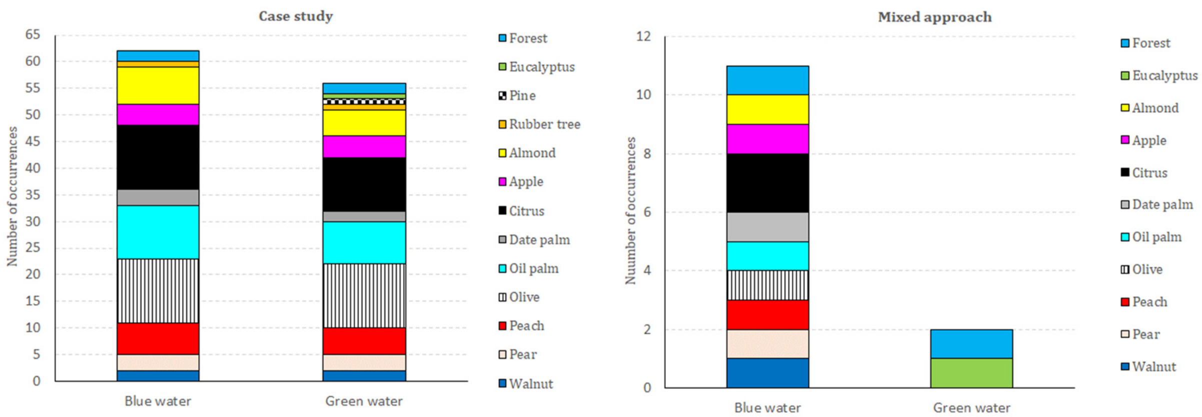

Figure 7. Tree types and WF components for the case studies and mixed approaches.

Globally, 56% of the occurrences refer to the blue water component and 44% to the green water component, which demonstrates that green water is often excluded from the WF assessment. However, some studies on forest species, for which irrigation is not performed, address only the green water component. This is the case of May et al. [59] for pine and eucalyptus, Quinteiro et al. [14] for eucalyptus, and Schyns et al. [74] for forest trees not specified.

3.2.4. Sustainability Assessment/Impact Assessment

The sustainability assessment phase of the WF approach consists of evaluating whether the water estimated during the accounting phase is sustainable from an environmental, social, and economic point of view. The impact assessment phase of the LCA-based approach consists of the assessment of the magnitude of the potential environmental impacts related to water consumption (e.g., water scarcity footprint). However, only 13 studies (34%) were classified as case studies and mixed approaches included these phases. As shown in Figure 8, 69% of the case studies (24 studies) assessed the results only from the accounting or inventory phases and only 33% (11 studies) performed sustainability assessment or impact assessment. In the mixed approaches, one study presented results at the accounting level [38], one study performed a sustainability assessment [61], and also one study performed an impact assessment [14].

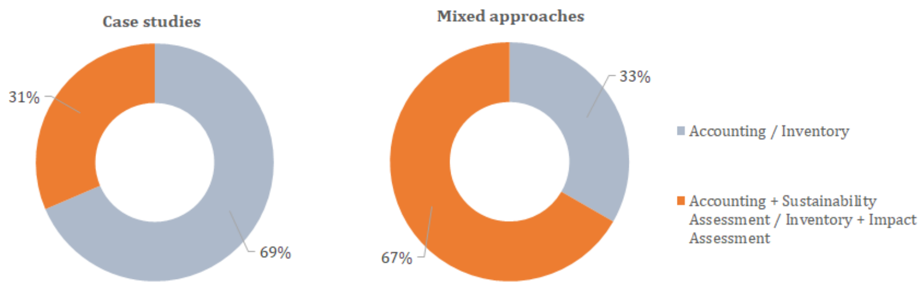

Figure 8. WF phases and water components evaluated in case studies and mixed approaches.

In the sustainability assessment or impact assessment phase, all 11 case studies focused on blue water, while 1 mixed approach addressed green water and 1 study evaluated the blue water component. It is noteworthy that the study that included the green water at the impact assessment level was exclusively analysing that component. On the other hand, there are 6 case studies that accounted for or inventoried both blue and green water components but at the sustainability assessment or impact assessment phase have only considered the blue water component.

Figure 9 shows the diversity and temporal evolution of the sustainability assessment and impact assessment methods used in the 13 reviewed case studies and mixed approaches that included this phase. Although the first case study on WF of trees dates from 2008 (Figure 2), the first studies that include this phase are from 2015, which demonstrates the time elapsed until the development of sustainability assessment and impact assessment methods and, consequently, a full operationalisation of the WF concept. The WFN is the most used approach (5 studies), covering, however, only the environmental sustainability assessment component, as the methodology to evaluate social and economic dimensions is still not sufficiently developed to be operationalised [85,86]. Within the LCA-based approach, different impact assessment methods to quantify the blue water scarcity footprint of forest and orchard trees have been applied as a likely consequence of an evolution of the methods that took place in the last years [40,87]. In 2015 and 2016, the method applied was the one developed by Pfister et al. [26], in 2018 and 2020 it was applied the method developed by Ridoutt and Pfister [88], whereas the AWARE method [40] has been applied since 2019. The AWARE method was recommended by the UNEP-SETAC Life Cycle Initiative Flagship Project [89]. For the green water scarcity footprint based on LCA, only one method [14] has been applied to forest and orchard trees.

3.3. WF Accounting/Inventory Results

Figure 10 and Table 2 show the WF accounting/inventory results obtained in the case studies and mixed approaches focusing on orchard trees and forests, respectively. The water volumes are expressed per kg of fruit produced in Figure 10 and per m^3 of wood produced in Table 2. Some studies were not included in Figure 10 and Table 2 because water volumes are expressed in different units. Regardless of the WF approach followed, the WF consumption can vary greatly for the same tree species depending on several aspects that include local edaphoclimatic conditions and methodological choices. Blue and green water consumption depends on planting dates, system management practices, soil properties and water holding capacity, rainfall levels, temperature, and irrigation requirements [9]. In addition, it is important to note that even when considering the same WF approach, different methodological choices can be adopted, such as addressing only one water component, using different methods to estimate the ET of trees, and using a different spatial resolution to calculate the water accounting/inventory dataset. Therefore, a comparison of WF results between different studies should be performed with caution, considering all these aspects.

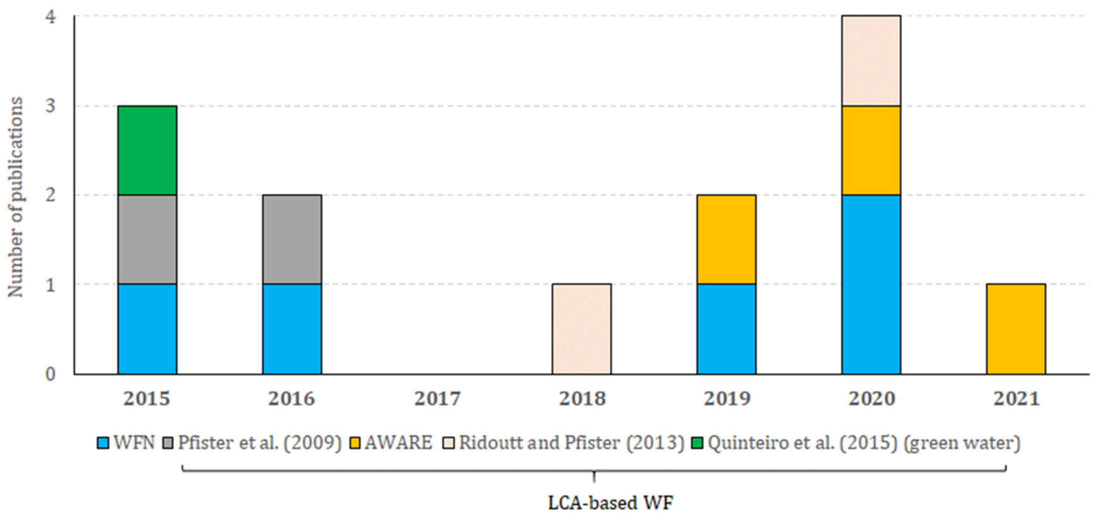

Figure 9. Sustainability and impact assessment methods under WFN and LCA-based WF approaches applied to forest and orchard trees case studies and mixed approaches and their temporal distribution.

Table 2. WF results obtained for forest trees at the accounting or inventory phase for case studies and mixed approaches that reported water volume per m^3 of wood produced.

Reference	Blue Water Consumption (m^3/m^3 Wood)	Green Water Consumption (m^3/m^3 Wood)	Total Water Consumption (m^3/m^3 Wood)
[38]	-	-	▪ 617 (pine) * ▪ 496 (eucalyptus) * ▪ 541(broadleaves) *
[59]	-	▪ 380 (eucalyptus—native forest for wood) ▪ 120 (pine)	-
[73]	12 (coniferous, non-coniferous)	281 (coniferous, non-coniferous)	-

Note: * average values from different countries.

Regarding the selection of different methods to estimate the ET of trees, for instance, Zotou et al. [81] compared the use of the equation of Penman–Monteith modified by FAO [81,90,91] and the modified Blaney–Criddle equation [92] to estimate the reference monthly ET of blue and green water of several trees (almond, apple, lemon, orange, olive, peach, and pear) in Greece. They found that higher values of ET were estimated by the modified Blaney–Criddle equation (except in almond), mainly due to an overestimation of the ET during the summer. According to these authors, the equation of Penman–Monteith provides more reliable results as it uses a larger climate dataset, while the modified Blaney–Criddle equation is easier to apply and more conservative.

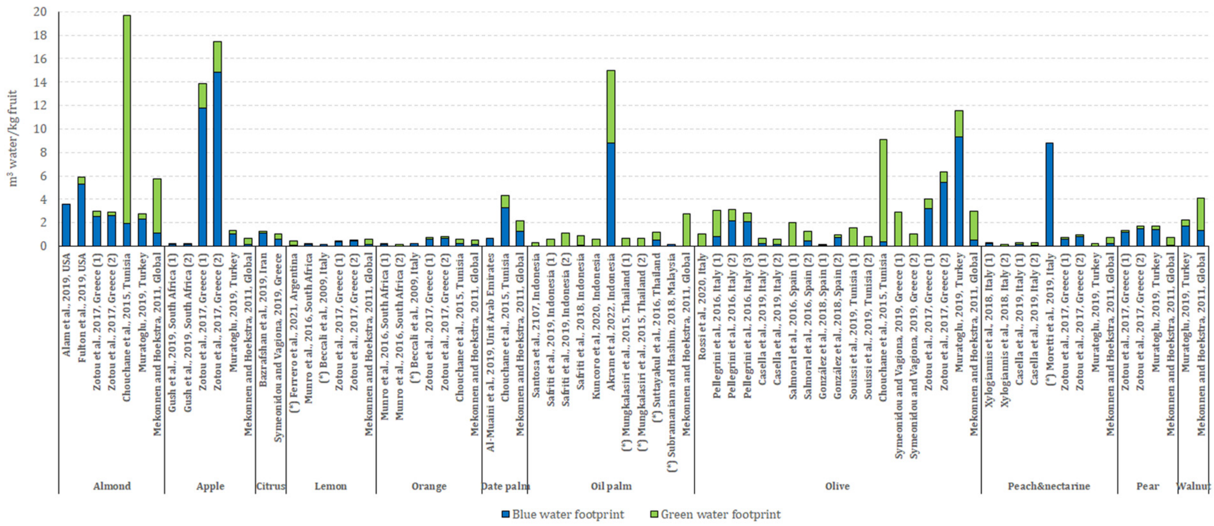

Figure 10. WF results obtained in case studies and mixed approaches for orchard trees at the accounting or inventory phase. Notes: (*) refers to results following the LCA-based approach; numbers (1–3) refer to different occurrences within a study due to different scenarios studied.

Concerning the effect of different management practices, for instance, Pellegrini et al. [67] compared the WF consumption of different agronomic cropping systems of olive trees in Italy: traditional (<200 trees per hectare), intensive (250–500 trees per hectare) and high-density plantations (1200 trees per hectare). The high-density plantations allow to maximise production yields compared to the traditional ones. The study concluded that intensive plantations had the highest consumption of blue water followed, in this order, by high-density and traditional plantations. Regarding green water, the traditional plantation had the highest demand followed, in this order, by intensive and high-density plantations.

The effect of tree age and soil type on water use was analysed by Safitri et al. [70] for oil palm fresh fruit bunch in Indonesia through monitoring soil moisture, rainfall, and water table throughout the tree's growth. The water requirement of trees was almost 100% supplied by green water as green water from rainfall on the upper oil palm root zone delivered the highest contribution to oil palm root water uptake in comparison to the blue water on the bottom layer root zone. They concluded that within the same soil type, younger trees have a higher water consumption. They also found variations depending on the soil type, with lower values of water consumption for spodosol soil types than for inceptisol and ultisol soil types.

For forest trees, Table 2 shows a wide range of variation for water consumption (120 to 617 m^3 water/m^3 wood), which is mainly fulfilled by rainfall. Therefore, the WF calculation for wood production should include green water consumption, even though its accurate quantification is challenging as it is difficult to directly measure ET by forests across large areas [93]. Common solutions to overcome this difficulty include the use of models and remote sensing data [9,39].

4. Discussion

The WFN approach was developed and started to be implemented before the LCA-based approach (although LCA studies already included the water use impact category for many years, without formally using the term WF). Despite the differences between them, both approaches have the purpose of helping their practitioners to establish strategies to preserve water resources [41]. One important difference is that while the WFN approach accounts for the total green water consumed by a tree, some LCA practitioners argue that only the net green water consumed should be accounted for, i.e., the difference between, e.g., the green water of planted forest and orchard tree and the green water of a reference land use [9,43].

Another difference is that the WFN approach accounts for the water consumed in the accounting phase, maintaining the sustainability assessment as an optional phase, whereas the LCA-based WF approach requires both the quantification of the water consumed (in the inventory analysis phase) and the assessment of the environmental deprivation caused by the water consumed applying water scarcity indicators (in the impact assessment phase). The latter phase facilitates the analysis of whether it is necessary to re-allocate orchards to less water scarce regions [42]. Otherwise, water accounting may only help to minimize water use, but not necessarily the water scarcity levels of the region.

The results of this review showed that the WF results can vary significantly within the same tree type because of the different local edaphoclimatic conditions, tree management models as well as methodological choices adopted in the WF calculation. Among the orchard trees, almonds produced in Tunisia presented the largest WF per kg of fruit produced, about 20,820 m^3/t, mainly due to green water consumption, which is more than twice the global average WF for almonds estimated following the WFN approach, as reported by Couchane et al. [53]. Apple trees in Greece presented the second highest WF results because of the irrigation requirements to ensure apple productivity, which depends on the regional climatic conditions.

The calculation of the WF for forest and orchard trees presents several key challenges: accounting/inventory of the green water component, impact assessment of the green water component, methods used for estimating ET, and spatial and time resolutions.

The procedure for the calculation of green water consumption can influence the results and, therefore, efforts should be made to harmonize the inherent concepts. In some cases, the green WF is calculated considering the "gross green water" concept, but some authors have been advocating that it should instead be considered the "net green water" [9,39,93]. This is because natural and spontaneous vegetation also consumes water even without cultivation and land use management. The "gross green water" is the green water consumed by the vegetation under study, whereas "net green water" consists of the difference between the green water consumed by the vegetation under study and the green water consumed by the land use under natural conditions. Therefore, the application of the net concept would result in a more accurate estimation of the green water consumed by trees in the incoming forest and orchard trees WF studies.

The assessment of the net green water scarcity footprint has been also a matter of discussion in the LCA community. First, there is still no agreement on whether green water should be part of the WF metric [42]. In addition, among those that agree on including green water, there is still the issue of how to develop green water scarcity indicators. Green ET can affect the availability of blue water and land use affects ET that is recycled into the atmosphere and the precipitation levels. These complex interactions that affect the regional hydrological have been hampering the development of consensual green water scarcity indicators, which explains that most of the WF studies of forest and orchard trees do not assess the green water scarcity footprint (Table 1). As mentioned in Section 3.2.4., only one LCA-based WF method for evaluating the green water scarcity footprint has been applied to forest and orchard trees [14]. However, it should be noted that the LCA community has been working on developing spatial differentiated green water scarcity indicators [9,14,29,94–96], and initiatives for the harmonization of the impact assessment methods are required.

Another key challenge is the estimation of ET, which is a parameter affected by climate variables (e.g., solar radiation, temperature, humidity, and wind speed), plant/tree properties (type, height, roughness, reflection, rooting, leaf area index, canopy), as well as management and environmental conditions (salinity, soil zones, management and fertility deficiencies, plant density, and water content of soil). ET can be quantified by field measurements, namely by eddy covariance [97] and other techniques such as high-resolution weighing lysimeters [98,99] and Bowen ratio measurements [100]. However, these techniques can only be considered for plot and field measurements, hampering the measurement of a global spatially explicit ET [9]. The selection of the method to estimate ET of forest or orchard trees depends not only on edaphoclimatic parameters but also on the geographical area under study.

Given the inherent difficulty to measure ET in the field, it is often estimated through different methods, such as the Penman-Monteith equation [47,56,71,86], Blaney-Criddle [81], a soil water balance [84], remote sensing [29], relationships between total rainfall and evaporation for forests developed by Zhang et al. [101] and Zhang et al. [14,59,102]. Therefore, the adoption of different methods can result in different ET values for the same product, leading to WF variability in a lower or higher amplitude depending on the 'sensitivity' of the ET model to the edaphoclimatic conditions. This is shown in Figure 10, for instance, for the WF of almond, apple, lemon, olive, orange, peach, and pear calculated by Zotou et al. [66]. Indeed, the observed variability of blue and green water consumption values for the same orchard tree results mostly from the ET method applied and the parameters used in the calculation of the ET. In addition, the simplification of ET estimation models or the adoption of different assumptions can also lead to different results of ET. For example, May et al. [59] used the method proposed by Zhang et al. [102] to estimate the ET of forest species but did not consider parameters such as rotation lengths, fallow periods, and management intensity, which may over or underestimate the WF accounting/inventory results as recognized by the authors.

Over the past decades, several efforts have been conducted to develop remote sensing techniques for mapping ET at plot, field, landscape, regional and global scales, for instance, remote sensing enables the estimation of ET of forests at these large spatial scales (regional to global scale) [103], which is not possible, at least with acceptable accuracy, with analytical, hydrological, micrometeorological and plant physiology methods above mentioned [104].

In WF studies it is of paramount importance to consider both spatial and temporal differentiation since water availability and consumption vary depending on the tree's properties, soil conditions, management practices, and climate conditions [15,31]. The WF of trees is affected by climate conditions [69] and, thus, the non-consideration of the inter- and intra- annual variation of precipitation and temperature, as well as the trees-growing seasons, can mask the high variability of green and blue water consumption [105] and compromise the evaluation of the scarcity levels experienced by trees [9]. For instance, Muratoglu et al. [65] that focused on orchard trees in Turkey, stated that the estimation of blue water scarcity with a monthly resolution would provide more accurate results than annual estimations, and would give more precise information on local water saving or deficit.

The spatial and temporal resolution of the WF is likely dictated by the indicators used in the impact/sustainability assessment phase. Over the last years, the blue water scarcity indicators for river basins, watershed, and sub-watershed scales have been developed on a monthly basis, respectively by Hoekstra et al. [106], Pfister and Bayer [15], and Boulay et al. [40]. The use of monthly data during the impact assessment phase has been also recommended by the FAO Livestock Environmental Assessment and Performance (LEAP) Partnership which developed guidelines on WF for livestock production systems and supply chains [31].

Notwithstanding, it is still common the lack information on the exact month and location of water consumption at the accounting/inventory level. Therefore, the transposition of the inventory to WF impacts using water scarcity indicators at different spatial/temporal resolutions or the use of a spatial/temporal aggregated indicator at the impact/sustainability assessment phase would always bring uncertainty to the WF results. There is still some way to go to ensure an adequate relationship between spatial/temporal resolutions at the accounting/inventory and impact/sustainability assessment phases.

Information provided by WF studies can support decision-making on the establishment of local resources management strategies and land use planning (analysis of the most appropriate tree type to the local edaphoclimatic conditions) to reduce the risk of prolonged drought [61,67,78,91,95]. Therefore, it is of paramount importance to overcome the current limitations in the calculation of the WF of forest and orchard trees to obtain more reliable and robust results.

5. Conclusions

A growing interest in WF applied to forest and orchard trees was observed in recent years, mainly in case studies conducted in Europe (with Italy in the lead, followed by Spain and Finland) and Asia. It is noticeable that most of the European studies are concentrated in the Mediterranean where water scarcity is nowadays a major challenge.

Most of the studies are focused on orchard trees and only 23% address forest species. Olive and citrus trees were the tree types covered by more studies. The spatial and temporal differentiation was indicated in 86% and 36% of case studies and mixed approaches, respectively. The WFN approach was adopted in more studies than the LCA-based approach, representing 74% of the total case studies and mixed approaches. Most of the studies following the WFN calculated blue and green water consumption, whereas in studies following the LCA-based approach the blue water scarcity footprint is considered but the green water scarcity footprint is often excluded due to the incipient development of impact assessment methods. The bulk of the studies (65%) only presented accounting/inventory and, thus, did not conduct the sustainability assessment or impact assessment phases.

The reviewed studies showed that the WF results can vary significantly within the same tree type because of the different local edaphoclimatic conditions, tree management models as well as methodological choices adopted. Almonds produced in Tunisia presented the largest WF per kg of fruit produced, about 20,820 m^3/t, mainly due to green water consumption, which is more than twice the global average WF for almonds estimated following the WFN approach by Couchane et al. [53]. Apple trees in Greece presented the second highest WF because of the irrigation requirements to ensure apple productivity, which depends on the regional climatic conditions.

In conclusion, this review highlights the need for further research on the development of a consensual and harmonised method for the assessment of the green water scarcity footprint at the sustainability/impact assessment levels. Moreover, efforts of the WF applicants to achieve a more robust assessment of the WF of forest and orchard trees should be focused on the selection of the most adequate method to estimate ET considering the specificities of trees and climatic parameters under study, and on the adoption of high spatial and temporal resolutions. These are key aspects to support an efficient consumption of water use for achieving Sustainable Development Goal 6.

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