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The water footprint of biofuel produced from forest wood residue via a mixed alcohol gasification process

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Abstract
Forest residue has been proposed as a feasible candidate for cellulosic biofuels. However, the number of studies assessing its water use remains limited. This work aims to analyze the impacts of forest-based biofuel on water resources and quality by using a water footprint approach. A method established here is tailored to the production system, which includes softwood, hardwood, and short-rotation woody crops. The method is then applied to selected areas in the southeastern region of the United States to quantify the county-level water footprint of the biofuel produced via a mixed alcohol gasification process, under several logistic systems, and at various refinery scales. The results indicate that the blue water sourced from surface or groundwater is minimal, at 2.4 liters per liter of biofuel (l/l). The regional-average green water (rainfall) footprint falls between 400 and 443 l/l. The biofuel pathway appears to have a low nitrogen grey water footprint averaging 25 l/l at the regional level, indicating minimal impacts on water quality. Feedstock mix plays a key role in determining the magnitude and the spatial distribution of the water footprint in these regions. Compared with other potential feedstock, forest wood residue shows promise with its low blue and grey water footprint.

Keywords: biofuels, forest biomass, thinning residue, logging residue, short-rotation woody crop, water footprint

S Online supplementary data available from stacks.iop.org/ERL/8/035015/mmedia

1. Introduction

Since the 1980s, a series of studies has been launched that focus on using forest biomass as a cellulosic source. Scientists have found that forest biomass can be a promising feedstock that can be used to generate biofuel with similar ethanol yield per feedstock mass as corn but at relatively lower per-liter cost [1]. Using woody feedstock is believed to have such positive effects as reducing both erosion and the use of chemicals and fertilizer, in comparison with using conventional crop feedstock [2, 3]. From the late 1990s, researchers have even more extensively reviewed and evaluated the environmental sustainability of forest-based biofuels from the life-cycle perspectives of addressing greenhouse gas emissions and carbon sequestration in particular [4–7]. However, water requirement is rarely part of the discussion on the environmental performance of forest-based biofuel, and it is treated merely as an input parameter that regulates the growth of biomass [8], if it is taken into account at all. Prior studies also highlighted that the effects of forest-based biofuel on the appropriation of regional water remain limited and can be a critical issue regulating the potential production of biofuel [9–11].

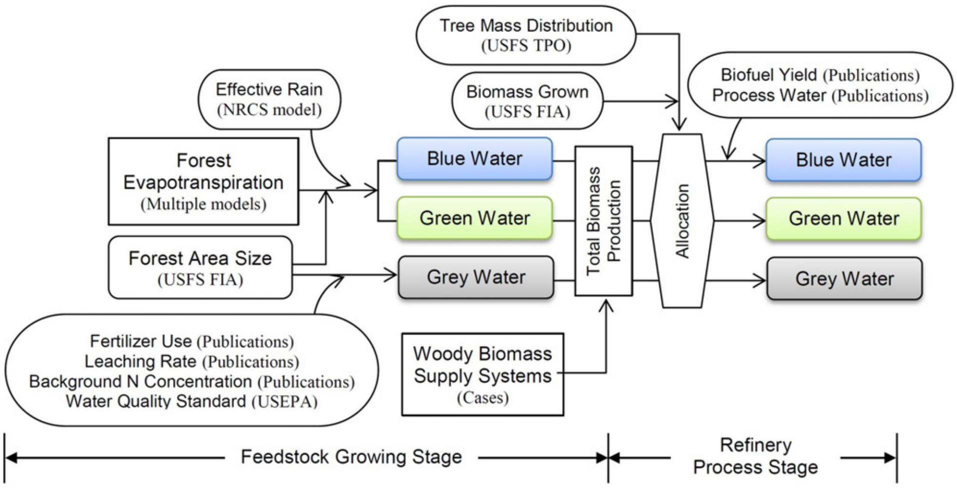

Figure 1. Calculation steps and key data sources. Sources of data or models used to obtain each variable are marked in parentheses, which are detailed in section 2.

This study is a part of a multi-institute effort that includes Oak Ridge National Laboratory, Idaho National Laboratory, National Renewable Energy Laboratory, and Argonne National Laboratory to examine cellulosic biofuel production from woody feedstock via a mixed alcohol gasification process under various logistic systems, refinery sizes, and feedstock characteristics in the southeastern United States. The techno-economic and environmental impact analyses were conducted for several future biofuel-production scenarios developed on the basis of projected feedstock price in the region. The economics and technology analysis are presented elsewhere [12]. Thus, the hardwood and softwood feedstock is harvested primarily from the existing private timber plantations or non-preserved forest stands. Short-rotation woody crop plantation can be established at various geographical areas in the US that suitable for its growth. In this study, SRWC is grown in existing forests without land use change. Thus, water footprint changes resulted from land conversion would be out of the study scopes.

In this work, we aim to analyze the impacts of biofuel produced from forest wood feedstock on the use of water resources and water quality. We develop a mathematical method to quantify the water footprint associated with the production system. The water footprint includes blue water (surface and ground water through irrigation and conversion process), green water (rainfall), and grey water (wastewater discharge) associated with feedstock growth and conversion. In other words, the blue and green water footprint represents actual water consumption associated with a production system, whereas the grey water footprint is the sum of the volume of polluted water discharged to a stream and the additional water required to dilute the pollutant to an acceptable concentration in the stream. The pollutant we addressed in this study is nitrogen. Nitrogen has been a primary agricultural grey water component historically. It also plays an important role in current biofuel feedstock development because a majority of feedstock requires significant nitrogen fertilizer input. For this research, two forested areas in the southeastern United States were selected based on forest wood stand density: Aiken, South Carolina represents low density area, and Rankin, Mississippi represents high density area. The water footprint results are presented in liters of water per liter of bioethanol (l/l). This approach can be further applied to other forest types to develop a national assessment of the water footprint for forest residue-based biofuel.

2. Method and data sources

Because of the complexity of the forest biomass harvest scheme, the challenges of assessing a forest-based biofuel water footprint involve defining the production of wood feedstock components (such as thinning, logging residues, round wood) and determining the fraction of harvested feedstock in total forest biomass. In this study, we separate biofuel production into a feedstock-growing stage and a refinery-process stage. Blue, green, and grey water are calculated on the basis of forest types of hardwood and softwood in each stage (figure 1).

2.1. Site description and feedstock supply systems

We evaluated a mixture of feedstock harvested from hardwood and softwood forests at a county level. The feedstock mix includes several types of woody materials: logging residue, thinning residue, pulpwood, and short-rotation woody crops (SRWC). Normally, the logging and thinning residue contains both hardwood and softwood, whereas pulpwood can be harvested from a dominant forest type and SRWC collected from a future production plantation, depending on the geographical location of the production sites.

Two areas were selected on the basis of tree stand density: a high-concentration area in Rankin County, Mississippi, and a low-concentration area centered at Aiken, South Carolina. In this region, loblolly and sweet gum are chosen to represent softwood and hardwood, respectively. The feedstock harvest data were generated by Muth *et al* [12], simulating two biomass supply logistic systems—namely, conventional supply systems (CSS) and distributed preprocessing supply systems (DPSS). The fundamental design of a CSS platform features sourcing feedstock from the adjacent areas of a refinery. Four levels of refinery capacities are investigated, including 600, 1000, 2000, and 5000 dry metric tons per day (DMTD) (table S1 available at stacks.iop.org/ERL/8/035015/mmedia). We assume the feedstock mix from thinning practices consisted of a hardwood–softwood residue ratio of 61/39 at Rankin, MS, and 48/52 at Aiken, SC, for the conventional case. As for the advanced case, feedstock is collected from the entire southeast region with a hardwood–softwood ratio of 55/46 across the entire studied area. In addition to the logging and thinning residue, the DPSS case also involves SRWC and pulpwood in the feedstock pool.

The logging residue is harvested from 10-year-old sweet gum stands and 15-year-old loblolly stands containing bark and branches. The thinning residue is collected from young trees from 4-year-old sweet gum stands and 8-year-old loblolly stands containing bark, branches, and stems. Both SRWC and pulpwood are sourced from loblolly in the studied region.

2.2. Estimation of mass distribution among the tree components

Due to the complex of feedstock and forest types, a critical step is to define the production rate of forest wood and its water requirements and develop water allocation. Our approach is to evaluate the entire forest in the region for the production and water needs, followed by calculating the fraction of wood harvest for biofuel and partitioning water requirement into wood components or feedstock (thinning, residue, round wood, etc).

As hardwood and softwood forests have very distinct evapotranspiration rates that consequentially govern green water, the harvested wood must be determined by forest type. Within each forest wood type, the above-ground biomass is partially harvested for round wood or removed as thinning and logging residues. Therefore, data on forest wood production were compiled from the Forest Inventory and Analysis (FIA) [13] and Timber Products Output (TPO) [14] published by the US Forest Service and screened by county, forest type, and tree type. We selected data from all private accessible timberlands with mid-, full-, and over-stocking status for analysis. Biomass data (in green tonnage) collected from TPO (2009) were further processed on the basis of tree age (0–40 years old) and feedstock type (logging residue, thinning, round wood). A weight per cent (wt/wt) of the harvested wood mass for biofuel (as projected in the supply system cases) in the total above-ground wood mass at a county is further derived from FIA data [13] (2011) and incorporated into the calculation to partitioning water requirement into wood harvested for biofuel. The TPO data [14] derived tree component weight per cent in total tree mass is used to further allocate wood-based biofuel water footprint into different type of feedstock (thinning, logging residue, or pulpwood) for each tree type. We assume a 10% mass loss during harvest.

2.3. Estimation of evapotranspiration (ET)

Evapotranspiration (ET) represents the water demand associated with feedstock growth, in which the fraction satisfied by effective rainfall is classified as green water and the remaining can be supported by irrigation or blue water. Therefore, ET is a fundamental variable in determining blue and green water if a production system involves consuming plant materials [15, 16]. In a forest-based biofuel-production system, the ET of softwood and hardwood must be computed separately (see SI section 2 available at stacks.iop.org/ERL/8/035015/mmedia). We reviewed the accumulation method (ACC) [17–19] and the leaf-area-index (LAI) method [20, 21] in this study. The ACC method estimates evaporation from the soil and canopy and the transpiration from the canopy. Sun *et al* [20] proposed a method using tree leaf-area-index (LAI), precipitation (P), and Penman–Monteith reference evapotranspiration (ET_0) as the inputs to project forest ET on a monthly basis. The LAI data are often available in various publications in which either on-site measurement or satellite image processes are used [22, 23].

For validation purposes, the results of ET calculated by applying each method on each type of forest are compared with available references [17, 18, 24]. Field data in these references clearly state the location of the experimental forest, years and seasons of experiment, and the local forest ET. The results indicate that the accumulation method (ACC) is appropriate for hardwood ET estimation, whereas the LAI method can be employed for softwood ET calculation (table S2 available at stacks.iop.org/ERL/8/035015/mmedia). Once the ET methods are selected for each type of forest, climate data from 1970 to 2000 are then incorporated to calculate forest ET, representing the normal condition. The required climate data are available from the Texas A&M University [25], National Climate Data Center [26], and Goddard Space Flight Center of NASA [27].

2.4. Water footprint

Blue water depth can be calculated from the ET discussed in the previous section by deducting effective rainfall. There are numerous methods that can be used to estimate the range of effective rainfall at a given location. We adopt the method proposed by the Natural Resources Conservation Service (NRCS) [28, 29] of the US Department of Agriculture. The remaining ET after deduction by effective rain is classified as depth of blue water. To obtain the volume of blue and green water, the monthly depths of blue and green water are multiplied by forest area provided by FIA, for both hardwood and softwood. The blue water would constitute irrigation requirement. In this study, we assume irrigation was not provided to be consistent with forestry practice in this region. Therefore, some trees may grow under water stress. Nevertheless, the areas with blue water requirement in this region are minimal. Previous research [30, 31] found that sweet gum and loblolly response to irrigation varies and that the greatest increase occurs at foliage mass. Albaugh *et al* [30] also stated that a water deficit of over 128–239 mm during the

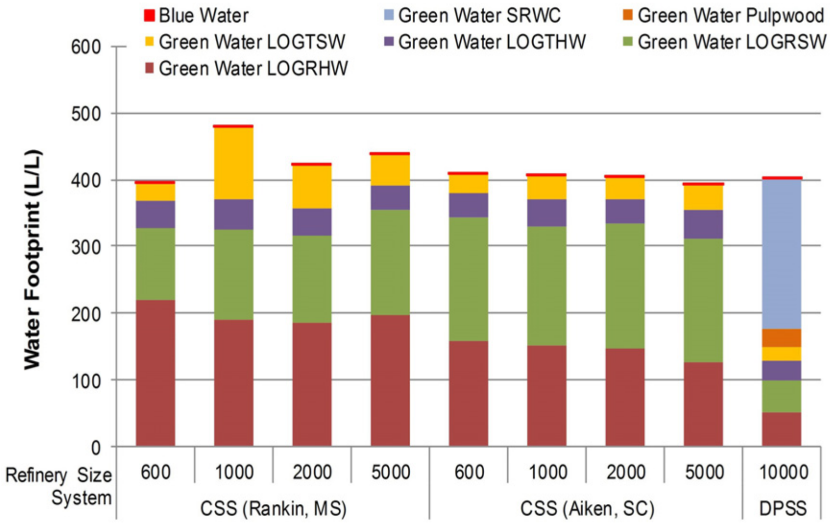

Figure 2. Distribution of biofuel blue water and green water footprint under different sizing (in DMTD) with feedstock containing 7% ash and 30% moist content. Green water is composed of water associated with thinning residue (LOGT), logging residue (LOGR), short-rotation woody crop (SRWC), and pulpwood from softwood (SW) and hardwood (HW). The values of the conventional case are averaged between Aiken and Rankin by using ethanol production as a weighting factor.

loblolly growing season contributes little to increase growth. Therefore, it is reasonable to assume that no irrigation (blue water) is associated with the feedstock-production stage.

Grey water is calculated on the basis of nitrogen fertilizer input, nitrogen leaching rate, nitrogen discharge standard, and the natural background concentration of nitrogen in local streams. The evaluation method and calculation equation were proposed by Hoekstra *et al* [32]. The nitrogen leaching rates—per cent of nitrogen input lost to the watershed stream through surface runoff or base flow—can be 1.97% [33] and 3.74% [34] for hardwood and softwood, respectively, based on published field data in this region. The nitrogen discharge should meet the Class I standards of 10 mg l^{-1} of total nitrogen set by the US Environmental Protection Agency. The natural nitrogen background concentration in the streams is available from the US Geological Survey report [35]. We assume the burden of fertilizer application is allocated to purposely grown pulpwood and SRWC. Hardwood does not receive fertilizer as its productivity is found less responsive to fertilizer than softwood productivity in the studied region [30, 31]. Softwood stands are assume to receive nitrogen fertilizer of 118.0 kgN ha^{-1} at each application [34], two applications per life cycle, therefore with a total of 236.0 kgN ha^{-1} in each 15-year rotation; whereas SRWC receives 100.8 kgN ha^{-1} at each application with a total of 201.6 kgN ha^{-1} in a 8-year rotation as suggested by US Department of Energy [36].

2.5. Refinery assumptions

In the refinery stage, process water consumed through cooling, boiling, loss to flue gas, and wastewater treatment are also classified as blue water. The process water and biofuel yield in biorefinery vary with the feedstock characteristics. Biofuel yield from gasification and catalytic conversion process is dependent on the moist and ash content of feedstock [12]. We assumed the woody feedstock features 7% ash content and 30% moisture content for both conventional and advanced systems. The combination results in consumption of 2.38 l/l and 2.43 l/l of process water in conventional and advanced systems, respectively, with an ethanol yield of 318.85 and 336.78 l/DMT, according to ASPEN process simulation [12].

3. Results and discussion

3.1. Conventional supply systems (CSS) case

Overall, the wood-based biofuel has a minimal blue water footprint, although variation in the moisture and ash content of the feedstock could have a small effect on the use of process water [12]. The county-level water footprint is dominated by green water ranging between 212 and 1705 l/l, with a regional average of 401–443 l/l, depending on refinery scale (figure 2).

Feedstock mix is the major driver determining the magnitude and the spatial distribution of the water footprint of biofuel produced from woody feedstock. Water footprint appears proportional to biomass. Logging residue contributes more to green water than thinning residue does, with an approximate 82% and 18% split, respectively. The softwood-dominated Aiken shows a relatively stable water footprint across all refinery sizes, whereas the hardwood-oriented Rankin site shows fluctuation, primarily caused by variation of soft wood log residue (figure 2). At a refinery size of 600 dry metric tons per day (DMTD), Rankin's green water footprint appears similar with Aiken at all refinery scales. With a refinery size between 1000 and 5000 DMTD, Rankin appears to have a slightly higher green water footprint than Aiken, ranging from 4% to 18% (figure 2). The difference is primarily caused by the location-dependent feedstock mix (figure 3). Generally, hardwood forest grown in this

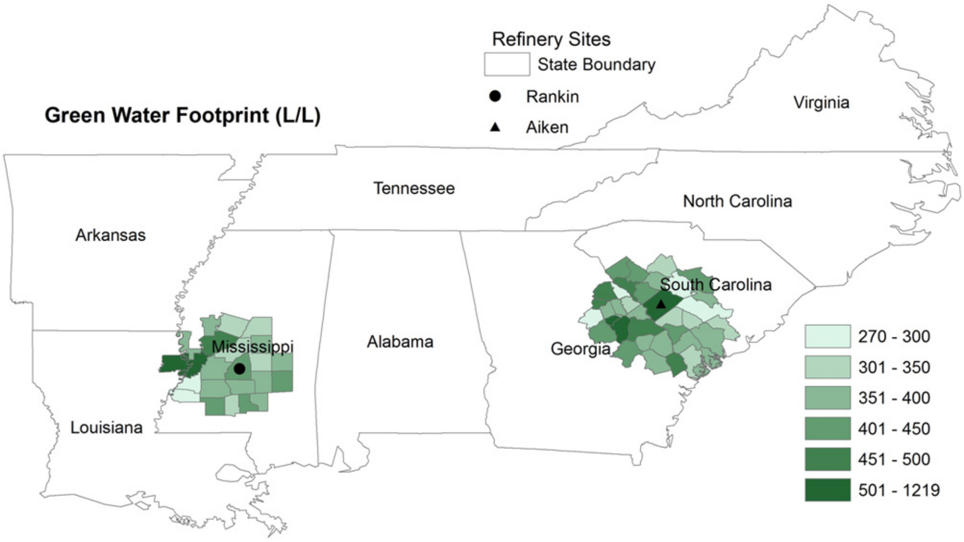

Figure 3. Green water footprint distribution of the CSS case. The maps represent water footprint under the scenarios of refinery size 2000 DMTD, with 7% and 30% of feedstock ash and moisture content, respectively.

region demands lower evapotranspiration volume per area (∼600 mm) than softwood does (∼800 mm). However, the proportion of hardwood trees contributing to the residue (40–50%) is larger than that of the softwood trees (20–30%) on the basis of the TPO database [37]. Results also suggest that at the same residue harvest rate, softwood would grow ∼2.5 times faster than hardwood, producing a larger amount of biomass in each stand, which agrees with the observed higher ET requirement. There is no grey water associated with CSS as the feedstock is entirely forest wood residue.

3.2. Distributed preprocessing supply systems (DPSS) case

In the DPSS case, feedstock collection is no longer limited by geographic regions, as the platform is able to process, store, and transport the processed feedstock with greater efficiency. Both pulpwood and short-rotation woody crop (SRWC) become available and play an important role in the resource mix and therefore impact the water footprint. There is extensive spatial heterogeneity in the green water footprint—the lowest county-level green water footprint is 28 l/l and the highest is 3147 l/l, with a regional average of 400 l/l. As indicated in figure 2, green water use in the advanced case is dominated by SRWC.

In contrast to the CSS case, the feedstock-growing areas that are available for collection expanded significantly in the DPSS case. The feedstock-growing areas not only cover the CSS centers (Aiken and Rankin) and the areas in between, but they also extend east to the rest of South Carolina; north to North Carolina, Virginia, and Tennessee; west to Arkansas and Louisiana; and south to Georgia. As a result, the case leaves a certain level of water footprint in each of the 787 counties in the studied region, as each county contributes a share of feedstock (figure 4). The number of counties with a high-intensity green water footprint appears mostly in the west regions of the studied area. Virginia, South Carolina, and North Carolina appear to have the lowest green water footprint with a state average ranging between 307 and 351 l/l. The contribution of feedstock sourcing from the expanded county list also increases the variance between the highest and lowest county green water footprint in the DPSS (figure 4) case comparing with the CSS (figure 3), or 3118 versus 905 l/l.

By adding pulpwood and SRWC in the feedstock pool, DPSS setting also results in grey water footprint associated with the biofuel production. Unlike green water footprint, grey water footprint spatial distribution appears relatively homogeneous in the DPSS case (figure 4). On the county level, the grey water footprint at the DPSS setting ranges between 0.8 and 119 l/l with a regional average (entire DPSS area) of 25 l/l, in which 88% is associated with SRWC. Note that some counties appear to have zero grey water if SRWC and pulpwood are not produced for biofuel. Same as green water footprint, Virginia, South Carolina, and North Carolina appear to have a relatively low grey water footprint of 18–19 l/l under the DPSS setting.

Overall, woody biofuel water footprint (vol. water per vol. fuel production) is closely associated with biofuel yield. For example, in the DPSS case, by varying yield from 1% to 10%, both regional-average green and grey water footprint would also change 1% and 9% accordingly.

3.3. Uncertainty

Several preset assumptions and the design of data sources may have introduced uncertainties in estimating the water footprint of woody biofuel. The representative tree species selected in this region include loblolly and sweet gum, and we assume the SRWC is harvested from softwood. In reality, other species would also likely be potential feedstock, and the feedstock mix could be extensive. In other regions, this combination may not be applicable. For instance, fir trees and hickory can be the major softwood and hardwood in other regions in the United States, and poplars and willow can be grown as typical SRWC if climate and site condition permit [38].

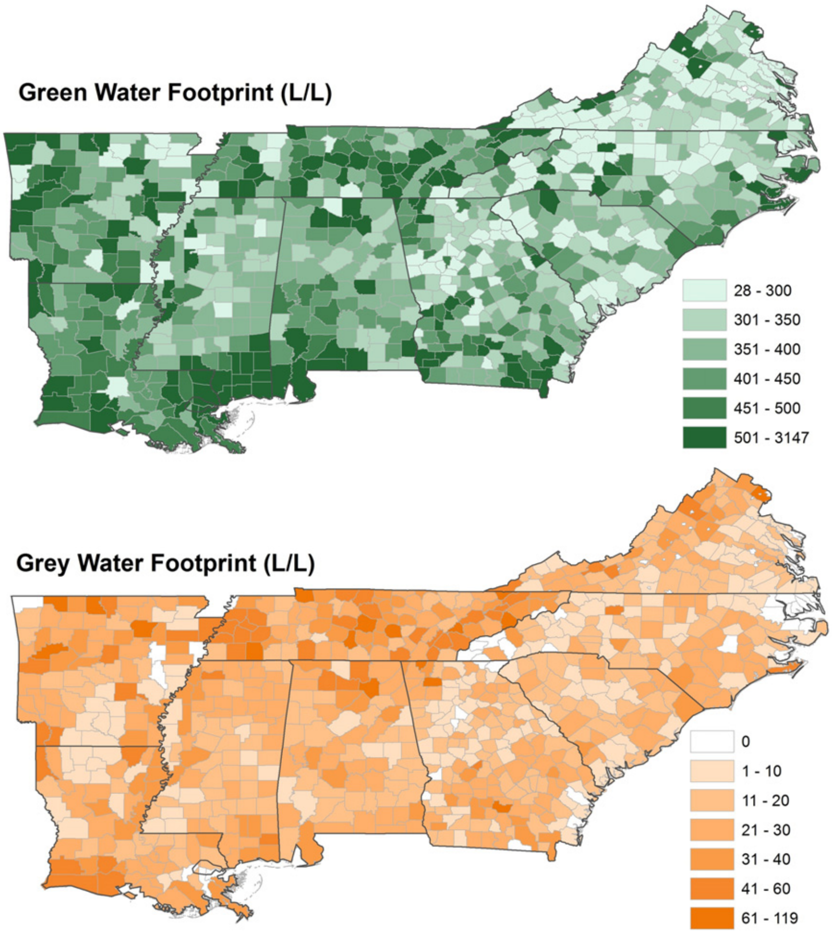

Figure 4. Green and grey water spatial distribution of the DPSS case under the combination of 30% and 7% moist and ash contents, respectively.

Another uncertainty associated with the selection of representative tree species is the estimation of evapotranspiration. Often, forest stands can be a composite ecosystem accommodating both softwood and hardwood, which made ET data validation for single type forest difficult. The estimate of forest ET can be improved by employing additional approaches, such as remote sensing [39]. In terms of grey water, reporting of the nitrogen leaching rate from nitrogen fertilizer application in managed forest is very limited in public domain. Finally, the mass allocation method can also play a significant role in affecting water footprint. In this approach, the total forest green water volume is partitioned to the harvested portion of the biomass following a mass-based allocation. However, although the forest ET data can be county-based the ratio of residue mass harvested in timber production appears to be a state-level projection in the TPO data, not at county-level resolution. Thus, if a given county shows exceptionally low softwood thinning or residue production, the same state-level fraction (i.e. thinning or residue/total forest biomass) is applied to allocate total forest green water to the harvested feedstock in that county. As a result, the county will show high water footprint per unit biomass or per volume of biofuel. This is a calculation deficiency due to insufficient data. Therefore, extensive forest monitoring data would be needed to fill this data gap.

4. Conclusions

The biofuel produced from woody residue appears to have the advantage in water consumption because of its relatively small water footprint (grey and blue water in particular), in comparison with other biofuel feedstock [15, 40]. For example, the regional-average blue water footprint in the ten U.S. agricultural regions of Appalachia, Southeast, and Delta ranges between 7 and 111 l/l, 18–309 l/l, 6–47 l/l, and 12–594 l/l for corn, corn stover and wheat straw bioethanol, and soybean biodiesel, respectively [15]. Blue water footprint of forest-based biofuel is minimal and only results from the refinery-process stage without irrigation inputs, which is similar to perennial grass biofuel, while grey water footprint is significantly smaller with an average of 25 l/l. To put this into perspective, the lowest grey water footprint from the conventional feedstock is estimated to be 97 l/l if produced from soybean at the Delta region, and else feedstock would result much greater grey water than this level [15]. The green water footprint shows extensive heterogeneous spatial distribution, whereas the grey water footprint is relatively homogeneous. Choice of feedstock mix plays a key role in determining the magnitude and spatial distribution of the water footprint in these regions.

This study and the proposed method incorporate and analyze the latest available data and literature to quantify the biofuel water footprint produced from forest feedstock. It advances the understanding of water resource use by identifying regional forest type and feedstock mix and its role in water footprint thereby allowing the selection of low water footprint cellulosic feedstock in biofuel development. As shown in the results, the short-rotation woody crops can play a significant role to determine the magnitude of local wood-based biofuel water footprint. Note that the findings of this study represent the scenarios of water footprint associated with a feed mix including growing short-rotation woody crops on existing forests. The impacts on water use are likely to change when land conversion takes place with the development of short-rotation woody crops. Therefore, future study is required to investigate water footprint dynamics associated with new feedstock as well as other forest regions in the United States.

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