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# The water-land-food nexus of natural rubber production

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ABSTRACT

The increasing global demand for natural rubber (100% increase in the last 15 years) is for most part met by Malaysia and Indonesia, and – to a lesser extent – other countries in South-East Asia and Africa. The consequent expansion of rubber plantation has often occurred at the expenses of agricultural land for staple crops, particularly in South-East Asia, where 90% of the land suitable for agriculture is already under cultivation. Here we investigate the extent to which the ongoing increase in rubber production is competing with the food system and affecting the livelihoods of rural communities living in the production areas and their appropriation of natural resources, such as water. We also investigate to what extent the expansion of rubber plantations is taking place through large scale land acquisitions (LSLAs) and evaluate the impacts on rural communities. Our results show how rubber production needs more than 10 million ha of fertile land and up to 136–149 $\times$ $10^9$ $m^3$ $y^{-1}$ of freshwater (125 $\times$ $10^9$ $m^3$ $y^{-1}$ of green water and 11–24 $\times$ $10^9$ $m^3$ $y^{-1}$ of blue water). These resources would be sufficient to produce enough food to significantly reduce malnourishment in Indonesia, Thailand, and Vietnam if replaced by rice production. Overall, natural rubber production has important environmental, social, and economic impacts. Indeed, despite their ability to bring employment and increase the average income of economically disadvantaged areas, rubber plantations may threaten the local water and food security and induce a loss of rural livelihoods – particularly when the new plantations result from LSLAs that displace semi-subsistence forms of production – thereby forcing the local populations to depend on global food markets.



## 1. Introduction

The world's rubber demand more than doubled in the last fifteen years (International Rubber Study Group, 2016), as a result of the rising demand for tire manufacturing. Rubber can be produced both from natural and synthetic material (Qiu, 2009). Because of its better properties (Ahrends et al., 2015) natural rubber accounts for about half of the world supply (International Rubber Study Group, 2016). Future projections show that global rubber demand will continue to grow as a result of the boom of the auto industry in developing countries (Ziegler et al., 2009; Ahrends et al., 2015).

Previous studies have shown how natural rubber production has important environmental impacts (Qiu, 2009). The expansion of rubber plantations often happens at the expenses of forests that are replaced by rows of rubber trees (Giambelluca et al., 2016; Warren-Thomas et al., 2015), causing habitat destruction and consequent biodiversity losses (Li et al., 2007; Qiu, 2009; Fu et al., 2009; Warren-Thomas et al., 2015; Ahrends et al., 2015). Rubber plants are also known by local populations as ‘water pumps’ (Qiu, 2009; Tan et al., 2011; Giambelluca et al., 2016) because they take up more water than the forest and croplands they replace (Guardiola-Claramonte et al., 2008). Thus, natural rubber production may have important local hydrological impacts, decreasing groundwater recharge and river runoff (Ziegler et al., 2009; Tan et al., 2011; Giambelluca et al., 2016). Other environmental impacts include accelerated soil erosion (Ziegler et al., 2009), declining water quality from the use of fertilizers and pesticides (Ziegler et al., 2009; RTG, 2014), land use change and loss of biodiversity (Li et al., 2007; Qiu, 2009; Fu et al., 2009; Ahrends et al., 2015; Warren-Thomas et al., 2015).

South-East Asia is the epicenter of the world's natural rubber production (FAO, 2016). In that region, rubber is mainly planted in smallholder farms of size ranging between one and 4 ha (Fox and Castella, 2013), though there are also larger plantations (Hazell et al., 2010). More recently, new rubber plantations have been established by private enterprises that have acquired large tracts of forested land and cropland, a phenomenon known as “large-scale land acquisition” (LSLA) (Fox and Castella, 2013; Ahrends et al.,

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2015; Warren-Thomas et al., 2015).

While previous work has focused on the environmental effects of natural rubber production, there is only a limited understanding of the impact on local food security in production areas. Despite its ability to bring wealth to many low-income areas (Qiu, 2009), natural rubber production may locally induce water and food insecurity and cause a loss of rural livelihoods (Ahrends et al., 2015). This is particularly true when the new plantations result from LSLAs that displace semi-subsistence forms of production, thereby forcing the local populations to depend on global markets for their access to food (Ahrends et al., 2015; Rulli and D'Odorico, 2014; Rulli et al., 2016). When small-scale farmers have to buy food products, they become vulnerable to market price volatility (Davis et al., 2014). In this study we focus on most (95%) of the rubber plantations existing worldwide and determine the harvested land, the green water and blue water requirements, and relate the recent land and water appropriations for rubber production to the global phenomena of LSLAs and virtual water trade (e.g., Hoekstra and Hung, 2002; Rulli et al., 2013a; Carr et al., 2013). We then discuss potential effects of rubber expansion on food production and benefits to local communities.

## 2. Methods

We analyzed the status of land, water resources and food security in the top 27 natural rubber producing countries that account for about 95% of the global land area cultivated with rubber.

A schematic representation of the conceptual framework used in this study to investigate the water-land-food nexus of natural rubber productions is provided in Fig. 1, which highlights the assessment of freshwater resources and the impacts of water availability on food security.

### 2.1. Land use

In each of the analyzed countries we determined the land area that is available for cultivation by comparing the extent of suitable land for agriculture with the land already cropped. Country-specific data on the extent of suitable land for agriculture under rainfed and/or irrigated conditions were taken from the GAEZ (Global Agro-Ecological Zones) dataset (Fischer et al., 2008), while the extent of arable and permanent crop areas was from FAOSTAT (FAO, 2016). Data on harvested rubber are taken from FAO for the year 2013 (FAO, 2016). We also analyzed LSLAs for rubber plantation and compare the acquired area with land availability both in the target country, and in the investors' country, using data provided by the Land Matrix portal (2017).

### 2.2. Water resources

We calculated the water footprint of rubber in different regions of the world solving a vertical soil-water balance equation at a daily time scale. We assessed the total amount of water required by plants (i.e. crop water requirement CWR) to avoid water stress and how it is partitioned between green water (GW) (i.e. water provided by rainfall) and blue water (BW) (i.e. irrigation water needed by plants). CWR is equal to the amount of water plants release into the atmosphere as water vapor fluxes (evapotranspiration, ET).

As input, we used climatic data from CRU CL 2.0 (New et al., 2002), soil parameters, such as the maximum available soil water content (i.e., at 'field capacity'), and crop characteristics such as the planting date, crop coefficient (see below), and length of growing stage according to Chapagain and Hoekstra (2004) (See supplementary material S1-S3).

### 2.3. CWR is assessed as

$$CWR = \sum Kc^{*}ETo \qquad (1)$$

where Kc is the crop coefficient (a coefficient taking in account crop

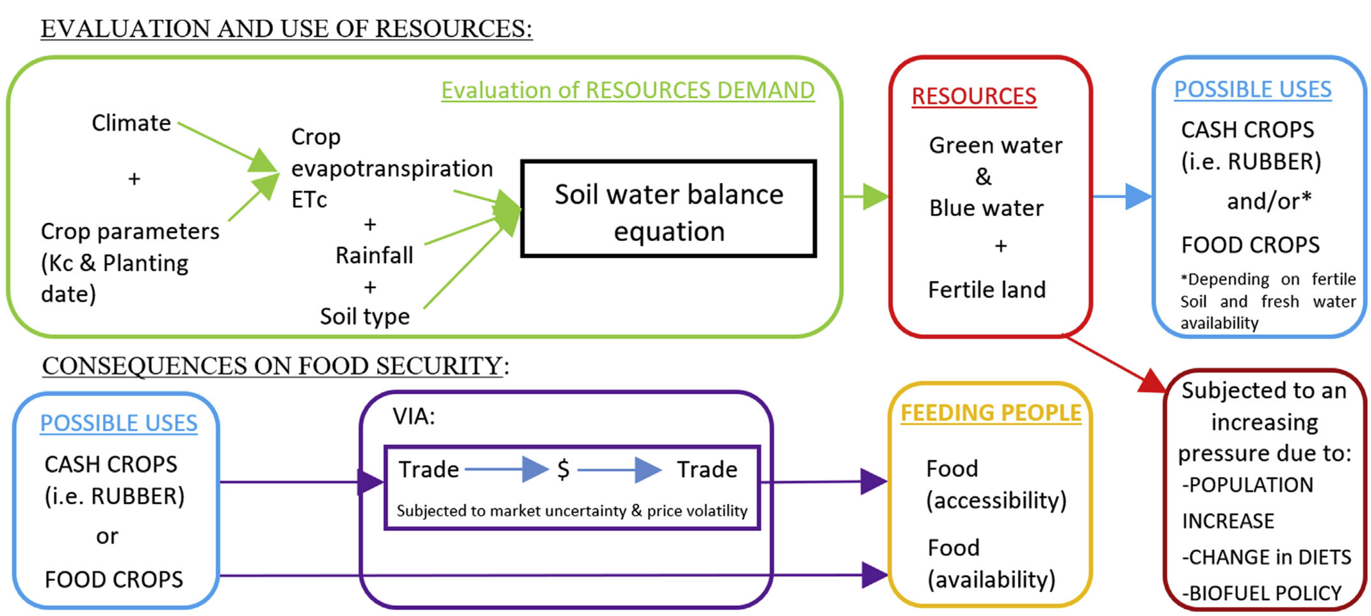


**Fig. 1. Conceptual framework of water-land-food nexus of natural rubber productions**. Fertile land and freshwater represent the necessary, but limited, resources needed to maintain crop productions, whose demand is increasing due to population increase, change in diets and biofuel policies. In the green box is described the relations between climatic parameters, crop parameters and soil type necessary to assess green and blue water demand of different crops (i.e. rubber or rice), while in the purple box is highlighted the different steps to ensure food security for cash crops and food crops. Thus, a graph with the process synthesis could represent a useful tool for a first glance approach of such a complex and dynamic nexus between water, land and food, as recommended by Heckl et al. (2015). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

characteristics during different growing stages such as crop cover density and total leaf area (Allen, 2003)), and $ET_o$ is the reference evapotranspiration (i.e. ET of a hypothetical well-watered grass of uniform height, actively growing and completely shading the ground). CWRs are partly or completely met by rainwater (GW) and, in case of deficiency, by irrigation (BW).

To determine the amount of water that needs to be supplied by irrigation we calculate the actual evapotranspiration in the absence of irrigation, which depends both on potential evapotranspiration and on soil water content, and we assume irrigation to be equal to the difference between potential and actual evapotranspiration. Thus, the GW consumed by crops is the sum of daily evapotranspiration in the absence of irrigation, while BW is evaluated as the difference between CWR and GW. Consumptive water used by plants is equal to CWR if BW is actually provided to plants (i.e. through irrigation), whereas in the absence of irrigation CWR is equal to GW.

The model has been run using the best available information on the distribution of rubber plantations in each country. Particularly, for 6 countries (Cambodia, China, Lao PDR, Myanmar, Thailand and Vietnam) more detailed information was available about the location of rubber plantations, based on Li and Fox (2012). Of the other countries included in this study we focused on those in which Large Scale Land Acquisition have been reported to occur (The Land Matrix, 2017), we calculated the GW and BW consumption averaged within each country for all the sets of coordinates in which acquisition of agricultural land for rubber (since the year 2000) has occurred according to The Land Matrix (2017). Finally, in the case of Brazil, India and Bangladesh we considered average GW and BW within the most harvested region for rubber according to Ahrends et al. (2015) (Supplementary material S3).

There are no global data on the use of irrigation for rubber trees. Here we consider 2 different scenarios. In the first we assume that rubber is fully irrigated everywhere, so consumptive water use is determined as the sum of GW and BW. In the second one, we account for irrigation only in 6 countries of South East Asia for which detailed map are available; in those countries we assumed that blue water was used only in areas equipped for irrigation (based on the 10 km resolution map from Siebert et al. (2005)). Potential blue water use (i.e., the difference between CWR and GW) is reduced multiplying by the percentage of average irrigation equipment in rubber plantations (Supplementary material S6).

Finally, since we can expect investors to maximize crop production in the acquired land (Anseeuw et al., 2012; Rulli et al., 2013a, 2013b), we calculated the consumptive water use for LSLAs (or “water grabbing”) as the sum of GW and BW, regardless of the current existence of irrigation infrastructure. The underlying assumption is that, if needed, agribusiness corporations will invest in irrigation systems.

To evaluate the impact of natural rubber production on freshwater resources, we estimated the average water consumption in grid cells of 10 km $\times$ 10 km and compared it to the water consumption of the seven main food crops (rice, maize, sugarcane, vegetables, pulses, sorghum and wheat) in South East Asia, selected using GAEZ crop maps (Fischer et al., 2008). The volume of water is calculated for each cell and each crop as the GW and BW (expressed as water depths) multiplied by the area cultivated with that crop within the cell.

### *2.4. Impact on food and GDP*

We calculated the potential impact of rubber production on food availability assessing the number of people that could be fed if the land areas cropped with rubber trees were used to produce rice. Caloric content of rice was set equal to 280 kcal/100 g (D'Odorico et al., 2014) while the Human Energy Requirement (HER) was conservatively taken equal to 3000 kcal/capita/day as suggested by FAO (FAO, 2009). Country-specific data of population, malnourishment and rice yields were taken from the FAO database for the year 2013 (most up-to-date values) (FAO, 2016). The impact of natural rubber production on the GDP of these 27 countries in 2013 (FAO, 2016) was evaluated considering a rubber price of USD2866 per metric tons as in year 2012 (http://www.indexmundi.com).

### *2.5. Trade*

Rubber trade data (including pre-vulcanized rubber) were obtained from the Comtrade database for the year 2013 (http://comtrade.un.org). “Flows” of virtual land and virtual water were calculated as the rubber's export and rubber net export rates times the country-specific land and green water footprints respectively. Values reported in weight were converted to rubber field area using country-specific crop yields (FAO, 2016) and into water by considering the crop water requirement previously evaluated for each country.

## 3. Results

### *3.1. Land use*

Natural rubber plantations mainly occur in South East Asia, particularly in Indonesia, Thailand, Malaysia, China, Vietnam, and India, which account for 85% of total world area planted with rubber trees (about 10 million hectares). Africa is now harvesting 7% of the land cultivated with natural rubber globally. Africa's top rubber producer is Nigeria (340,000 ha) followed by Cote d'Ivoire (130,000 ha). Despite its smaller land cultivated with rubber, Cote d'Ivoire produces 50% more rubber than Nigeria. In America natural rubber is cultivated in Brazil and Guyana, with Brazil being the top harvester and producer (FAO, 2016) (Fig. 3).

Our results show how many of the Asian countries where natural rubber is cultivated (such as Bangladesh, India, China, Thailand, Sri Lanka, and Myanmar) are approaching the exhaustion of their land suitable for agriculture, while others (e.g., Philippines, Indonesia and Vietnam) have already displaced forest ecosystems to plant rubber. Conversely, in Cambodia and Lao PDR about 68% and 62% of the agricultural land, respectively, is still available for agricultural expansion (Fig. 2 and Supplementary material S5).

The analysis of LSLAs shows that, globally, about 4 million hectares have been acquired for rubber plantations since 2009. Asia is the most targeted continent with 1.75 million hectares transacted, for most part in Cambodia, Indonesia, Lao PDR and Malaysia. Presently, in Asia only 22% of LSLAs for rubber are under production, 77% of them in Malaysia. LSLAs in Africa account of about 1.6 million hectares, which is more than twice the area cultivated with rubber in 2013. Presently only 12% of this land is under production. The top African countries targeted by land investors for rubber production are Ghana, Ethiopia, and Liberia. In Oceania, the most targeted country is Papua New Guinea, where land investors have acquired 700,000 ha, which still have to be put under production (Fig. 2 and Table 1)

### *3.2. Water*

The main hydrologic impacts of rubber plantations are associated with the higher evapotranspiration relative to native vegetation (Mann, 2009; Tan et al., 2011; Giambelluca et al., 2016). The average CWRs calculated are in the range of 1200mm/y-1400 mm/y, with some outliers in Senegal, Guyana, and Ethiopia where the CWRs are even higher (Table 2). Thus, the amount of water required

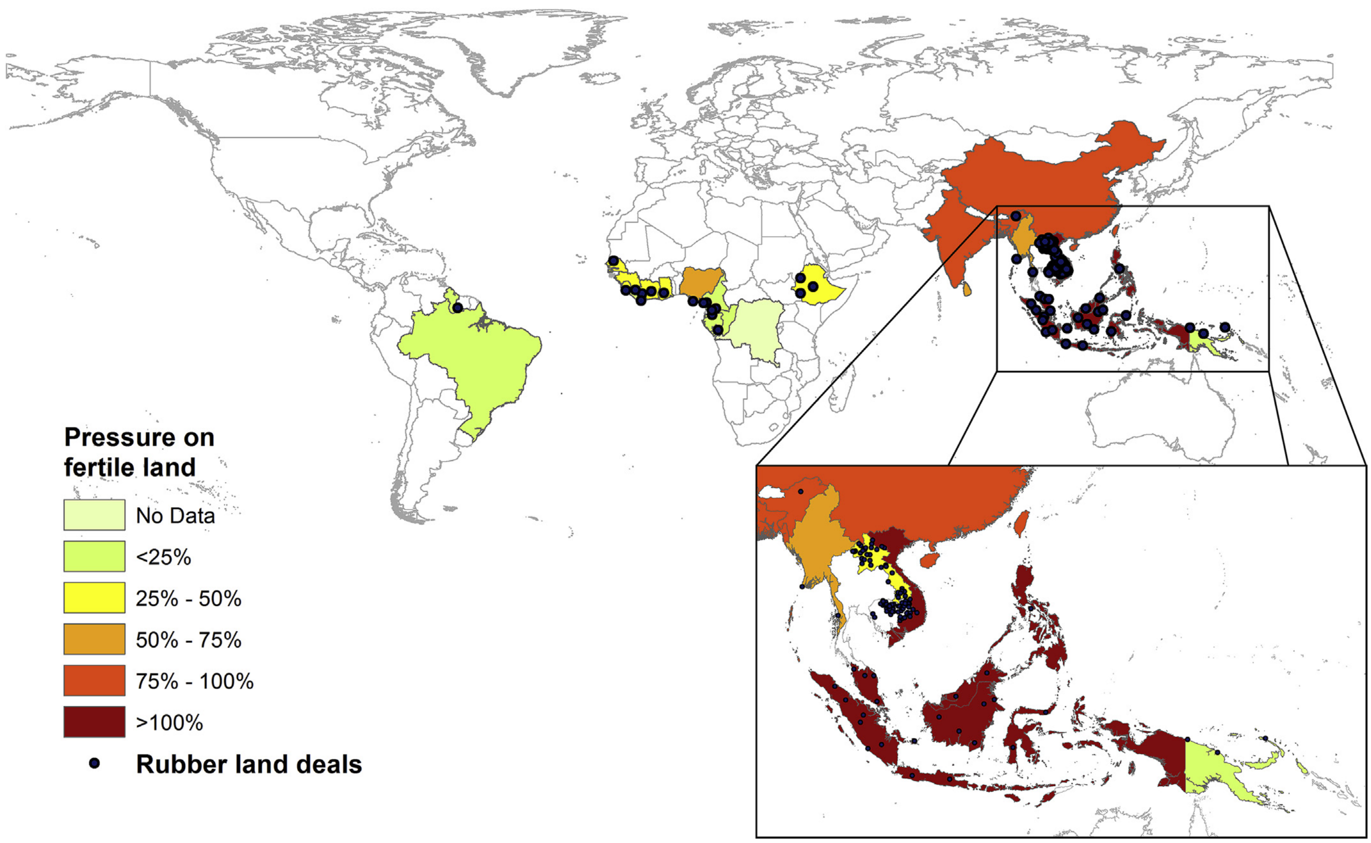


**Fig. 2. Status of fertile land and location of Large Scale Land Acquisition Areas**. To be notice how almost 20% of acquisition occurred in areas where pressure on soil is already very high (i.e. >75%).

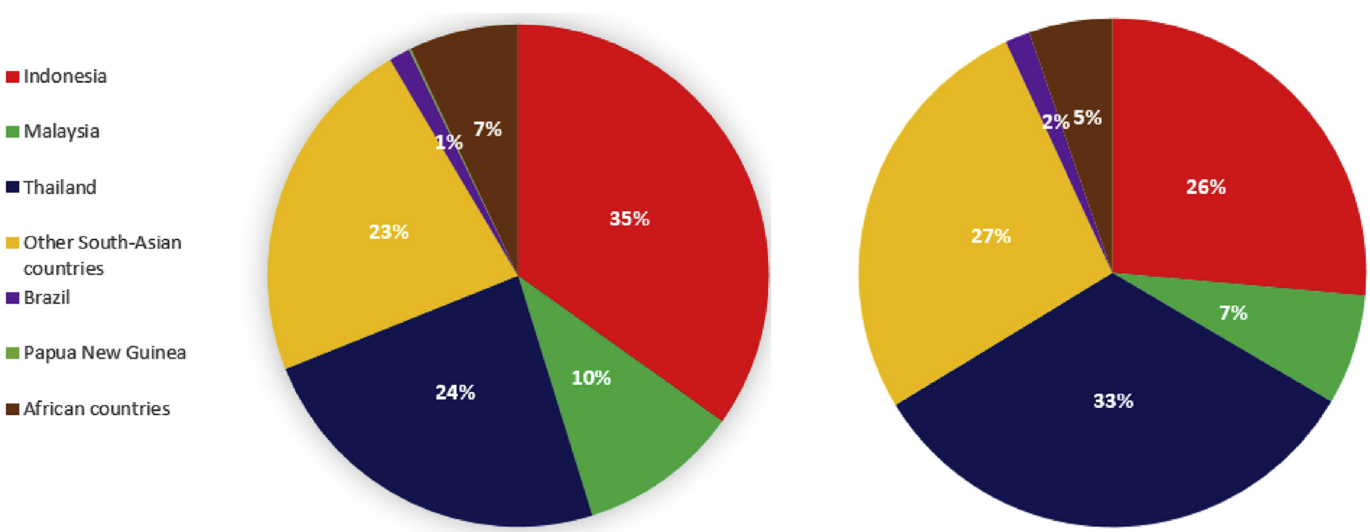


**Fig. 3. Main rubber harvesting** (left chart) **and production countries** (right chart) as a percentage of total harvested area in 2013 (FAO, 2016) and production (FAO, 2016).

by rubber plantations is much greater than the major food crops (i.e. wheat and maize), whose CWRs are typically in the 300–600 mm/y range (Chapagain and Hoekstra, 2004; Chiarelli et al., 2016). The values calculated in our study for CWRs are in agreement with field measurement of evapotranspiration of rubber trees in Cambodia, China, and Thailand (Tan et al., 2011; Giambelluca et al., 2016). With respect to main crop cultivations in South-East Asia (in the year 2000), water demand accounting also for rubber is on average 4.1% higher, with a peak of 162% in some coastal areas of Thailand, where rubber plantations are seeing a very rapid expansion (Muethaisong and Leemanonwarachai, 2014).

In 2013 the production of natural rubber required the consumption of about $125 \times 10^9$ $m^3$ of green water (GW) and $11–24 \times 10^9$ $m^3$of blue water (BW) (See Table 2). In Liberia, Malaysia, Indonesia and Thailand rubber production accounts for 29%, 21%, 13%, and 11% of the total green water use in agriculture, respectively. Notice that, because of data limitations, we are unable

**Table 1**
**Areas of large scale land acquisition** (Land Matrix, 2017) and associated water in contracted areas. In agreement with Land Matrix, with intended size we refer to an area that was formerly or is currently intended to be acquired by investor reflecting the possible intention for future expansion, while contracted area is the current area that has been leased or purchased by the investor.

| LSLA 2017 | Intended area[a] ($10^4$ ha) | Contracted area[a] ($10^4$ ha) | Under production area[a] (%) | Green water ( $\times 10^9$ $m^3$) | Blue water ( $\times 10^9$ $m^3$) | Total ( $\times 10^9$ $m^3$) |
|---|---|---|---|---|---|---|
| Cambodia | 6.6 | 74.9 | 4% | 7.5 | 3.4 | 10.9 |
| Indonesia | 33.0 | 54.5 | 26% | 8.2 | 0.5 | 8.8 |
| Lao PDR | 53.5 | 22.5 | 30% | 2.3 | 1.0 | 3.3 |
| Myanmar | 13.0 | 4.0 | 0% | 0.4 | 0.2 | 0.6 |
| Malaysia | 0.0 | 19.3 | 77% | 1.9 | 0.9 | 2.8 |
| Vietnam | 0.0 | 0.2 | 6% | 0.0 | 0.0 | 0.0 |
| Philippines | 10.0 | 0.0 | 0% | 0.0 | 0.0 | 0.0 |
| **Asia** | **116.1** | **175.3** | **22%** | **20.3** | **6.0** | **26.4** |
| Cameroon | 18.4 | 15.0 | 50% | 1.6 | 0.2 | 1.8 |
| Congo | 5.0 | 5.0 | 0% | 0.7 | 0.0 | 0.7 |
| Côte d'Ivoire | 1.9 | 1.3 | 43% | 0.1 | 0.0 | 0.2 |
| DR Congo | 4.3 | 5.1 | 18% | 0.6 | 0.1 | 0.6 |
| Ethiopia | 37.1 | 31.2 | 0% | 1.7 | 4.1 | 5.8 |
| Gabon | 41.9 | 23.9 | 26% | 2.5 | 0.5 | 3.1 |
| Ghana | 41.5 | 41.5 | 0% | 4.4 | 3.6 | 8.0 |
| Guinea | 2.2 | 2.2 | 0% | 0.2 | 0.1 | 0.3 |
| Liberia | 40.3 | 31.1 | 4% | 3.1 | 1.0 | 4.0 |
| Nigeria | 4.5 | 2.8 | 57% | 0.3 | 0.1 | 0.4 |
| Senegal | 2.0 | 2.0 | 28% | 0.0 | 0.5 | 0.5 |
| Sierra Leone | 16.8 | 2.0 | 61% | 0.2 | 0.1 | 0.2 |
| **Africa** | **215.9** | **163.1** | **12%** | **15.4** | **10.2** | **25.6** |
| Guyana | 15.8 | 0.4 | 0% | 0.1 | 0.0 | 0.1 |
| **America** | **15.8** | **0.4** | **0%** | **0.1** | **0.0** | **0.1** |
| Papua New Guinea | 0.0 | 69.5 | 0% | 11.7 | 0.0 | 11.7 |
| **Oceania** | **0.0** | **69.5** | **0%** | **11.7** | **0.0** | **11.7** |
| **Total** | **347.8** | **408.3** | **14%** | **47.6** | **16.2** | **63.8** |

[a] Data are from Land Matrix (2017).

**Table 2**
**Water and land consumed by natural rubber production in 2013** in the 27 countries analyzed. For 6 countries (Cambodia, China, Lao PDR, Myanmar, Thailand, and Vietnam) blue water is reported for the full-irrigated scenarios and for irrigation occurring only in area equipped for irrigation.

| Country | Average Green water use for rubber (mm) | Average Blue water requirement by rubber (mm) | Rubber harvested area in 2013 ($10^4$ ha)[a] | Rubber production ($10^3$ t) [a] | Green water ( $\times 10^9$ $m^3$) | Blu water ( $\times 10^9$ $m^3$) | Total water ( $\times 10^9$ $m^3$) |
|---|---|---|---|---|---|---|---|
| Bangladesh | 887.3 | 277.2 | 6.0 | 6 | 0.5 | 0.2 | 0.7 |
| Cambodia | 998.3 | 460.9 | 3.6 | 43 | 0.4 | 0.2–0.0 | 0.5 |
| China | 870.7 | 351.8 | 68.6 | 865 | 6.0 | 2.4–0.4 | 8.4 |
| India | 1110.7 | 379.0 | 44.2 | 900 | 4.9 | 1.7 | 6.6 |
| Indonesia | 1614.9 | 31.3 | 355.6 | 3108 | 57.4 | 1.1 | 58.5 |
| Lao PDR | 1003.0 | 447.0 | 0.0 | No data | 0.0 | 0.0–0.0 | 0.0 |
| Malaysia | 1304.0 | 0.0 | 105.7 | 826 | 13.8 | 0.0 | 13.8 |
| Myanmar | 988.4 | 433.2 | 20.4 | 148 | 2.0 | 0.9–0.1 | 2.9 |
| Philippines | 1321.9 | 62.5 | 18.5 | 111 | 2.4 | 0.1 | 2.6 |
| Sri Lanka | 988.1 | 412.7 | 13.6 | 130 | 1.3 | 0.6 | 1.9 |
| Thailand | 899.3 | 579.7 | 242.1 | 3863 | 21.8 | 14.0–4.9 | 35.8 |
| Vietnam | 956.0 | 259.0 | 54.8 | 949 | 5.2 | 1.4–0.3 | 6.7 |
| Brazil | 1277.0 | 0.0 | 14.0 | 186 | 1.8 | 0.0 | 1.8 |
| Cameroon | 1183.9 | 86.1 | 5.5 | 56,0 | 0.7 | 0,0 | 0.7 |
| Congo | 1390.8 | 42.9 | 0.2 | 2,0 | 0,0 | 0,0 | 0,0 |
| Côte d'Ivoire | 1000.6 | 268.5 | 13.5 | 290,0 | 1.4 | 0.4 | 1.7 |
| DR Congo | 1110.6 | 131.1 | 5.1 | 12,0 | 0.6 | 0.1 | 0.6 |
| Ethiopia | 622.6 | 960,0 | 0,0 | No data | 0,0 | 0,0 | 0,0 |
| Gabon | 1056.6 | 228.5 | 2.7 | 21,0 | 0.3 | 0.1 | 0.3 |
| Ghana | 892.2 | 738.3 | 1.5 | 21,0 | 0.1 | 0.1 | 0.2 |
| Guinea | 1065.9 | 380.3 | 1.1 | 16,0 | 0.1 | 0,0 | 0.2 |
| Liberia | 1091.9 | 176.6 | 7.6 | 63,0 | 0.8 | 0.1 | 1,0 |
| Nigeria | 989,0 | 292.4 | 34.5 | 144,0 | 3.4 | 1,0 | 4.4 |
| Senegal | 239.2 | 2415.3 | 0,0 | No data | 0,0 | 0,0 | 0,0 |
| Sierra Leone | 880.8 | 382.7 | 0,0 | No data | 0,0 | 0,0 | 0,0 |
| Papua New Guinea | 1702.1 | 0.0 | 1.4 | 0 | 0.2 | 0.0 | 0.2 |
| Total | | | | | **125** | **24–11** | **149–136** |

[a] Data from FAO (2016).

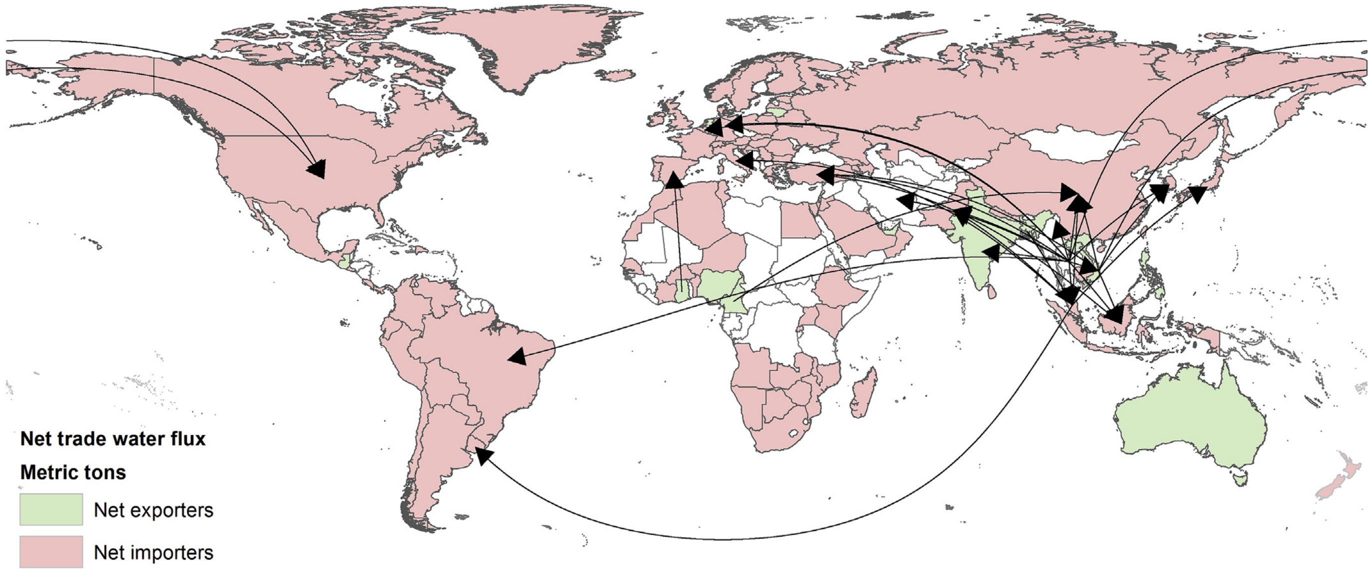


**Fig. 4. Green + Blue water trade of natural rubber**. Countries are colored based on net trade flux while arrows represent the first 28 higher water fluxes. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

to determine the exact amount of blue water consumption for irrigation. Thus, we estimate the potential blue water consumption ($24 \times 10^9$ m$^3$) which is the amount of irrigation water that would be required to allow for the maximum attainable yield of rubber. In other words, it is the amount of irrigation water that is required for production in conditions with no water limitation. For six countries in South East Asia we were able to assess the percentage of rubber plantation occurring in areas equipped for irrigation (at the year 2000) and found that in Thailand 35% of rubber plantation are in areas equipped for irrigation, 20% in Vietnam, and 18% in China. Thus, global BW demand for rubber is reduced to $11.1 \times 10^9$ m$^3$ per year (Table 2). Water consumption for rubber production associated with LSLA includes about in $48 \times 10^9$ m$^3$ per year of green water and $16 \times 10^9$ m$^3$ per year of blue water (See Table 1). Interestingly, in the countries that are most targeted by LSLA for rubber production (e.g., Papua New Guinea and Indonesia), the CWR is almost completely met by rainwater (i.e., green water) because these countries benefit from high precipitation rates typical of the wet tropics (Rulli and D'Odorico, 2013b; Rulli et al., 2013). Conversely, Thailand, Sri Lanka, India, Senegal and Ghana require a relatively high rate of blue water consumption for irrigation (Table 2) to sustain the maximum attainable yields of rubber trees.

### 3.3. Land and water trade associated to rubber export

Land and water used for rubber production are mostly displaced through trade. The analysis of trade reveals that, globally, 0.76 million hectares of land and $7 \times 10^9$ m$^3$ of GW and $3.9 \times 10^9$ m$^3$ of BW were virtually exported in 2013. The main center of the world's raw natural rubber trade is in Thailand, followed by Vietnam, Ghana, and Malaysia. In these countries rubber exports account for a substantial fraction of the total virtual water exports associated with agricultural products. About 37% of country total green water exports are contributed by rubber in Thailand, followed by Vietnam (6%), Ghana (4%), and Malaysia (2%). While in Asia the international trade of rubber remains within the region, in Africa natural rubber is exported to the Americas and Europe (Table 4). Net exporters are Vietnam, Cameroon, and Ghana, while Malaysia and China are great net importers. Netherlands, Australia and the United Arab Emirates are the main exporters of imported natural rubber (See Fig. 4, Supplementary Fig. S1-S2 and Supplementary Table S7–S9).

### 3.4. Food security & economic development

Natural rubber represents an attractive economic source of revenue for low income farmers, and rubber production could have important consequences on the wealth of local populations (Musikavong and Gheewala, 2016; Kenney-Lazar, 2016a). Farmers can earn up to USD2200 per hectare per year with natural rubber compared to almost USD400 per hectare from tea or rice crops (Qiu, 2009). In some cases, rubber plantation helped the development of local economies, as reported in South China and Lao PDR, where township's income increased almost tenfold between 1988 and 2003 (Mann, 2009). In 2013, rubber production accounted for 1–3% of the gross domestic product (GDP) in most of the rubber producing countries included in this study (Thailand, Vietnam, Indonesia, and Cote d'Ivoire) while it reached about 9.3% in Liberia (Table 3).

Rubber production can threaten the food security of local populations when it is cultivated in poor countries where part of the population is malnourished and depends heavily on locally farmed products (FAO, 2016). A trend observed across South-East Asia is the replacement of paddy rice with natural rubber plantations (Haberecht, 2009; Li and Fox, 2012); we also evaluate the frequency with which a crop is replaced by rubber, using the GAEZ map in 2000 for 7 main crops. We find that in 73% of the cases rubber replaces rice and in 10% of the cases it replaces maize in areas originally harvested with food crops. This finding justifies our choice to consider rice as the reference crop while studying the impact of rubber expansion on food production (Supplementary Material S6).

Furthermore, Asian countries do not have enough suitable land for agriculture to meet the increasing demand for food crops. In these countries, where all the land suitable for agriculture is already under production (Fig. 2 and Supplementary material S5) and there are no options for agricultural expansion, rubber plantations are claiming land that was previously used for food crops. In an ideal scenario in which natural rubber plantations are converted to paddy rice, it would be possible to produce enough food to substantially reduce malnourishment (below 5% in the case of

**Table 3**
**Socio-economic effects of natural rubber in the 27 countries analyzed**. Current pressure on agricultural land represents the current use of suitable land for agriculture with respect to the total suitable cropland area.

| | Current pressure on agricultural land (arable land and permanent crop/suitable land) (%) | Malnutrition 2013[a] (%) | Malnutrition decrease (rubber replaced by rice) (%) | Impact of natural rubber on GDP (%) |
|---|---|---|---|---|
| Bangladesh | 92 | 17 | 17 | 0 |
| Cambodia | 32 | 16 | 14 | 0.8 |
| China | 85 | 10 | 10 | 0 |
| India | 96 | 15 | 15 | 0.13 |
| Indonesia | 121 | 8 | <5 | 0.98 |
| Lao PDR | 38 | 19 | 19 | 0 |
| Malaysia | 151 | <5 | <5 | 0.14 |
| Myanmar | 62 | 16 | 12 | 0.66 |
| Philippines | 145 | 14 | 12 | 0.12 |
| Sri Lanka | 69 | 24 | 17 | 0.56 |
| Thailand | 79 | 8 | <5 | 2.64 |
| Vietnam | 106 | 13 | <5 | 1.59 |
| Brazil | 18 | <5 | <5 | 0 |
| Guyana | 4 | 12 | 12 | No data |
| Cameroon | 25 | 10 | 10 | 0.5 |
| Congo | 3 | 28 | 28 | 0 |
| Côte d'Ivoire | 32 | 14 | 6 | 2.6 |
| DR Congo | No data | No data | Not applicable | 0.1 |
| Ethiopia | 46 | 34 | 34 | 0 |
| Gabon | 3 | <5 | <5 | 0.4 |
| Ghana | 44 | <5 | <5 | 0.1 |
| Guinea | 34 | 17 | 17 | 0.7 |
| Liberia | 15 | 33 | 28 | 9.28 |
| Nigeria | 69 | 7 | 6 | 0.01 |
| Senegal | 31 | 11 | 11 | 0 |
| Sierra Leone | 49 | 24 | 24 | 0 |
| Papua New Guinea | 13 | No data | Not applicable | 0.18 |

[a] Data from FAO (2016).

Indonesia, Thailand and Vietnam) (Table 3).

### 3.5. The future of rubber

Rubber demand is expected to further grow in future and reach 16.7 million tons by 2020; 91% of this rubber will be produced in South-East Asia (World Rubber Summit, 2012). In Montane Mainland South East Asia (MMSEA) 6 million ha of arable land are expected to be harvested with natural rubber, fourfold the current area (Fox et al., 2012), thus, additional 42.8 $\times$ $10^9$ $m^3$ of GW and 3.1 $\times$ $10^9$ $m^3$ of BW will be required in those areas on top of the 19 $\times$ $10^9$ $m^3$ of BW currently consumed for irrigation according to a fully irrigated scenario. Furthermore, intended large scale land acquisition for rubber account for 347.8 million ha, which corresponds to about 85% more land than the acquired areas that have already been contracted.

## 4. Discussion

Rubber production uses a huge amount of water because of the very high evapotranspiration rates rubber trees can sustain (Qiu, 2009; Tan et al., 2011; Giambelluca et al., 2016). While further research is needed to ascertain the current water uses for irrigation in rubber plantations, we have used suitable assumptions to estimate green and blue water consumption for natural rubber production and related it to local water availability and other uses; our results demonstrate how rubber production has a strong impact on freshwater resources in countries, such as Thailand, Malaysia and Liberia, that are already experiencing moderate water stress conditions (Mekonnen and Hoekstra, 2016). While many forested areas are often converted into rubber plantations, almost 30% of the new rubber plantations in South East Asia are established in fertile agricultural areas where they replace food crops (Li et al., 2012), especially rice fields (Haberecht, 2009; Li and Fox, 2012). This transition has been documented in China (Fu et al., 2009), Cambodia (Haberecht, 2009), and India (Abraham and Chudek, 2008), suggesting the existence of important trade-offs between the economic benefits of a cash crop such as rubber, and food production (Qiu, 2009).

The implications of land exploitation for rubber plantations are more complex, especially in South-East Asia, where there is already limited availability of fertile land for agricultural production. In that region the demand for food crops is expected to increase due to population growth and changes in diets. In countries such as India and Indonesia, which are sustaining a large share of the global oil palm demand (Hansen et al., 2015), all the land suitable for agriculture is already under use, and only few options exist to feed their

**Table 4**
**Land, GW and BW consumed exported by studied country**. (The last column represents the net export for exporter country, while country in italic are net importer countries (See Supplementary Material S8 for the complete list)).

| Exporte[a] | Netweight (t) | Export area (ha) | Percentage of export area | Volume of Green Water ($\times$ $10^9$ $m^3$) | Volume of Blue Water ($\times$ $10^9$ $m^3$) | Net export (t) | Net Land export (ha) | Net GW export ($\times$ $10^9$ $m^3$) | Net BW export ($\times$ $10^9$ $m^3$) |
|---|---|---|---|---|---|---|---|---|---|
| Bangladesh | 1648 | 16,353 | 0.27 | 0.15 | 0.05 | 871 | 8638 | 0.08 | 0.02 |
| *Brazil* | 1 | 1 | 0.00 | 0.00 | 0.00 | 0 | | 0.00 | 0.00 |
| Cameroon | 9570 | 9789 | 0.06 | 0.12 | 0.01 | 9563 | 9783 | 0.12 | 0.01 |
| *China* | 3123 | 2477 | 0.04 | 0.02 | 0.01 | 0 | | 0.00 | 0.00 |
| *Cote D'Ivoire* | 0 | 0 | 0.00 | 0.00 | 0.00 | 0 | | 0.00 | 0.00 |
| Ghana | 6255 | 7818 | 0.29 | 0.07 | 0.06 | 6251 | 7813 | 0.07 | 0.06 |
| India | 7725 | 3862 | 0.01 | 0.04 | 0.01 | 2929 | 1465 | 0.02 | 0.01 |
| *Indonesia* | 5907 | 6760 | 0.00 | 0.11 | 0.00 | 0 | | 0.00 | 0.00 |
| Lao PDR | 4912 | NA | NA | NA | NA | 4898 | NA | NA | NA |
| *Malaysia* | 33,538 | 42,904 | 0.04 | 0.56 | 0.00 | 0 | | 0.00 | 0.00 |
| Nigeria | 661 | 1594 | 0.00 | 0.02 | 0.00 | 646 | 1558 | 0.02 | 0.00 |
| Philippines | 771 | 321 | 0.00 | 0.00 | 0.00 | 713 | 297 | 0.00 | 0.00 |
| *Sri Lanka* | 794 | 829 | 0.01 | 0.01 | 0.00 | 0 | | 0.00 | 0.00 |
| *Thailand* | 1,038,421 | 635,353 | 0.24 | 5.71 | 3.68 | 0 | | 0.00 | 0.00 |
| Vietnam | 51,257 | 29,670 | 0.05 | 0.28 | 0.08 | 48,043 | 27,809 | 0.27 | 0.07 |
| **Total** | **1,164,582** | **757,732** | | **7.09** | **3.91** | | **57,362** | **0.56** | **0.17** |

[a] Country in italic are net importer.

malnourished population (about 15% and 8% of their people are malnourished, respectively).

The farmers' economy is also strongly affected by the trade market in multiple ways. First, their livelihoods depend on the price of natural rubber in the global market. Second, farmers depend on markets to purchase primary commodities, such as food. Third, all the economic benefits of the natural rubber industry could vanish if a pest known as "leaf blight" (*Microcyclusulei*), which is already strongly affecting rubber plantations in Brazil, reaches major rubber production areas in West Africa and South-East Asia (Mann, 2009). In addition, natural rubber's price volatility depends on many factors, such as the oil price (Ahrends et al., 2015). In 2011 the price of natural rubber reached a high peak, but in almost a year it decreased by about 70% (www.indexmundi.com/commodities, 2016). Thus, there are clear and ongoing trade-offs among economic development, environment, and the livelihoods of local populations. Socio-economic concerns arise from the volatility of the rubber price, potential loss of food security, increased dependence on global markets of both rubber and food, and exposure to LSLA practices.

Governments often see in the expansion of rubber production opportunities to improve their economy, particularly in the years between 2000 and 2012 when rubber trade with China has been increasing. Thus, governments of some Southeast Asian Countries such as Laos and Myanmar have pushed for an expansion of plantations within big concession areas, often encouraging foreign investors, rather than supporting local farmers (Keeny-Lazar, 2016a, 2016b). Conversely, the Thai government promoted integrated livelihood systems in which rubber farmers are also involved in livestock production or aquaculture (Kenney-Lazar, 2016a, 2016b).

Currently, governments are still looking at rubber expansion, especially in large-scale plantations, as a possibility to improve the local economy (Bissonnette and Koninck, 2017). In the case of Vietnam, government has been urging farmers to shift their production to rubber plantations (Dao, 2015). A similar approach has been adopted by the government of Nigeria, the second largest rubber producer in Africa, though production is nowadays declining because of oil discoveries in this country (https://www.foramfera.com/rubber-tree-cultivation-in-nigeria-the-investment-opportunity/). Some recent studies showed that it is possible to use rubber for the production of biofuel in Sub-Saharan Africa, thus potentially increasing the demand for rubber production in the region (Onoji et al., 2016). Future of rubber expansion is expected to occur in large-scale rubber plantations more than as small-scale farming. For instance, in Myanmar there are plans to convert 1.5 million ha into rubber production in the next 13 years (Kenney-Lazar, 2016a), with strong potential impacts on the local water and food security. It has also been noticed how most tropical Asia and particularly Southeast Asia, is undergoing a transition from large-scale plantations to smallholder farms for an important number of cash crops (Bissonnette and Koninck, 2017). Moreover, some private companies are starting to show more interest in the environmental impacts of agriculture and in adopting a sustainable production model that respects both the environment and local communities. The Sustainable Natural Rubber initiative (SNRI) is setting standards for sustainable rubber production, as promoted during the World Rubber Summit (Singapore in 2012).

## 5. Conclusion

The development of the world's natural rubber plantations is problematic due to socio-economic consequences and water limitations that will likely exacerbate water competition with food production and other industries. This certainly appears to be the case for some countries in water stressed regions such as Thailand and Cambodia. The trade of natural rubber is associated with a substantial displacement of water and land to importers' countries such as Malaysia, China and the USA. The production of natural rubber directly competes with food crops for land and land based resources, thereby compromising the local water and food security, an effect that remains for most part underappreciated.

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## Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jclepro.2017.12.021.

## References

Abraham, J., Chudek, J.A., 2008. Studies on litter characterization using 13C NMR and assessment of microbial activity in natural forest and plantation crops' (teak and rubber) soil ecosystems of Kerala, India. Plant soil 303 (1–2), 265–273.
Ahrends, A., Hollingsworth, P.M., Ziegler, A.D., Fox, J.M., Chen, H., Su, Y., Xu, J., 2015. Current trends of rubber plantation expansion may threaten biodiversity and livelihoods. Glob. Environ. Change 34, 48–58, 78.
Allen, R., 2003. Crop coefficient. Encycl. Water Sci., 120010037 https://doi.org/10.1081/E-EWS.
Anseeuw, W., Boche, M., Breu, T., Giger, M., Lay, J., Messerli, P., Nolte, K., 2012. Transnational Land Deals for Agriculture in the Global South.
Bissonnette, J.F., Koninck, R.D., 2017. The return of the plantation? Historical and contemporary trends in the relation between plantations and smallholdings in Southeast Asia. J. Peasant Stud. 1–21.
Carr, J.A., D'Odorico, P., Laio, F., Ridolfi, L., 2013. Recent history and geography of virtual water trade. PLoS One 8 (2), e55825. https://doi.org/10.1371/journal.pone.0055825.
Chapagain, A.K., Hoekstra, A.Y., 2004. Water Footprints of Nations.
Chiarelli, D.D., Davis, K.F., Rulli, M.C., D'Odorico, P., 2016. Climate change and large-scale land acquisitions in Africa: quantifying the future impact on acquired water resources. Adv. Water Resour. 94, 231–237.
D'Odorico, P., Carr, J.A., Laio, F., Ridolfi, L., Vandoni, S., 2014. Feeding humanity through global food trade. Earth. Future 2 (9), 458–469.
Davis, K.F., D'Odorico, P., Rulli, M.C., 2014. Land grabbing: a preliminary quantification of economic impacts on rural livelihoods. Popul. Environ. 36 (2), 180–192.
Dao, N., 2015. Rubber plantations in the Northwest: rethinking the concept of land grabs in Vietnam. J. Peasant Stud. 42 (2), 347–369.
FAO, 2009. Feeding the World, Eradicating Hunger, World Summit on Food Security, Rome.
FAO, 2016. FAOSTAT Website, FAO Statistic Division available at: http://faostat3.fao.org/home/E. . (Accessed June 2015).
Fischer, G., Nachtergaele, F., Prieler, S., Van Velthuizen, H.T., Verelst, L., Wiberg, D., 2008. Global Agro-ecological Zones Assessment for Agriculture (GAEZ 2008). IIASA, Laxenburg, Austria and FAO, Rome, Italy, p. 10.
Fox, J., Castella, J.C., 2013. Expansion of rubber (heveabrasiliensis) in mainland Southeast Asia: what are the prospects for smallholders? J. Peasant Stud. 40 (1), 155–170.
Fox, J., Vogler, J.B., Sen, O.L., Giambelluca, T.W., Ziegler, A.D., 2012. Simulating land cover change in montane mainland southeast Asia. Environ. Manag. 49, 968–979.
Fu, Y., Brookfield, H., Guo, H., Chen, J., Chen, A., Cui, J., 2009. Smallholder rubber plantation expansion and its impact on local livelihoods, land use and agro-biodiversity, a case study from Daka, Xishuangbanna, southwestern China. Int. J. Sustain. Dev. World Ecol. 16 (1), 22–29.
Giambelluca, T.W., Mudd, R.G., Liu, W., Ziegler, A.D., Kobayashi, N., Kumagai, T.O., Yin, S., 2016. Evapotranspiration of rubber (Hevea brasiliensis) cultivated at two plantation sites in Southeast Asia. Water Resour. Res. 52 (2), 660–679.
Guardiola-Claramonte, M., Troch, P.A., Ziegler, A.D., Giambelluca, T.W., Vogler, J.B., Nullet, M.A., 2008. Local hydrologic effects of introducing non-native vegetation in a tropical catchment. Ecohydrology 1 (1), 13–22.
Haberecht, S., 2009. From Rice to Rubber. Development, Transformation, and Foreign Investment in Northern Laos: an Actor-oriented Approach.
Hansen, S.B., Padfield, R., Syayuti, K., Evers, S., Zakariah, Z., Mastura, S., 2015. Trends in global palm oil sustainability research. J. Clean. Prod. 100, 140–149.
Hazell, P., Poulton, C., Wiggins, S., Dorward, A., 2010. The future of small farms: trajectories and policy priorities. World Dev. 38 (10), 1349–1361.
Heckl, I., Cabezas, H., Friedler, F., 2015. Designing sustainable supply chains in the energy-water-food nexus by the P-graph methodology. In: Chemical Engineering Transactions. Italian Association of Chemical Engineering-AIDIC.

Hoekstra, A.Y., Hung, P.Q., 2002. Virtual water trade. A quantification of virtual water flows between nations in relation to international crop trade. Value water Res. Rep. Ser. 11, 166.
International Rubber Study group, 2016. Statistical Summary of World Rubber SituationQ4 2000 – Q1 2016. International Rubber Study group, Singapore.
Kenney-Lazar, M., 2016a. Assessment of Governance Mechanisms, Livelihood Outcomes and Incentive Instruments for Green Rubber in Myanmar. Working Paper 207. Bogor, Indonesia: CIFOR.
Kenney-Lazar, M., 2016b. Assessment of Governance Mechanisms, Livelihood Outcomes and Incentive Instruments for Green Rubber in the Lao PDR. Working Paper 206. Bogor, Indonesia: CIFOR.
Land Matrix, 2017. The Land Matrix Global Observatory. International Land Coalition (ILC), Centre de Coopération Internationale en Recherche Agronomique pour le Dévelopement (CIRAD), Centre for Development and Environment (CDE), German Institute of Global and Area Studies (GIGA) and Deutsche (GIZ). . (Accessed October 2016).
Li, Z., Fox, J.M., 2012. Mapping rubber tree growth in mainland Southeast Asia using time-series MODIS 250 m NDVI and statistical data. Appl. Geogr. 32 (2), 420–432.
Li, H., Aide, T.M., Ma, Y., Liu, W., Cao, M., 2007. Demand for rubber is causing the loss of high diversity rain forest in SW China. Biodivers. Conserv. 16 (6), 1731–1745.
Mann, C.C., 2009. Addicted to rubber. Science 325 (5940), 564–566.
Mekonnen, M.M., Hoekstra, A.Y., 2016. Four billion people facing severe water scarcity. Sci. Adv. 2 (2), e1500323.
Muethaisong, K., Leemanonwarachai, T., 2014. An investigation of China's import demand for technically specified natural rubber (TSR) from Thailand. Statistics 3, 1–192.
Musikavong, C., Gheewala, S.H., 2017. Assessing ecological footprints of products from the rubber industry and palm oil mills in Thailand. J. Clean. Prod. 142, 1148–1157.
New, M., Lister, D., Hulme, M., Makin, I., 2002. A high-resolution data set of surface climate over global land areas. Clim. Res. 21, 1–25.
Onoji, S.E., Iyuke, S.E., Igbafe, A.I., Nkazi, D.B., 2016. Rubber seed oil: a potential renewable source of biodiesel for sustainable development in sub-Saharan Africa. Energy Convers. Manag. 110, 125–134.
Qiu, J., 2009. Where the rubber meets the garden. Nature 457 (7227), 246–247.
RTG (Royal Thai Government), 2014. Cabinet Resolution on November 4, 2014.
Rulli, M.C., D'Odorico, P., 2013. The water footprint of land grabbing. Geophys. Res. Lett. 40 (23), 6130–6135.
Rulli, M.C., D'Odorico, P., 2014. Food appropriation through large scale land acquisitions. Environ. Res. Lett. 9 (6), 064030.
Rulli, M.C., Saviori, A., D'Odorico, P., 2013. Global land and water grabbing. Proc. Natl. Acad. Sci. 110 (3), 892–897.
Rulli, M.C., Bellomi, D., Cazzoli, A., De Carolis, G., D'Odorico, P., 2016. The water-land-food nexus of first-generation biofuels. Sci. Rep. 6.
Siebert, S., Döll, P., Hoogeveen, J., Faures, J.M., Frenken, K., Feick, S., 2005. Development and validation of the global map of irrigation areas. Hydrology Earth Syst. Sci. Discuss. 2 (4), 1299–1327.
Tan, Z.H., Zhang, Y.P., Song, Q.H., Liu, W.J., Deng, X.B., Tang, J.W., Sun, X.M., 2011. Rubber plantations act as water pumps in tropical China. Geophys. Res. Lett. 38 (24).
Warren-Thomas, E., Dolman, P.M., Edwards, D.P., 2015. Increasing demand for natural rubber necessitates a robust sustainability initiative to mitigate impacts on tropical biodiversity. Conserv. Lett. 8 (4), 230–241.
Ziegler, A.D., Fox, J.M., Xu, J., 2009. The rubber juggernaut. Science 324 (5930), 1024–1025.