Ecological Indicators 77 (2017) 304–313

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Original Articles

Water, land and carbon footprints of sheep and chicken meat produced in Tunisia under different farming systems

Ridha Ibidhi[a,b,*], Arjen Y. Hoekstra[c,d], P.Winnie Gerbens-Leenes[e], Hatem Chouchane[c]

[a] Laboratoire des Productions Animales et Fourragères, Institut National de la Recherche Agronomique de Tunisie (INRAT), Université de Carthage, 2049 Ariana, Tunisia
[b] Faculté des Sciences de Bizerte, Université de Carthage, 7021 Zarzouna, Tunisia
[c] Twente Water Centre, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands
[d] Institute of Water Policy, Lee Kuan Yew School of Public Policy, National University of Singapore, 259770 Singapore, Singapore
[e] Center for Energy and Environmental Studies (IVEM), University of Groningen, The Netherlands

ARTICLE INFO

Article history:
Received 23 July 2016
Received in revised form 12 February 2017
Accepted 15 February 2017

Keywords:
Environmental footprint
Water
Land
Carbon
Sheep and chicken meat
Tunisia

ABSTRACT

Meat production puts larger demands on water and land and results in larger greenhouse gas emissions than alternative forms of food. This study uses footprint indicators, the water, land and carbon footprint, to assess natural resources use and greenhouse gas emissions for sheep and chicken meat produced in Tunisia in different farming systems in the period 1996–2005. Tunisia is a water-scarce country with large areas of pasture for sheep production. Poultry production is relatively large and based on imported feed. The farming systems considered are: the industrial system for chicken, and the agro-pastoral system using cereal crop-residues, the agro-pastoral system using barley and the pastoral system using barley for sheep. Chicken meat has a smaller water footprint (6030 litre/kg), land footprint (9 m^2/kg) and carbon footprint (3 CO_2-eq/kg) than sheep meat (with an average water footprint of 18900 litre/kg, land footprint of 57 m^2/kg, and carbon footprint of 28 CO_2-eq/kg). For sheep meat, the agro-pastoral system using cereal crop-residues is the production system with smallest water and land footprints, but the highest carbon footprint. The pastoral system using barley has larger water and land footprints than the agro-pastoral system using barley, but comparable carbon footprint.

1. Introduction

One of the challenges the world faces over the next decades is to preserve its natural resources and at the same time produce sufficient food to satisfy the demand of a growing human population. Between 1950 and 2015, the world population has quadrupled and global resource consumption and waste emissions have grown beyond the Earth's carrying capacity. Food production significantly contributes to the increasing human appropriation of the world's limited freshwater and land resources (Steinfeld et al., 2006; De Vries and De Boer, 2010) and to the emission of greenhouse gases (Herrero et al., 2013). The resulting increase in water and land scarcity in turn affects food security. The accumulation of human pressure is the main cause of many environmental issues and world leaders face the challenge of selecting appropriate policies and investments to prevent further detrimental effects. In order to monitor the pressures humanity exerts on the environment, different impact categories should be measured through a set of appropriate indicators, for example using the family of footprint indicators, including the water, land and carbon footprint (Galli et al., 2012, 2013). The footprint indicators have the potential to provide a comprehensive picture of environmental pressures (Hoekstra and Wiedmann, 2014; Fang et al., 2014). The multi-indicator approach is important in order to measure the pressure on water, land and climate. The water footprint (WF) measures the freshwater appropriated to produce goods or services, expressed as a water volume per unit of product (Hoekstra, 2009; Hoekstra et al., 2011). The WF includes three components: the green WF (evapotranspiration of rainwater from the field to produce for example a crop); the blue WF (net withdrawal of water from surface water or groundwater); and the grey WF (the volume of freshwater required to assimilate pollutants). The land footprint (LF) is the amount of land used to produce goods and services and is expressed in area per unit of product. The LF of a product reflects the real amount of land, wherever it is in the world, that is used to produce the product (Borucke

* Corresponding author at: Laboratoire des Productions Animales et Fourragères, Institut National de la Recherche Agronomique de Tunisie (INRAT), Université de Carthage, 2049 Ariana, Tunisia.
E-mail addresses: ibidhi_ridha@hotmail.fr, ibidhi.ridha1@gmail.com (R. Ibidhi).

http://dx.doi.org/10.1016/j.ecolind.2017.02.022
1470-160X/

et al., 2013; Giljum et al., 2013). Both WF and LF can be used to show the dependency of consumption in one place on natural resources (water or land) in another place, since products are traded, and with them the water and land virtually embedded in this product trade (Čuček et al., 2012). The carbon footprint (CF) refers to the greenhouse gas (GHG) emissions, expressed in CO_2 equivalent units (CO_2e), associated with a product process or service (Ruviaro et al., 2015). The CF includes the three main gases included in the Kyoto protocol: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The conversion of the gases to CO_2-eq is done using the global warming potential (GWP) of each gas, where GWP values for CO_2, CH_4 and N_2O are 1, 25 and 298 CO_2-eq/kg, respectively, assuming a 100-years time horizon (IPCC, 2007).

Livestock, for the production of meat and milk, is the world's largest user of land resources, with pasture and land dedicated to the production of animal feed representing 70% of the total agricultural area (Steinfeld et al., 2006). Thus, the production of animal feed can be considered as one of the major hotspots in the environmental impact from livestock production (Ridoutt et al., 2014). Globally, grasslands cover about one third of the vegetated area and contribute about one fifth to the global carbon cycle (Goudriaan et al., 2001; Sala, 2001). Along a precipitation gradient, grasslands are located between forests and deserts. When annual precipitation is higher than 1200 mm per year, usually forests dominate, whereas when precipitation is lower than 150 mm per year, usually sites are dominated by deserts. Grasslands cover a broad range of environmental conditions with an annual aboveground productivity from 50 to 800 $g\,m^{-2}$ that is linearly related to precipitation (Sala et al., 1988). Grasslands are used to graze cattle, sheep, goats or other animals and in this way contribute to the production of food (Sala, 2001).

In this paper, we assess the WF, LF and CF of chicken and sheep meat produced under different farming systems in Tunisia. We then compare the water and land use efficiency and GHG emission between chicken and meat and across production systems for sheep. The period of analysis is 1996–2005. The livestock sector is one of the most important activities in Tunisia. It plays an important role, economically and socially, by contributing 35–40% to the agricultural gross domestic product (GDP) and 4–5% to total GDP (Ministry of Agriculture, 2013). Meat consumption in Tunisia increased substantially during the past few decades, especially the consumption of poultry. Consumer behaviour shows a shift from red meat to white meat consumption, which is partly explained from the low price of poultry compared to red meat. For a country with limited natural resources like Tunisia, climate change will have drastic repercussions. The country is increasingly experiencing extreme summer temperatures and periods of extreme drought and wetness. Water resources in Tunisia are already overexploited. The indirect effects of climate change, such as soil erosion and a decline in agricultural production, are impacting economically important sectors and threatening human habitats and ecosystems (Radhouane, 2013). The production of sheep meat in Tunisia relies on the availability of pasture and additional feed grown in Tunisia itself, while the dominant industrial production of poultry relies on imported feed, mainly from Brazil (Ministry of Agriculture, 2013). Mekonnen and Hoekstra (2010) estimated the WF of sheep meat in Tunisia using an average WF of pasture for Northern Africa and, by allocating all water consumption in crop production to the crop yield, assumed a zero WF for crop residues used for feed. Tunisia, however, shows distinct climatic zones, the North, Centre and South, with average annual rainfall and grassland productivity decreasing from North to South, resulting in three different sheep production systems. The current study takes the climatic differences into account and assumes that when crop residues are applied for feed, they have an economic value and thus a WF. The current study is the first to assess the three different types of environmental footprint of sheep and chicken meat production, expressed per unit of production to enable comparison.

Table 1
Land use and percentage of total land area in Tunisia.

Land use	Land area (1000 ha)	Percent of total land area
Total land area[a]	15536	100
Total agricultural land[b]	10079	65
Woodlands[b]	1039	8
Grasslands[b]	4830	31
Croplands[b]	4211	27

[a] FAO (2016a).
[b] Ministry of Agriculture (2013).

2. Environmental conditions and meat production in Tunisia

2.1. Climate and land use

The country has three climatic zones that divide the country into three regions: North, Central and South Tunisia (Chouchane et al., 2015). Due to its geographic position, Tunisia is under the influence of two climates, the Mediterranean climate in the north and the desert climate of the Sahara in the south. Central Tunisia shows characteristics of both climates. The annual average rainfall varies from less than 100 mm in the extreme South to over 1200 mm in the extreme North (Kayouli, 2006).

Tunisia is one of the Maghreb countries in North Africa. As the other countries in the region, it includes large areas of grasslands that vary quantitatively and qualitatively across bioclimatic zones (Kayouli, 2006; Le Houerou, 1975). Many are being destroyed by overgrazing and encroachment of agriculture (Puigdefabregas and Mendizabal, 1998). Tunisia as a whole suffers from high water scarcity, north Tunisia experiences moderate water scarcity, central Tunisia significant scarcity and South Tunisia severe water scarcity (Chouchane et al., 2015). Grasslands cover nearly one third of the total land area (Table 1). In Tunisia, grasslands are mainly applied for sheep grazing. Additionally, sheep get access to fallow lands; generally, croplands are fallow (not used for cropping) once every two years.

Climatic differences cause differences in crop water use (CWU) in the country's grasslands. Table 2 gives CWU per governorate as well as average CWU per region based on data from Mekonnen and Hoekstra (2010). CWU is largest in the North, averaging 4243 m^3/ha, and smallest in the South, averaging 2325 m^3/ha.

2.2. Productivity of grasslands

The second national Tunisian forest and grassland inventory (Ministry of Agriculture, 2010) made an inventory of plants that occur in the natural grasslands in the three regions in Tunisia. Table 3 gives an overview of the dominant grassland species in the North, Centre and South of Tunisia, the dry matter content (DM) per species and the average dry matter content for grassland species in the North, Centre and South of Tunisia.

The climate, including precipitation variation, causes different combinations of dominant grassland species among the Northern, Central and Southern part of Tunisia. Annual grassland yields vary as well. Table 4 shows indicative yields (in both tonne of dry matter and tonne of fresh weight per hectare) and average grassland dry matter (tonne/tonne) (FAO, 1985) for the three regions in Tunisia. North Tunisia has the largest grassland yields, about five times larger than yields in the South when expressed in tonnes DM per hectare, while the Centre finds itself in between the two extremes.

Table 2
Crop water use for grassland (m^3/ha) per governorate in Tunisia and average CWU for the North, Centre and South.

North	CWU (m^3/ha)	Centre	CWU (m^3/ha)	South	CWU (m^3/ha)
Ariana	3921	Kairouan	4061	Gabes	2383
Baja	4442	Kasserine	4415	Kebili	2201
Bizerte	4374	Mahdia	3224	Medenine	2448
Jendouba	4669	Monastir	3405	Tataouine	2317
Kef	4714	Sfax	3209	Tozeur	2276
Nabeul	3830	Sidi Bouzid	3571		
Siliana	4412	Sousse	3674		
Tunis	3886				
Zaghouan	3937				
Average	4243	Average	3651	Average	2325

Source: Mekonnen and Hoekstra (2010).

Table 3
Dominant grassland species per region in Tunisia (from Ministry of Agriculture, 2010), the dry matter content (DM) per grassland species and the average dry matter content per region.

Species in North	DM (%)	Species in Centre	DM (%)	Species in South	DM (%)
Artemisia campestris[a]	30.5	*Stipa tenacissima*[a]	72.1	*Retama retam*[a]	43.1
Avena sterilis[b]	30	*Rosmarinus officinalis*[a]	47.5	*Stipa tenacissima*[a]	72.1
Seriphidium herba-album	–	*Artemisia herba-alba*[a]	30.5	*Seriphduim herba-album*	–
Lolium rigidum	–	*Astragalus armatus*[a]	30	*Artemisia herba-alba*[a]	30.5
Hippocrepis spp.	–	*Artemisia campestris*[a]	30.5	*Artemisia campestris*[a]	30.5
Lathyrus aphacaLotus spp.[a]	–	*Aristida pungens*[a]	30	*Aristida pungens*[a]	30
Medicago ciliaris[a]	26.8	*Cynodon dactylon*[a]	47.5	*Cynodon dactylon*[a]	47.5
Medicago littoralis[a]	26.8			*Traganum nudatum*	–
Medicago orbicularis[a]	26.8			*Anthyllis oropediorum*[a]	40
Medicagopolymorpha[a]	26.8				
Trifolium cherleri[a]	44				
Average	30.2	Average	41.2	Average	42

[a] FAO (1985).
[b] Kayouli (2006).

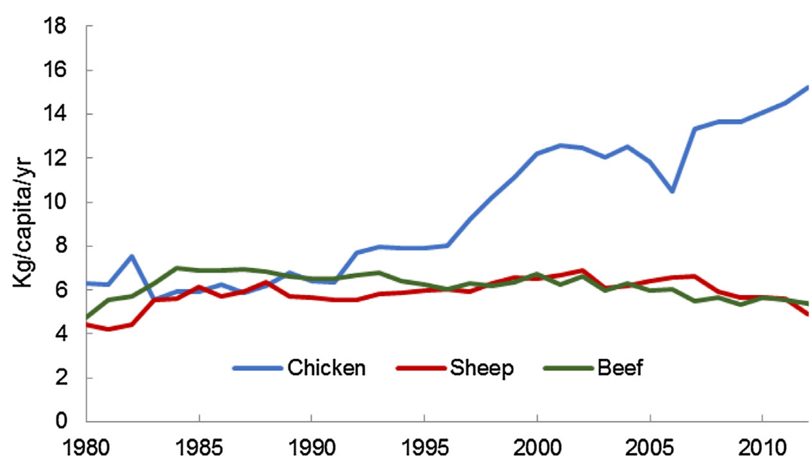

Fig. 1. Meat consumption in Tunisia over the period 1980–2013. Source: FAO (2013).

Table 4
Grassland yields for the three regions in Tunisia.

	North	Centre	South
Grassland yield (tonne DM/ha)[a]	4.2	1.90	0.90
Grassland yield (tonne fresh biomass/ha)[b]	14	4.75	2.25

[a] Le Houerou (1975).
[b] Kayouli (2006).

2.3. Meat consumption and production

Over the period 1980–2013, the population of Tunisia increased by 70%, while annual per capita GDP tripled from 1400 to 4300 US$ (World Bank, 2015). In general, economic growth goes along with changes in food consumption patterns, such as an increasing meat consumption (Gerbens-Leenes et al., 2010). Fig. 1 shows that this has also been the case in Tunisia. Although the consumption of sheep and beef remained stable between 1980 and 2013, especially the consumption of poultry increased, from 6.3 to 15.5 kg per capita per year.

2.3.1. Sheep production

The sheep production system in Tunisia includes three types of production that differ in the feed applied and the region of production: (i) the agro-pastoral system with crop residues (APCR), in which sheep graze in natural pasture and fallows, and get cereal crop residues in summer; (ii) the agro-pastoral system with barley (APB), in which sheep graze and receive additional feed in the form of barley, by-products, such as olive cake and dried leaves, that constitute a supplementary feed resource mainly in summer; and (iii) the pastoral system with barley (PB) in which sheep graze on degraded rangelands and are supplemented with concentrate feed in the form of barley. The grazing land quality is a key factor to differentiate between the PB and the APB system. In the PB system, animals graze on very poor quality land and spend a long time grazing, while in the APB system the grazing land quality is marginal (slightly better than in the PB system) and animals spend relatively less grazing time.

The APCR system is located in northern Tunisia that is more humid than the Centre and South, with average annual rainfall between 500 and 1000 mm, and where most cereal production occurs. The APCR system is characterized by limited productivity. The grasslands in this system can also be used to produce arable crops, so that most of the grassland area has been turned to arable land for crop production.

The APB system is mainly located in the Centre of Tunisia and partly in the South in semi-arid and arid regions with average annual rainfall between 200 and 400 mm (Nefzaoui et al., 2012). Recently, due to land degradation, overstocking and water scarcity, the system in which sheep were fed using grazing from the grasslands shifted to the APB system because grazing land became marginal so that herds needed additional feed given in the form of barley (Ammar et al., 2011). By-products are used in this system as a supplement feed with seasonal availability. In the APB system, sheep herds are essentially situated in hills, mountain areas and peri-urban zones near to villages and it is traditionally based on grazing. Shepherds almost disappeared and are used only for the rare transhumance of flocks. According to the importance of the flock size, its composition, and importance of the family labour, farmers use several alternative systems of shepherding, such as guardianship by a family member or recruitment of a shepherd. Sheep graze on private and collective rangelands. However, the continuous access to these collective rangeland areas, coupled with the increasing livestock numbers, implies that rangelands are subjected to a gradual degradation process (Ammar et al., 2011). Sheep in this system spent less time grazing compared to the PB system in the south (Ammar et al., 2011).

The PB system is typical for the dry Southern part of Tunisia where average annual rainfall is less than 200 mm. In the South, nomadic farmers have herds that move over long distances with extensive use of marginal grasslands. Transhumance is the most common practice in this system, animals rely on pasture mainly in collective rangelands. When transhumance cannot be carried out, other techniques are applied, such as efficient use of water ponds, cisterns, and small dikes, or the use of tanks to transport water to livestock settlements. Collective rangelands are large open lands that require the presence of specialized shepherds, aware of the resources distribution in time and in space (Ammar et al., 2011). Nomadic activities are linked to feed shortage and water scarcity (Nefzaoui et al., 2012). In this system, sheep receive additional feed, mainly in the form of barley.

2.3.2. *Poultry production*

The poultry sector has increased rapidly since the 1970s (Raach-Moujahed et al., 2011). The Tunisian Poultry and Rabbit Association distinguishes two main poultry production systems in Tunisia: the industrial and the traditional system (GIPAC, 2013). The industrial system provides 91% of the total poultry production in Tunisia; the traditional system produces the other 9% (GIPAC, 2013). Recently, poultry production has developed from a simple traditional production system to a highly efficient industrial sector. The industrial system is mainly concentrated along the Tunisian coast. The system is characterized by a high productivity compared to the traditional system, in the best cases reaching to 1.5 kg feed DM per kg carcass. The industrial system applies imported feed, mainly from Latin America and Europe that consists of concentrates with high protein content and amino acid supplements. The traditional chicken system is concentrated in rural areas. It is characterized by low efficiencies of 4 kg feed DM per kg carcass (Raach-Moujahed et al., 2011). The FCE of poultry produced in the industrial system is on average estimated to be 2 kg of feed DM per kg of carcass (Mekonnen and Hoekstra, 2010).

Table 5
Feed composition of sheep for three production systems, the agro-pastoral system with crop residues (APCR), the agro-pastoral system with barley (APB) and the pastoral system with barley (PB), feed composition of chicken and feed conversion efficiency (FCE) per production system.

Production system	Sheep			Chicken
	APCR	APB	PB	Industrial
Grass (%)[a]	75	96	96	0
Crop residues (%)[b]	25	0	0	0
Concentrates and supplemented feed (%)[a]	0	5	5	100
FCE (kg feed DM/kg carcass)[a]	33	16.7	16.7	2

[a] Mekonnen and Hoekstra (2010).
[b] OEP (2014).

Table 6
Typical concentrates composition for feeding sheep and chicken and origin of raw products.

Ingredients	Inclusion (%)	Origin[c]
Concentrates for sheep[a]		
Barley	5.0	Tunisia
Concentrates for chicken[b]		
Wheat	2.7	France
Soybean meal	27.2	Brazil
Maize	61.2	Brazil
Oil palm	2.7	Brazil
Rapeseed	6.2	USA

[a] For the APB and PB systems. Source: Ministry of Agriculture (2013).
[b] Provided by Poulina Company (2016).
[c] ITC (2007).

3. Methods and data

In Tunisia, chicken represents 70 percent of the total poultry meat production GIPAC (2013). Sheep production represents the main source of income for small farmers and the consumption of sheep meat is a religion related practice in the Arabic world. For the assessment of the WF, LF and CF of meat produced in Tunisia, we therefore included the two main meat types, chicken and sheep meat. Our choice is based on the importance of these products from a production and consumption perspective, in combination with their economic and social importance in Tunisia. Based on the combination of agro-ecological factors and production practices, we distinguish between the three grassland-based systems of sheep production as discussed in the previous section. Regarding chicken production, we focus on the industrial system, which has a dominant market share, thus excluding the traditional system in the analysis.

The assessment of the WF, LF and CF of sheep and chicken meat was done in two steps. First, we calculated the footprints for the different feed ingredients and second, we translated these footprints to a footprint per kg of resultant carcass based on feed conversion efficiencies. Table 5 gives an overview of the feed characteristics for the sheep production systems. The table also gives the feed conversion efficiencies (FCE), which are defined as the amount of feed dry mass needed to produce a unit of meat. According to Mekonnen and Hoekstra (2010) the average FCE of sheep raised in North Africa is 21.2 kg of feed (dry mass) per kg of meat (carcass weight). Table 6 shows typical concentrates composition (%) used for feeding sheep and chicken and the origin of raw products. The

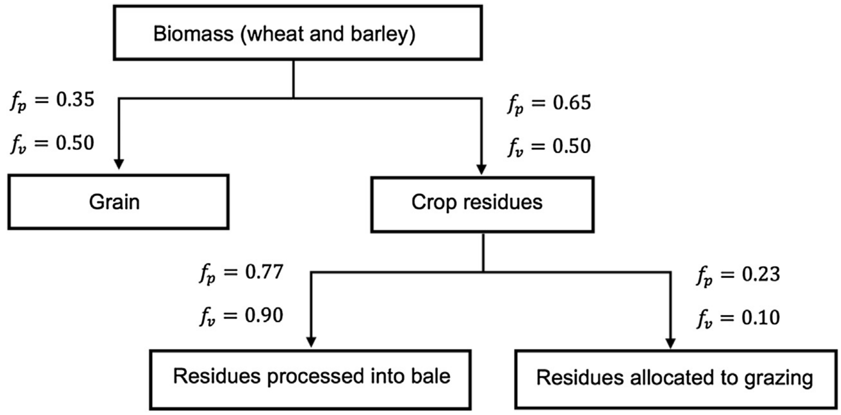

Fig. 2. Wheat and barley product tree with product and value fractions. First, biomass gives grain and crop residues; second, crop residues are processed into bale and left for sheep to graze.
Source: Own elaboration based on data from Ministry of Agriculture (2013).

feed composition data for sheep were obtained from the Ministry of Agriculture (2013) while the data for chicken were collected from Poulina Company (2016), the biggest company in Tunisia producing both chicken feed concentrates and chicken. The main countries of origin for animal feed were estimated from ITC (2007).

3.1. Water footprint of sheep and chicken meat

For the definition and assessment of the green, blue and grey WF of meat we follow the Global Water Footprint Assessment Standard as from the Water Footprint Network (Hoekstra et al., 2011). The WF of an animal consists of two components: the indirect WF of the feed and the direct WF related to the drinking and service water consumed on-farm (Mekonnen and Hoekstra, 2010). Per production system, we calculated the WF as a water volume per kg of carcass as:

$$WF = WF_{feed} + WF_{drink} + WF_{serv} \quad (1)$$

where WF_{feed}, WF_{drink} and WF_{serv} represent the WFs related to feed, drinking water and service water consumption, respectively. WFs for drinking and servicing were taken from Mekonnen and Hoekstra (2010). Three factors dominate the WF of the feed: the feed conversion efficiency (FCE), the feed composition and the feed origin (Mekonnen and Hoekstra, 2012; Gerbens-Leenes et al., 2013). We calculated the WF of feed for sheep and chickens per production system by multiplying the amounts of feed ingredients with their respective WF (accounting for the origin of the feed):

$$WF_{feed} = \sum_{i=1}^{n} \left(Feed\,[i] \times WF_p\,[i] \right) \quad (2)$$

where $Feed[i]$ is the amount of feed ingredient i in kg per kg of carcass and $WF_p\,[i]$ is the average water footprint of feed ingredient i in litre/kg. Data on WFs of feed concentrates were taken from (Mekonnen and Hoekstra, 2010), data on WFs of crop residues and pasture were calculated in this study.

In Tunisia, almost three quarters of the total cereal cropland area is used for wheat, the other quarter for barley (Ministry of Agriculture, 2013). In summer, croplands with cereal residues are the most important grazing lands for sheep. Typical cereal crop residues in Tunisia, therefore, include 75% wheat and 25% barley.

In general, agriculture grows crops for their reproductive or storage organs that have an economic value. It grows cereals, for example, to produce grains and potatoes to produce tubers. The growth of these organs, however, requires the preceding growth of complete plants with stems and foliage. The ratio of the economic yield (crop yield) and the total aboveground biomass production is the harvest index (HI) (Egli, 1998) that determines the fraction of the total biomass production available for human consumption. The difference between the total biomass production and the economic yield (crop yield) is the crop residue. Fig. 2 shows the production diagram for wheat and barley. Mekonnen and Hoekstra (2010) have calculated crop yield WFs and have assumed that the WFs of crop residues are zero. We argue that residues applied for sheep have a value and also a WF. We therefore reallocated the crop WFs over the crop residues and the crop yields using the weight and value fractions and distributed the WF to the grains and to the crop-residues according to their yield (product fraction f_p) and economic value (value fraction f_v).

To assess the WF of the crop residue (WF_r), we first calculated the WF of the total biomass of the crop (WF_t) based on the WF of the crop yield (WF_{c1}) as from Mekonnen and Hoekstra (2010, 2011) and the harvest index (HI):

$$WF_t = HI \times WF_{c1} \quad (3)$$

This means that the water footprint that in the earlier study was allocated to the crop yield alone is now allocated to the biomass of the crop as a whole. We assumed a harvest index of 0.35 for both wheat and barley, based on Zwart et al. (2010) and Ouji et al. (2010), respectively. Next, WF_t is allocated over the crop yield and the residue fraction. The (adjusted) WF of the crop yield (WF_{c2}) and the WF of the crop residue (WF_r) are calculated as:

$$WF_{c2} = \frac{f_v\,[y]}{f_p\,[y]} \times WF_t \quad (4)$$

$$WF_r = \frac{f_v\,[r]}{f_p\,[r]} \times WF_t \quad (5)$$

where f_v[y] and f_v[r] are the value fractions for the crop yield and crop residue, respectively, and f_p[y] and f_p[r] the product fractions of the crop yield and crop residue, respectively. The product fraction of an output product that is processed from an input product (mass/mass) is defined as the quantity of the output product obtained per quantity of input product. The value fraction of an output product (monetary unit/monetary unit) is defined as the ratio of the market value of this product to the aggregated market value of all the outputs products obtained from the input products (Hoekstra et al., 2011).

Natural pasture is the main feed source for sheep in Tunisia. The WF (m^3/tonne) of grass from pasture was calculated per region by

Table 7
The amounts of feed per kg of sheep carcass weight, the green, blue and grey water footprint of feed (litre/kg) and the land footprint of feed (m^2/kg) for the three sheep production systems.

Feed component[a]	Feed (kg/kg carcass)[b]	Water footprint of feed (litre/kg)[c]			Land footprint of feed (m^2/kg)[d]
		Green	Blue	Grey	
APCR system					
Grass	24.5	303	0	0	0.7
Crop residues	8.5	314	11	15	0.6
APB system					
Grass	15.9	769	0	0	2.1
Barley	0.8	3561	75	181	6.7
PB system					
Grass	15.9	1033	0	0	4.4
Barley	0.8	3561	75	181	6.7

[a] The feed amounts included here represent the average feed intake of sheep.
[b] OEP (2014) and Mekonnen and Hoekstra (2010).
[c] WF of barley from Mekonnen and Hoekstra (2010); other data calculated in this study.
[d] Based on own elaboration.

dividing the average crop water use (*CWU*, m^3/ha) from Table 2 by the grassland yield (*Y*, tonne/ha) from Table 4:

$$WF_{pasture} = \frac{CWU}{Y} \quad (6)$$

3.2. Land footprint of sheep and chicken meat

The LF of sheep and chicken (in m^2 per kg of carcass) depends on the land associated with animal feed production. It includes the grazing land and the land used to produce feed concentrate ingredients. In addition, in the case of sheep, a fraction of the cropland where animals eat crop residues during fallow periods is allocated as LF of sheep. We calculated the LF of feed for sheep and chickens per production system by multiplying the amounts of feed ingredients with their respective LF (accounting for the origin of the feed):

$$LF_{feed} = \sum_{i=1}^{n} \left(Feed\,[i] \times LF_p\,[i] \right) \quad (7)$$

where $Feed[i]$ is the amount of feed crop i in kg per kg of carcass and $LF_p\,[i]$ is the average land footprint of feed ingredient i in m^2/kg. For grass and crops contained in feed concentrates, $LF_p\,[i]$ is the inverse of $Y\,[i]$, the yield of feed crop i in kg/m^2. The LF of cereal crop residues (LF_r) is calculated in a similar way as the WF of crop residues, which means as follows:

$$LF_r = \frac{f_v\,[r]}{f_p\,[r]} \times \frac{HI}{Y} \quad (8)$$

with Y representing the crop yield, HI the harvest index, $f_p\,[r]$ the product fraction of the crop residue and $f_v\,[r]$ the value fraction of the crop residue.

3.3. Carbon footprint of meat

For the calculation of the CF of sheep and chicken meat, we consider all greenhouse gas emissions for the processes in the meat production chain, including: the production of feed; the enteric fermentation from feed digestion; manure handling; and transport and slaughter (Steinfeld et al., 2006). We applied the LCA-based Global Livestock Environmental Assessment Model (GLEAM) of the Food and Agriculture Organization (Gerber et al., 2013; FAO, 2016b). We included four interrelated modules. Module I describes the herd structure, its technical performance and animal specific production parameters. Module II calculates the emissions related to feed production, based on the input of the animal's diet composition. Cultivation and processing emissions of all feed resources, such as fresh and conserved grass, forages, crop residues and compound feeds, are included. Diet composition is input to this module. Module III determines GHG emissions from manure. Nitrous oxide emissions from manure were estimated given the N content in manure and type of storage used, including direct deposition from grazing. Methane emissions of manure storage have been derived by calculating volatile solids and the type of storage, including deposition in pastures. All emissions related to feeding (methane from enteric fermentation), to fertilization of feed crops, to manure excretion during grazing, and to storage of manure (methane and nitrous oxide) are included. The post-farm module (IV) includes impacts generated between the farm gate and the retail point. Three different groups of activities are considered: transport, slaughter, processing and refrigeration of animal commodities. Emission data related to transport and slaughter were mainly obtained from the Ministry of Agriculture (2013) and the GIPAC (2013). Module IV calculates the total GHGs emissions of the system, integrating the other modules. Emissions of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are summed into CO_2 equivalents (CO_2-eq).

4. Results

The WF and LF per unit of feed differ among the three sheep production systems. Table 7 gives the amounts of feed for the three systems per unit of carcass weight (kg/kg), the green, blue and grey WF of feed (litre/kg) and the LF of feed (m^2/kg). Grass does not have a blue nor a grey WF, because it does not receive irrigation water or fertilizer and pesticides. The green WF is a function of the crop water use (m^3/ha) and the yield (tonne/ha). CWU decreases from North to South. The average CWU for Northern Tunisia is 4243 m^3/ha, for the Centre 3651 m^3/ha and for the South 2325 m^3/ha. Grass yields also decrease from North to South, from 14 t/ha in the North, 4.8 t/ha in the Centre to 2.3 t/ha in the South. Because the grass yields decrease faster than CWU, the resulting green WFs increase from 303 litre/kg in the North to 1033 litre/kg in the South. The decreasing grass yields from North to South cause the LF to go up in the opposite direction from 0.7 to 4.4 m^2/kg.

Table 8 shows the WF of sheep carcass for the APCR, APB and PB system. The PB system has the largest WF, almost 20,000 litre per kg carcass, followed by the APB system with 15,000 litre per kg carcass, and the APCR system with 10,000 litre. For all three production systems, the total WF is dominated by the green WF component. Despite the less favourable feed conversion efficiency in the northern APCR system, the WF of the sheep from this system is smallest, as a result of the relatively small WF of the feed, which again results from the relatively favourite ratio of grass yield to evapotranspiration. The blue and grey WFs in the three systems are comparable. Drinking and service water are responsible for 36%

Table 8
The green, blue, grey and total water footprint of sheep carcass per production system.

Component	Water footprint of sheep carcass (litre/kg)			
	Green	Blue	Grey	Total
APCR system				
Grass	7424	0	0	7424
Crop residues	2588	88	124	2800
Drinking water	0	41	0	41
Service water	0	9	0	9
Total	10012	138	124	10273
APB system				
Grass	12196	0	0	12196
Barley	2973	63	151	3187
Drinking water	0	41	0	41
Service water	0	9	0	9
Total	15170	113	151	15434
PB system				
Grass	16383	0	0	16383
Barley	2973	63	151	3187
Drinking water	0	41	0	41
Service water	0	9	0	9
Total water footprint	19357	113	151	19621

Source: Based on own elaboration.

of the blue WF in the APCR system and 44% in the other two systems. The remainder of the blue WF in the APCR system relates to evaporated irrigation water from the crop fields where sheep eat crop residues during fallow periods (note that we allocated a fraction of the irrigation water consumption to the crop residue); in the other two systems, the remainder of the blue WF refers to irrigation water consumption for producing barley.

Table 9 gives the feed components of chicken feed in Tunisia, the countries of origin of the feed, the amounts of feed per unit of carcass (kg/kg), the green, blue, grey and total WFs per unit of feed (litre/kg) and the green, blue, grey and total WFs per unit of chicken carcass (litre/kg). The WF is dominated by the green WF, especially by maize and soybean meal from Brazil. The grey WF contributes 4% to the total, with main contributions from maize and soybean meal. The contribution of the blue WF to the total feed-related WF is very small. Drinking and service water contribute about 70% to the total blue WF of chicken.

Table 10 shows the LF of sheep carcass per production system. The APCR system shows the smallest LF (22 m^2/kg), and the PB system the largest LF (76 m^2/kg). In the APCR system, sheep graze on natural grasslands and croplands after harvest (especially in summer). In this system, the LF is relatively small because of the relatively high land productivity (yields) in the North (Table 4).

Table 11 gives average yields of the feed components of chicken feed in Tunisia for the different origins (tonne/ha), the LF per unit of feed (m^2/kg), and the LF of chicken meat (m^2/kg carcass).

The CF of meat production varies considerably across animal categories and farming systems. Table 12 shows the main GHG emissions per step of the production chain of sheep and chicken meat, per production system, showing also the contribution of each GHG (CO_2, CH_4 and N_2O) to the total emission. The CF of produc-

Table 9
The amounts of feed per kg of chicken carcass, the countries of origin of the feed, the water footprint per feed component, and the water footprint per kg of chicken carcass.

Component[a]	Feed origin[b]	Feed (kg/kg carcass)[c]	Water footprint of feed (litre/kg)[d]			Water footprint of chicken carcass (litre/kg)			
			Green	Blue	Grey	Green	Blue	Grey	Total
Wheat	France	0.06	581	1	5	35	0.1	0.3	35
Soybean meal	Brazil	0.60	2566	1	18	1540	0.6	11.0	1551
Maize	Brazil	1.35	1621	1	125	2188	1.4	170.0	2359
Oil palm	Brazil	0.06	4994	2	301	300	0.1	18.0	318
Rapeseed	USA	0.14	3500	3	33	473	0.4	4.5	478
Total feed						4535	2.5	200.0	4740
Drinking water						0	4.1	0	4
Service water						0	2.1	0	2
Total water footprint						4535	8.7	200	4746

[a] The feed amounts included here represent the average feed intake of chicken.
[b] ITC (2007).
[c] GIPAC (2013).
[d] Mekonnen and Hoekstra (2010).

Table 10
The land footprint (LF) of sheep carcass per production system (m^2 per kg carcass).

APCR system	LF (m^2/kg)	APB system	LF (m^2/kg)	PB system	LF (m^2/kg)
Natural pasture	18.0	Natural pasture	33.0	Natural pasture	71.0
Crop-residues	4.6	Barley	5.6	Barley	5.6
Total	22.0	Total	39.0	Total	76.0

Source: Based on own elaboration.

Table 11
Average yields of the feed components of chicken feed in Tunisia for the different origins, the land footprint per feed component, and the land footprint per kg of chicken carcass.

Feed component	Feed origin[a]	Yield (tonne/ha)[b]	Land footprint of feed (m^2/kg)	Land footprint of chicken carcass (m^2/kg)
Wheat	France	3.6	2.8	0.2
Soybean meal	Brazil	2.8	3.6	2.1
Maize	Brazil	3.2	3.1	4.3
Oil palm	Argentina	4.0	2.5	0.2
Rapeseed	USA	2.0	5.0	0.7
Total land footprint				7.4

[a] ITC (2007).
[b] FAO (2013).

Table 12
Carbon footprint of sheep and chicken meat (kg CO_2-eq/kg carcass weight).

	Sheep			Chicken
	APCR	APB	PB	Industrial
Feed production (CO_2)	2.2	1.2	0.5	1.3
Farm emissions				
Enteric fermentation (CH_4)	11.0	6.1	7.8	0
Manure management (CH_4)	4.2	5.1	6.1	0.2
Manure management (N_2O)	8.3	7.1	5.7	0.3
Processing emissions				
Transport (CO_2)	0.4	0.4	0.6	0.4
Slaughter (CO_2)	0.4	0.4	0.4	0.4
Total carbon footprint	26.6	20.4	21.1	2.6

Source: Based on own elaboration.

Table 13
Water, land and carbon footprint of sheep and chicken meat produced in Tunisia.

Production system	Sheep			Chicken
	APCR	APB	PB	Industrial
Meat conversion factors[a]	0.80	0.80	0.80	0.78
Water footprint (litre/kg of meat)	12800	19300	24500	6030
Green WF	12500	19000	24200	5690
Blue WF	172	141	141	14
Grey WF	155	189	189	319
Land footprint (m^2/ kg of meat)	28	48	96	9
Grazing LF	22	41	89	0
Crop LF	6	7	7	9
Carbon footprint (CO_2-eq/kg of meat)	33	26	26	3.3
CO_2	4	3	2	2.7
CH_4	19	14	17	0.2
N_2O	10	9	7	0.4

[a] Chapagain and Hoekstra (2003).

ing chicken meat (2.6 kg CO_2-eq per kilogram of carcass) is nine times smaller than the average CF of producing sheep meat (23 kg CO_2-eq per kilogram of carcass). The CF of sheep is highest for the APCR system (27 kg CO_2-eq/kg carcass), intermediate for PB (21 kg CO_2-eq/kg carcass) and lowest for APB (20 kg CO_2-eq/kg carcass). Farm emissions in the form of enteric fermentation (methane) and manure management (methane and nitrous oxide) are the dominant factors in the CF of sheep, contributing to around 90% of the CF. The CF of the feed decreases from North to South, from 2.2 kg CO_2/kg in the APCR system in the North, to 1.2 kg CO_2/kg for the APB system in the Centre to 0.5 kg CO_2/kg in the South.

Table 13 presents the summary of the footprints of sheep and chicken per unit of meat, including the meat conversion factors to convert the footprints expressed per unit of carcass to footprints per unit of meat. Chicken meat is more efficient than sheep meat in terms of water, land and carbon footprint. The WF of chicken meat is two to four times smaller than for sheep meat; the LF of chicken is three to ten times smaller than for sheep; and the CF of chicken is eight to ten times smaller than for sheep. For sheep production, the APCR, located in the North, is less water and land intensive than the APB and PB farming systems located mainly in the Centre and South. However, the APCR systems has highest GHG emissions.

5. Discussion

The finding that chicken meat is more efficient from an environmental point of view than sheep meat corresponds to findings from earlier studies (Pimentel et al., 2004; Mekonnen and Hoekstra, 2010). Although chicken contributes to about half of the total meat consumption in Tunisia, its contribution to the total WF, LF and CF is relatively small. Producing sheep meat requires 2–4 times more water per kg than producing chicken meat, 3–10 times more land and results in 8–10 times more greenhouse gas emissions.

The estimates in this study differ from earlier studies but are in similar ranges. The WF of sheep meat estimated in this study (12,800 to 24,500 litre/kg) is in the same order of magnitude as the WFs of sheep meat from grazing systems calculated by Mekonnen and Hoekstra (2010), who give a global average of 16,300 litre/kg for sheep meat from grazing systems and a specific estimate for Tunisia of 14,500 litre/kg. There are various factors that may explain differences between the outcomes of the current and the other study. Mekonnen and Hoekstra (2010) considered an average value of the WF of pasture of 315 litre/kg, while in the current study we estimated the WFs of pasture for the three principal agro-ecological zones in Tunisia: the North, Centre and South, with estimated WFs of 303, 769 and 1033 litre/kg respectively. Furthermore, Mekonnen and Hoekstra (2010) considered the WF of cereal crop residues as a zero, while in the current study we allocated the WF of crop production over the yield and residue based on their respective economic values, arriving at a WF of 340 litre/kg crop residue.

The LF of 28–96 m^2 per kg of sheep meat in Tunisia found in this study is higher than the 20 m^2 per kg of sheep meat found for Kenya by Bosire et al. (2015). The LF of 9 m^2 per kg of chicken meat (7.4 m^2 per kg of chicken carcass) for industrial chicken in Tunisia is comparable to the estimate of 7 m^2 per kg of industrial chicken meat in the Netherlands by Gerbens-Leenes and Nonhebel (2002) and the estimate of 6.4 per kg of chicken carcass in the UK by Williams et al. (2006).

The CF of sheep meat from grazing systems in Tunisia is estimated here to range from 26 to 33 kg CO_2-eq/kg meat, with the most significant parts stemming from methane and nitrous oxide emissions during manure management and methane emissions through the digestive process (enteric fermentation). The overall value is above the global estimate of 24 kg CO_2-eq/kg meat reported by Opio et al. (2013), but below the range reported by Ripoll-Bosch et al. (2013) in Spain (39–52 kg CO_2-eq per kg of meat). The CF of chicken meat of 3.3 kg CO_2-eq/kg meat estimated in the current study for Tunisia is below the global average of 5.4 kg CO_2-eq/kg meat reported by MacLeod et al. (2013).

The current study has a number of limitations and uncertainties that are due to a lack of data which can limit the accuracy of results. We used data for typical farming systems in Tunisia, ignoring the fact that production system practices and diet composition can be different from farm to farm. Moreover, the origin of the animal feed represents another issue that can limit the accuracy of our results, since the WF, LF and CF of feed varies significantly according to its origin. We derived WFs for feed concentrate crops from Mekonnen and Hoekstra (2010) that can contain an uncertainty of ±20% (Schyns and Hoekstra, 2014). Furthermore, feed conversion efficiencies (FCE) for sheep and chicken production systems were taken from Mekonnen and Hoekstra (2010). However, FCE data for Tunisia are absent so that we used average data for the region. Other limitations relate to the WF assessment for pasture. We assumed that pasture for sheep is natural since natural pastures represent 70% of the total pasture area in Tunisia; but yields may be lower from overexploited pastures. Further, we used rather old estimates for grassland yields in Tunisia, from Le Houerou (1975) supplemented with some more recent data from Kayouli (2006), due to the absence of recent values.

Our study shows that the combination of footprint indicators provides an integrated approach to assess the pressure on the environment to produce chicken and sheep meat across different farming systems in Tunisia. It confirms the claim made by other authors that the combination of footprint indicators enriches the overall picture of environmental assessment when compared to considering one type of footprint only (Steen-Olsen et al., 2012; Rushforth et al., 2013). Whereas most environmental studies on livestock focus on carbon or land, the biggest problem in Tunisia is probably water scarcity. Tunisia faces severe water scarcity during several months per year, worst in the South (Chouchane et al., 2015; Mekonnen and Hoekstra, 2016). The limited availability of water constrains the production of sheep meat, which probably already reached it maximum level. An increase of meat consumption in Tunisia will thus rely on the import of feed or meat itself. While the consumption of meat and the livestock sector in Tunisia are still a blind spot in its national environmental policy, this study suggests to consider the future of Tunisia's meat consumption and production not only from a development but also from an environmental perspective.

6. Conclusion

The study finds that the total WF of chicken meat is two to four times smaller than for sheep meat. The green and blue WFs for chicken are smaller, but the grey WF, related to pollution, is larger. Another difference is that the WF of chicken meat mainly lies outside Tunisia, related to imported feed from Brazil, whereas the WF of sheep meat lies within Tunisia itself. The LF of chicken is three to ten times smaller than for sheep; and the CF of chicken is eight to ten times smaller than for sheep. The WF and LF of sheep and chicken meat are dominated by feed production. The same is true for the CF of chicken meat, but not for the CF of sheep meat, which is dominated by GHG emissions from manure and the digestive process. For animal products, smaller WFs often correlate to smaller LFs and CFs, related to the fact that all three footprints tend to become smaller if animals need less feed to produce one kilogram of meat and if the land providing the feed is more productive. For ruminants like sheep, where the CF is not dominated by feed production but by GHG emissions from the animals themselves, the CF may no longer correlate to WF and LF. We show this in the current study for sheep. Methane, produced during digestion of sheep, is a strong greenhouse gas and thus has a big CF. Sheep meat production in the APCR system in the North is more efficient in terms of land and water use, but emits more GHG than in the Central and Southern systems. Compared to the APB system, the APCR system uses 33% less water and 44% less land but emits 30% more GHG. The larger emission of GHG relates to the fact that the feed conversion efficiency in the APCR system is less favourable, which means they require more feed per unit of meat, leading to more methane production during digestion. At the same time, the APCR system is based on grazing land with higher land and water productivity than the APB system, leading to smaller LF and WF per unit of meat.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Acknowledgement

The work was partially developed within the framework of the Panta Rhei Research Initiative of the International Association of Hydrological Sciences (IAHS).

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