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Assessing physical and economic water productivity in crop-livestock systems

Sraïri Mohamed Taher(1), Assis Lamya(1) and Kuper Marcel(2)

mt.srairi@iav.ac.ma

1 : DPBA, Institut Agronomique et Vétérinaire Hassan II, Rabat, MAROC
2 : UMR G-EAU, CIRAD, Montpellier France.

Abstract

Different sources of water are used by farmers to achieve their goals. This is particularly true in the South Mediterranean region, in a country like Morocco. A study was therefore conducted in the Saïss Plain to assess the physical and economic water productivity of mixed crop-livestock systems. The results showed that it is important to shift the focus of analysis on a single crop to overall farm performances. Second, water productivity indicators very often do not reflect the water mix used. The results imply that additional research should be devoted to the sustainability of water uses, with a particular focus on rainfall in the water mix.

Keywords: Crop-livestock Systems; Morocco; Sustainability; Water Productivity; Water mix.

Evaluation des valorisations volumétrique et économique de l'eau dans des systèmes de polycultures/élevage

Résumé

Des sources diverses d'eau sont utilisées par les agriculteurs pour réaliser leurs objectifs. Cela est plus particulièrement vrai dans la région sud méditerranéenne, dans un pays comme le Maroc. De ce fait, cette étude a été conduite dans la plaine du Saïss afin de quantifier les valorisations volumétrique et économique de l'eau dans des systèmes de polycultures/élevage. Les résultats ont montré qu'il est important de focaliser l'analyse sur les performances globales des exploitations agricoles au lieu de ne considérer qu'une seule culture. En second lieu, il a été remarqué que les résultats de la valorisation économique de l'eau n'accordent pas d'intérêt à l'origine de cette ressource. Nos résultats impliquent que des efforts additionnels de recherche sont nécessaires pour étudier la durabilité des usages de l'eau, avec un intérêt plus marqué pour la pluie dans le mix hydrique mobilisé.

Mots-clés : Durabilité, Maroc, Mix hydrique, Systèmes de polycultures/élevage, Valorisation de l'eau.

تقويم التثمين الحجمي و الإقتصادي للماء في الأنظمة المتعددة الزراعات و الإنتاج الحيواني

محمد الطاهر السرايري، لمياء أسيس، مارسيل كوبر

ملخص

موارد ماء متعددة تستعمل من طرف المزارعين لتحقيق أهدافهم. هذا المعطى يتجسد في المنطقة الجنوب المتوسطية، في بلد مثل المغرب. لهذا الغرد، أنجزت هذه الدراسة في سهل سايس من أجل تقويم التثمين الحجمي و الاقتصادي للماء في الأنظمة المتعددة الزراعات و الإنتاج الحيواني . أثبتت النتائج بأن يجب تحليل الأداء الإجمالي للضيعات الفلاحية بدلا من التركيز على زراعة معينة و لوحظ أيضا بأن نتائج التثمين الاقتصادي للماء لا تولي اهتماما لأصل هذا المورد. و تؤكد النتائج بأن مجهودا إضافيا من البحث مطلوب من أجل دراسة ديمومة استعمال الماء، مع اهتمام متزايد للمطر في المزج من المياه المعبئة.

الكلمات المفتاحية: ديمومة، المغرب، الأنظمة المتعددة الزراعات و الإنتاج الحيواني، المزج من المياه، تثمين الماء

Introduction

Water availability and water use efficiency are hot topics on the global agenda, particularly when assessing the needs of the agricultural sector to fulfil the growing demand for food (Mancosu et al., 2015). In view of the expected population growth, increasing water productivity in irrigation is a priority, especially in water scarce areas with high irrigation requirements. This is the case in the Mediterranean region, where climate change may cause significant problems for sustainable water uses (Saadi et al., 2015). As a consequence, in many regions of the world, and more particularly in semi-arid areas, water is already a limiting factor to increased crop and livestock production (Rockström et al., 2009). In such areas, farmers often rely on a water mix, that is, several sources of water, rainfall, surface irrigation water and groundwater as well as virtual water (the volumes of water needed for the production of off-farm feed resources elsewhere, mainly for livestock) to try and satisfy crop and livestock requirements (Siderius et al., 2015). However, the actual contribution of each water source to the total water volumes used in each specific context remains unclear and is often ignored, as very few studies have been devoted to this topic at farm level. Moreover, the effective water productivity of different crops and livestock in complex crop-livestock systems remains poorly documented (Descheemaeker et al., 2010). This is problematic, as newly implemented agricultural policies in the Mediterranean may promote intensification of cropping patterns (particularly orchards to replace rain-fed cereals and pulses) that may not only increase water use, but also change the mix of water resources used for crop production, often from a rainfall-based water mix to a mix that increasingly relies on groundwater. Often, the promotion of more efficient irrigation systems (especially drip vs. furrow irrigation) through public subsidies is presented as a means to reduce water consumption (Benouniche et al., 2014). A more worrying consequence of the rapid expansion of areas equipped for drip-irrigation is amplifying groundwater use, resulting in its depletion (Molle and Tanouti, 2017). Generalized groundwater use has accelerated at a very rapid pace leading to groundwater depletion in many semi-arid and arid areas at global scale (North Africa, South Asia, Southern Europe, California, etc.) (Famiglietti, 2014; Wada et al., 2010). It has also been demonstrated that the production of emblematic traded food commodities relies heavily on intensified groundwater depletion (Dalin et al., 2017). Seen from a different angle, researchers working on the concepts of 'blue' and 'green' water, have also shown renewed interest in integrated crop-livestock systems in which rainfall is the main source of water used (Falkenmark, 2007). In such systems, the interactions between crops and livestock make it possible to reduce the detrimental effects of crop pests, to reduce the use of pesticides (Lechenet et al., 2017) and to increase farm resilience in the face of climate uncertainty and economic risks (Ryschawy et al., 2013). More cautious approaches are thus required at farm and basin levels to implement sustainable uses of different water sources for several crops plus livestock activities. The objective of this paper is therefore to assess *in situ* water volumes used and their origins (rainfall, irrigation surface or groundwater as well as virtual water) by several crop/livestock farms to compare their physical and economic water productivity and to assess the consequences of the results on sustainable water uses in a semi-arid area.

Material and methods

Study area and sample farms

The study area is located in the Saïss Plain in northeastern Morocco, between the two large cities of Meknes and Fes (Figure 1). Saïss is a rich agricultural plain, originally known for its rain-fed farming systems (cereals, legumes, vineyards), as the annual average rainfall between 1985 and 2018 was 563 mm. Rainfall is concentrated from late October to the beginning of May, meaning irrigation is necessary in the hot summer months (late May to October). Following recurring droughts in the 1980s and 1990s, many farmers turned to groundwater. The profitability of irrigated farming in the area in turn increased groundwater use.

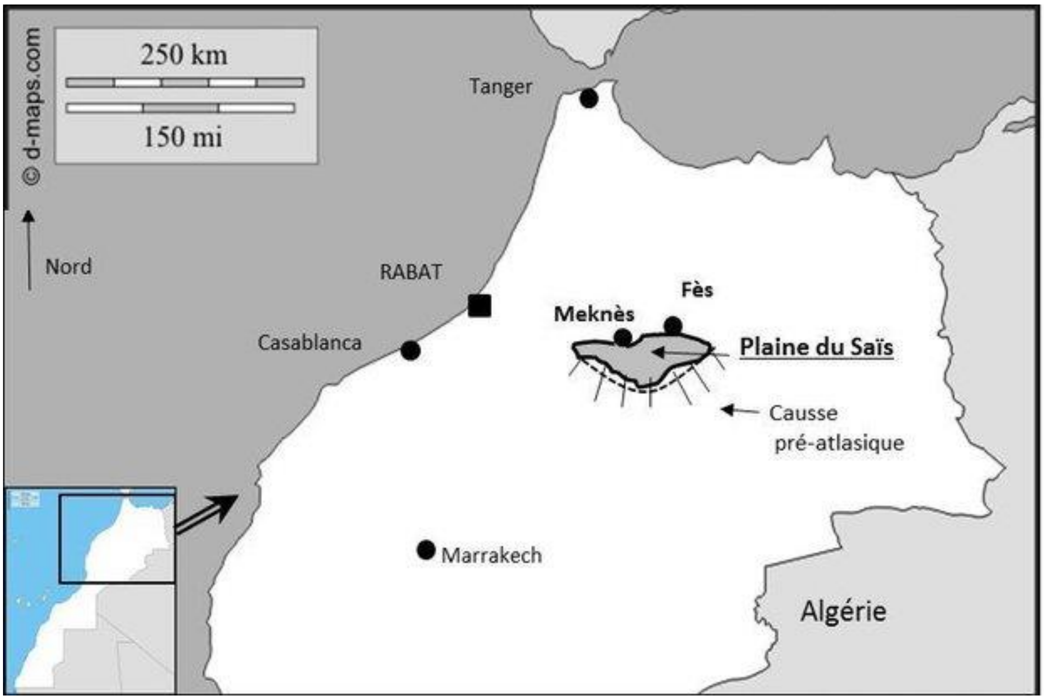

Figure 1: Map showing the location of the study area

The water balance of the Saïss Plain shows an annual average deficit of 100 million m^3, mainly due to the agricultural sector, which accounts for almost 85% of the groundwater consumption (DPA El Hajeb, 2017).

The study sample was designed to cover diverse types of farming dynamics, such as newly planted orchards belonging to newcomer investors, as well as more traditional family farming units, mainly livestock breeders or mixed livestock and crop farming (Table 1).

The study sample was deliberately limited to four farms to be sure of collecting reliable data on all cropping and livestock practices for a full year in a context in which farmers do not keep any records on their activities.

Table 1: Farm size, land occupation, herd structure and irrigation equipment

	Farm 1	Farm 2	Farm 3	Farm 4	Mean ± standard deviation
Total land (ha)	4.00	4.50	7.40	14.25	7.54 ± 4.72
Rented land (ha)	-	3.00	-	5.00	2.00 ± 2.45
Irrigated land (ha)	4.00	0.75	1.90	5.75	3.10 ± 2.88
Cereals(ha)	-	-	3.00	0.50	0.87 ± 1.09
Pulses (ha)	-	-	1.50	1.00	0.63 ± 0.78
Fodder (ha)	-	4.50	2.50	7.50	3.62 ± 4.53
- Alfalfa	-	0.50	0.75	-	0.32 ± 0.39
- Barley	-	2.25	-	2.00	1.06 ± 1.33
- Berseem	-	0.25	0.75	0.50	0.38 ± 0.47
- Oats	-	1.50	1.00	1.00	0.88 ± 1.09
- Fallow	-	-	-	4.00	1.00 ± 1.25
Bell pepper (ha)		-	0.30	-	0.08 ± 0.09
Onion (ha)		-	0.10	1.00	0.28 ± 0.34
Tomato (ha)		-	-	0.25	0.06 ± 0.08
Orchards (ha)	4.00	-	-	4.00	2.00 ± 1.50
- Apricots	1.00	-	-	-	0.25 ± 0.06
- Grapes	-	-	-	2.00	0.50 ± 0.63
- Nectarines	1.50	-	-	-	0.38 ± 0.09
- Peaches	1.50	-	-	-	0.38 ± 0.09
- Plums	-	-	-	2.00	0.50 ± 0.63
Herd structure					
Number of cattle	-	11	9	14	8.50 ± 10.63
Cows		5	6	7	4.50 ± 3.11
Number of sheep	-	12	11	13	9.00 ± 11.25
Ewes		7	7	7	5.25 ± 3.50
Origin of water	G (B)*	S**	G (W)***	G (W)***	-
Irrigation system	Drip	Furrow	Drip	Drip	-

** G (D): groundwater accessed through a borehole (130 m deep)*
*** S: surface water originating in a natural spring*
**** G (W): groundwater accessed through a well (40 to 45 m deep)*

Protocol used to record on-farm water use and agricultural performances

In each farm, a year-long research protocol was implemented from September 1, 2017 to August 31, 2018. It consisted of interviews, observations and visits to cultivated plots as well as the reconstitution of diets for the animal species reared. Each farm was visited once a month to obtain reliable data about the use of inputs (seeds, fertilizers, pesticides, etc.) in each plot. The diets used to feed the herd (whether milking cows, growing calves, or sheep - ewes and lambs -) were recorded and their nutrient contents (net energy and proteins) were checked to insure that they were able to support the recorded animal performances. In addition, all crop outputs were recorded (yields of main products, but also by-products, such as straw for cereals) and the gross monetary

incomes they allowed were determined. This enabled us to calculate a gross margin for each crop, which corresponded to the difference between the income from and the monetary value of inputs. Next, we calculated the net margin, particularly for orchards, as the cost of installing irrigation equipment and planting trees is high. Our hypothesis was that the required investments (digging a borehole, purchasing and planting fruit trees) have to be amortized, which corresponds to additional costs. We calculated amortization based on the assumption that the productive life time of trees was 30 years.

To determine the water used by each crop, we first used data on total rainfall over the survey period from the neighboring meteorological station (El Hajeb). Rainfall during the study period was 560 mm. This volume was converted into efficient rainfall using a coefficient of 80% (Salmoral et al., 2017). Volumes of irrigation water for each plot were determined by a series of enquiries related to the duration of irrigation and by measuring water outflows (m^3/h) from the wells or the boreholes or from the irrigation outlet in plots with surface irrigation. To assess the water volumes used by the herds, the same methodology was applied as that used in a previous study in the area (Sraïri et al., 2016). This method is based on the reconstitution of water volumes used to produce fodder. The equivalent amount of virtual water used by each herd was obtained by determining the diets used all year round. The quantities of feed produced off-farm, mainly imported grains (barley and maize) were converted into (virtual) water volumes, using international references: 1 m^3 of water per kilogram of cereal grains (Hoekstra and Chapagain, 2007).

Main indicators of physical and economic water productivity in mixed crop-livestock systems

After obtaining the raw data concerning crop and livestock inputs and outputs, indicators related to physical water productivity (i.e., the amount of water needed to obtain a kg of crop or animal products and the origins of this water) and economic water productivity (i.e., the amount of money generated by a single m^3 of water when used to produce a specific crop or animal product) were calculated (see Molden et al., 2010). For livestock products (i.e. milk and live weight gain) the water footprint indicator as defined by Mekonnen and Hoekstra (2012), was used taking into account both green and blue water uses.

Results

Crops and livestock yields and profitability in the sample farms

Crop yields varied considerably from one farm to another (Table 2). The variability can be explained by different factors. For example, for rain-fed crops like cereals (hard and soft wheat) and pulses like Faba beans, agricultural practices including the use of manure, and/or pest control could explain the differences. Yields of soft wheat ranged from 5.6 to 8.0 t/ha in farms 3 and 4. This difference can be explained by differences in agricultural practices, farm 4 used more manure to fertilize its soils. Farm 4 also obtained a good yield of Faba bean (2.7 t/ha), which, according to the local agricultural services, is higher than the average yield of 1.0 t/ha for this crop reported in the study region in the previous agricultural year (September 2016-August 2017).

Table 2: Crop yields and profitability of the sample farms

Farm	Crop	Yield (t/ha)	Profitability (Euros/ha)
1	Apricots	15.7	3,392
	Nectarines	19.1	4,701
	Peaches	20.9	5,370
2	Barley	2.8 (grains); 2.0 (straw)	80.2
	Oats	2.9 (grains); 2.7 (straw)	270
3	Hard wheat	2.4 (grains); 6.0 (straw)	50.1
	Soft wheat	5.6 (grains); 11.0 (straw)	743
	Bell peppers	26.7	1,826
	Onions	30.0	632
	Beans	2.0	577
4	Soft wheat	8.0 (grains); 14.0 (straw)	1,704
	Faba beans	2.7	407
	Onions	40.0	9,613
	Tomatoes	60.0	1,620
	Plums	35.0	20,327
	Grapes	25.0	8,331

For irrigated crops, the yields of fruit trees, which are only planted in two farms (1 and 4), were as follows: 15.7 t/ha for apricots, 19.1 t/ha for nectarines, 20.9 t/ha for peaches (all these fruits were harvested in farm 1) and 35 t/ha for plums (harvested in farm 4). Some of these yields were below the regional average, particularly nectarines and peaches, whereas others (apricots in farm 1, and particularly plums in farm 4) were higher. The best yield was recorded in farm 4 with a variety of plum (October 5) specially imported from France three years ago, well known for its late ripening and high sugar content. Concerning vegetable yields, similar variability was recorded for farms 3 and 4, which are the only farms to cultivate these crops. For example, the yield of onions did not exceed 30 t/ha in farm 3, whereas it reached 40 t/ha in farm 4.
Concerning crop profitability, orchards had the highest net margins per ha (from 3,400 to 20,330 Euros/ha) due to high yields (between 15 and 35 tons of fruits per ha) coupled with good farm gate prices (from 0.36 to 0.64 Euros/kg, the latter for plums). Such yields and prices made it possible to balance the price of inputs and the necessary investments in trees plantation, digging wells and boreholes, and even the cost of irrigation equipment (drip irrigation). In addition, in farm 4, where the profitability of orchards was the highest, state subsidies for the purchase of irrigation equipment enabled an almost 7% increase in profitability. At the other end of the scale from orchards, rain-fed crops like hard and soft wheat and Faba beans had limited net margins, not exceeding 1,700 Euros/ha, and sometimes less than 100 Euros/ha (e.g., in the case of dual-purpose crops like barley, which, in farm 2 was used as green fodder for cows at its early stages, then harvested for its grains at the end of the vegetative cycle). However, all these rain-fed crops also produced by-products like straw and stubble that are used for livestock production and thus added value to these crops. Finally, vegetable production was profitable, but with marked variability of its margins (up to 9,612 and 1,620 Euros/ha for onion and tomato in farm 4). The huge variability in profitability can be explained by the differences in crop yields (for instance, onion yields ranged from 30 to 40 t/ha depending on the farm) as well as on the amount of inputs used (for onions, farm 3 used more inputs than farm 4 but the resulting yield

was lower). The variation in onion yields can also be explained by the significantly higher volumes of irrigation water used by farm 4 compared to farm 3 (20,490 vs. 10,540 m^3/ha).

Livestock performances varied also considerably among farms with differences between dairy and live weight gain yields (Table 3). Such variability can mainly be explained by the strategic orientation of the farmer for the typical dual-purpose livestock systems: milk and/or live weight gain. The latter strategy was mainly used by farm 2, where the average milk yield delivered per cow did not exceed 930 liters/year, whereas it was almost three times higher in farms 3 and 4. The difference was also linked to recurrent reproduction failures of cows in farm 2, generating longer lactation cycles but with very limited milk yields. These reproduction failures had noticeable consequences for production costs as well as for milk yields and feed diets, and hence for dairy and live weight gain profitability. Consequently, feed costs to produce milk were the highest in farm 2 (0.30 Euro/kg of milk) due to low yields and nutrient losses as the diets of lactating cows were frequently insufficient and balanced.

Table 3: Animal production outputs and profitability of the sample farms

Farm	2	3	4
Average milk yield (kg/year·cow)	931	2,956	2,387
Total live weight gain (kg)	1,865	1,292	1,985
Cost of feed for dairy production (Euros/kg)	0.30	0.14	0.07
Feed production cost for live weight gain (Euros/kg)	1.04	2.22	1.19
Net margin for dairy production (Euros/year)	- 25.9	379	500
Net margin for live weight gain (Euros/year)	2,508	1,582	3,051

In farm 4, the lowest feed production cost per kg of milk (0.07 Euro/kg of milk) was recorded, attributed to the highest feed autonomy (limited use of off-farm feed resources) coupled with a relatively high annual milk yield per cow (2,387 l). Seasonal variations in milk volumes were also recorded, with maximum levels reached in winter and spring. Milk yields began decreasing steadily at the end of the rains and the resulting changes in dietary rations, in which the levels of green fodder were reduced, and partially replaced by rain-fed oat hay produced on-farm and/or purchases of concentrates (Figure 2). Finally, in contrast to dairy profitability, live weight gain was positive in all three farms with livestock, ranging from 1,582 to 3,051 Euros per year. The net margin was lowest in farm 3, which used considerable off-farm resources, resulting in the highest feed production cost: 2.22 Euros/kg of live weight.

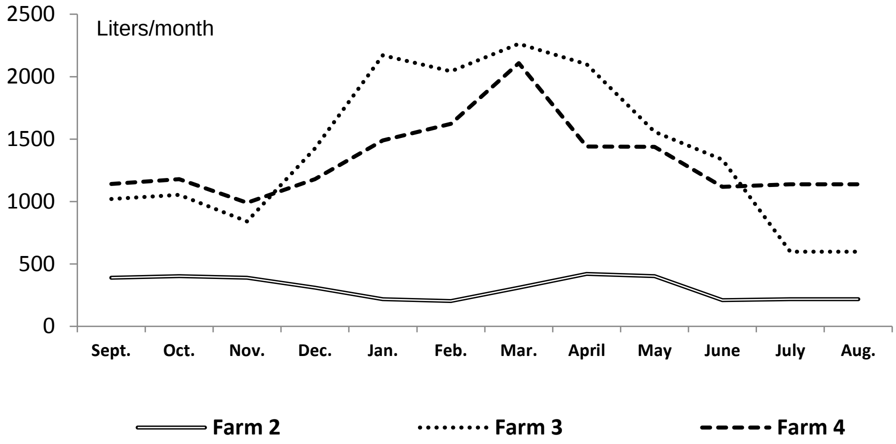

Figure 2: Monthly variations in milk deliveries per farm

Water uses and water productivity for the different crops and livestock in the sample farms

Surface water was only used to irrigate fodder (berseem clover), and it does not appear for the other crops. Three farms relied on groundwater for crops, from a 130 m deep borehole in farm 1, or a 40 to 45 m deep well in farms 3 and 4. All three farms installed drip irrigation systems, but only two of them (farms 3 and 4) benefited from state incentives (up to 75% of the invested sums). All three farms use car engines, which have been adapted to run with butane gas, as the source of energy to pump the water. This source of energy is subsidized by the state for domestic use. The analysis of the water volumes used by each crop enabled us to distinguish (*i*) purely rain-fed crops with no irrigation at all, like cereals (hard and soft wheat), and pulses (Faba bean) from (*ii*) irrigated crops, either orchards or vegetables. Total water volumes used by each crop are, therefore, highly variable, fluctuating from a minimum of 4,482 m^3/ha, corresponding to the amount of efficient rain to a maximum of 22,982 m^3/ha for onions (Table 4).

Table 4: Total water volumes used and origin of the water (rain-fed vs. irrigated) used by the sample farms

Farm	Crop	Total water used (m^3/ha)	Contribution to total water (%)	
			Rain-fed	Irrigated
1	Apricots	7,991	56.1	43.9
	Peaches	9,431	47.5	52.5
	Nectarines	9,431	47.5	52.5
2	Barley	4,482	100	-
	Oats	4,482	100	-
3	Hard wheat	4,482	100	-
	Soft wheat	4,482	100	-
	Bell peppers	22,489	-	100
	Beans	20,938	-	100
	Onions	10,542	-	100
4	Soft wheat	4,482	100	-
	Faba beans	4,482	100	-
	Plums	9,560	46.9	53.1
	Grapes	9,560	46.9	53.1
	Tomatoes	3,799	-	100
	Onions	22,982	-	100

Finally, water requirements of vegetable crops such as onions, tomatoes, beans (*Phaseolus vulgaris*) and bell peppers had to be entirely covered by groundwater, and water volumes reached more than 20,000 m^3/ha, implying they surely contribute to groundwater depletion. It is also worth noting that the volume of water used for the same irrigated crop varied considerably from one farm to another, as illustrated by the case of onions, which in farm 4 received almost double the volume provided in farm 3. By comparing the water volumes supplied to each crop and the corresponding crop yield and profitability, physical and economic water productivity indicators were calculated. The results are listed in Table 5 and clearly show that for rain-fed crops (cereals and pulses), physical water productivity varied from 0.2 to 1.7 m^3/kg of product.

The variability of performances among crops can be explained by two main factors: the yield and the nature of the products. For example, for cereals (hard and soft wheat), we considered not only the grain as product, but also the straw. At the opposite end of the scale from rain-fed crops, the physical water productivity of irrigated crops was relatively stable, particularly orchards, as a volume of 0.30 to 0.51 m^3 of water was needed to obtain a kilogram of fruits. On the other hand, water physical productivity for vegetable production was highly variable, and fluctuated between 0.30 and 10.47 m^3 (beans) of total water per kg of product. These differences were explained by the farmers' irrigation practices as well as by the variations in crop yields.

Concerning the economic water productivity, there was a clear gap between rain-fed and irrigated crops. In fact, economic water productivity barely reached 0.4 Euros/m^3 for rain-fed crops, and this value was only obtained in the specific case of soft wheat in farm 4, as the yield was very high (8 tons of grains and 14 t/ha of straw) due to very favorable climate and agronomic conditions. In the other farms, the economic water

productivity of rain-fed crops never exceeded 0.16 Euros/m^3, considering that this water volume was made of efficient rainfall.

By contrast, economic water productivity for irrigated crops, particularly that of fruit trees, was much higher, and reached a maximum value of 1.58 Euros/m^3 in the case of plums in farm 4 and a mean value of around 0.50 Euros/m^3 for the other species (apricots, nectarines and peaches); grapes showing an intermediate value of 0.96 Euros/m^3 in farm 4. For these crops, the volumes of water used in all the farms were an almost 50/50 mix of efficient rainfall and groundwater. Finally, the economic water productivity of vegetables was generally between that of orchards and rain-fed crops, as it fluctuated between a minimum of 0.03 Euros/m^3 for beans in farm 3 to a maximum of 0.47 Euros/m^3 for onions in farm 4.

Table 5: Total physical and economic water productivity of crops grown by the sample farms

Farm	Crop	Total physical water productivity (m³ of total water/kg of output)	Total economic water productivity (Euro/m³ of total water used)
1	Apricots	0.51	0.42
	Peaches	0.45	0.57
	Nectarines	0.49	0.50
2	Barley	0.92	0.02
	Oats	0.59	0.08
3	Hard wheat	0.53	0.01
	Soft wheat	0.27	0.16
	Bell peppers	0.84	0.08
	Beans	10.47	0.03
	Onions	0.35	0.06
4	Soft wheat	0.20	0.38
	Faba beans	1.70	0.09
	Plums	0.40	1.58
	Grapes	0.30	0.96
	Tomatoes	0.30	0.10
	Onions	0.50	0.47

When analyzing the water footprint of livestock products, an average volume of 1.84 m^3 (range 1.17 to 3.02 m^3 of total water in farms 3 and 2, respectively), was needed to obtain one kg of milk, whereas the mean water footprint to obtain one kg of live weight gain was 9.23 m^3 (range 7.36 to 12.09 m^3 in farms 2 and 3, respectively) (Table 6). It is worth noting that livestock did not contribute to groundwater use, as it mainly relied on rainfall (59% of total water) and virtual water (35% of total water). The remaining 6% of total water uses devoted to dairy production corresponded to limited irrigation of berseem in farm 2. For live weight gain, the figures were rather different, as virtual water (i.e., purchased feed produced off-farm) was the main source of water (63.3%) followed by rainfall (36%).

Table 6: Total physical and economic water productivity in milk and live weight gain in the sample farms

Farm		2	3	4
Milk	Volumetric water productivity (m^3 of water/kg)	3.02	1.17	2.25
	Economic water productivity (Euro/m^3 of total water)	- 0.01	0.07	0.09
Live weight gain	Volumetric water productivity (m^3 of water/kg)	7.36	12.1	9.84
	Economic water productivity (Euro/m^3 of total water)	0.18	0.19	0.16

Finally, the analysis of the economic water productivity of livestock revealed relatively low values in comparison with irrigated crops but comparable to those obtained for rain-fed crops. In fact, the average water economic productivity of the dairy activity did not exceed 0.09 Euro/m^3, a figure quite comparable with that of barley and oat production in farm 2, hard wheat (farm 3), and Faba bean (farm 4). Live weight gain showed better economic water productivity, which could reach a maximum value of 0.19 Euro/m^3, close to the values found for vegetables, but far below the economic water productivity of fruit trees. However, these findings should not mask two important aspects: (*i*) the origin of the water used, as it is clear that livestock production, be it milk or live weight gain, requires almost no irrigation, and (*ii*) the many assets provided by livestock (above all manure, but also more stable farm gate prices for milk and live animals compared with fruits and vegetables) contribute to the resilience of mixed crop-livestock systems because they provide steady incomes for farmers. These points are further discussed later in the paper.

Discussion

Water productivity has become an established concept, often used by policy makers to arbitrate decisions concerning support for different crops in a context of increased water scarcity (Hamdy et al., 2003). In Morocco, for instance, this concept played a fundamental role in deciding on cropping priorities (and hence the attribution of subsidies) in recent agricultural policies. We argue that this concept is problematic for at least two reasons. First, most research has not paid sufficient attention to the integrative use of water resources on-farm. Generally, the focus is on a single product (cereal grains, pulses, vegetables, fruits, live weight, milk, etc.), but does not consider the overall farm performances. This is especially problematic in the case of the typical mixed crop-livestock systems in Africa (Descheemaeker et al., 2010) with its many interdependencies, including the use of by-products like straw and stubble in livestock production, the manure produced by livestock maintaining soil fertility and the complementarities in the revenues generated by dairy farming (low but stable revenues all year round) and the sales of young heifers/calves or crop yields (relatively high revenues once a year/season). Second, water productivity indicators very often do not reflect the water mix farmers use to achieve their production goals. This means that the physical and economic water productivity in crop and livestock outputs as a function of the origin of the water used is not highlighted. In the Mediterranean context, agricultural systems have become increasingly reliant on (overexploited) groundwater through agricultural development programs promoting high value crops, including fruit

trees, early vegetables and intensive fodder production (Kuper et al., 2016; Berbel et al., 2018).Tailoring agricultural systems better to existing water resources will hence become increasingly important.

Even if our study was based on a limited sample due to the amount of data needed to conduct such research for a relatively long period (one year), our results allow us to draw some preliminary conclusions concerning water use by the agricultural sector in a semi-arid area (annual rainfall < 600 mm), with possibilities of additional groundwater uses.

The first finding shows that farms that invested in the "groundwater economy" by drilling boreholes or wells with drip-irrigation systems, often cultivate higher added-value crops, particularly orchards. More surprisingly, local farmers tend to maintain their livestock systems, even when planting orchards, as they are considered to be more robust to deal with price volatility on agricultural markets and water shortage due to the high percentage of the contribution of virtual water in such systems. Planting orchards is encouraged through public subsidies and it significantly increases the profit per ha compared with traditional rain-fed crops like cereals, pulses and fodder, and also ensures significantly higher economic water productivity. However, the limited profitability of rain-fed crops, mainly cereals and pulses, should be interpreted with caution, as their by-products, for example, straw and stubble, are needed to feed livestock in the dry season (Magnan et al., 2012), and consequently contribute to the profitability of the herds. In our three sample farms with livestock, the on-farm feed resources produced using rainfall as the only source of water are in fact the main feed resource for growing calves. They are also crucial to feed lactating cows in the dry season, since their milk yields fall sharply in comparison to the wet season. By contrast, the economic water productivity of irrigated crops (orchards and vegetables) is much higher, as it reached 10-times the value of rain-fed crops. This rather classical finding was also reported by Schyns and Hoekstra (2014): up to 1.8 Euros/m^3 for vegetables (tomatoes) and fruits (mandarins) but which rely mainly on irrigation compared to less than 0.1 to 0.2 Euros/m^3 for cereals and pulses. On the other hand, mixed crop-livestock farming can mitigate climate variability and price volatility (Bell et al., 2014). This is quite clear in our study, as the rain-fed crops are used to feed livestock which provides a steady income to farmers through regular milk sales, with no further impacts on groundwater resources. In contrast to rain-fed crops, irrigated fruit trees produce high profits: up to 3,400 Euros/ha (apricots in farm 1), 8,300 Euros/ha (grapes in farm 4) or even 20,300 Euros/ha (plums in farm 4). However, farms that used more groundwater for vegetable production, did not manage to reach similar profitability levels to those achieved by orchards. This reflects the numerous setbacks in horticultural production and also their higher price volatility in comparison to fruits. The results also show that farmers who opted for intensification of their agricultural systems through the use of groundwater, nevertheless kept their livestock. This is particularly true in farms managed by people who originate from the study area (farms 3 and 4), as they are aware of the many synergies enabled by combining crop-livestock production (Herrero et al., 2010), even though this entails in a heavy workload (Sraïri and Ghabiyel, 2017). In contrast, farm 1, which invested in orchards, is a typical small-scale farm belonging to a newcomer investor, who does not wish to dedicate work time and financial means to livestock. These newcomer investors have therefore amplified pressure on groundwater, in a typical mining exploitation of this resource, and have

created social frustration for the many farmers who cannot afford to dig deeper boreholes (Ameur et al., 2017).

These results also confirm, and this is the second finding, the important water footprint of livestock products. Such results are close to those reported in previous research in Morocco (Sraïri et al., 2016; Sraïri et al., 2009), but higher than the international reference of the water footprint for the production of milk and beef (respectively 1 and 15.5 m^3 of water, according to Hoekstra, 2012). The results also emphasize the frequent setbacks in livestock rearing caused by unbalanced diets, which have a negative effect on both milk yield and profitability. In such cases, action should be undertaken to avoid reproduction failures, which would improve the economic profitability of the farms, but would require close on-farm support to design balanced diets throughout the year (Sraïri et al., 2011). There is, therefore, definitely scope for improvement of the physical and economic water productivity of livestock systems.
Concerning the robustness of our results, we compared the physical water productivity of the crops grown in our study sample with existing global references for the same crops. We found rather similar results. For example, for cereal crops, a mean value of 0.23 m^3 of water was needed to obtain a kg of biomass (both grains and straw) of soft wheat, and this value reached 0.5 m^3 of water per kg of hard wheat. Considering an average harvest index of 33% for these crops, this means that the water productivity to obtain a kg of grains was 0.7 and 1.5 m^3 for soft wheat and hard wheat, respectively. The same range of values was reported by Mekonnen and Hoekstra (2016) in their assessment of the water footprint of cereal crops at global scale. Finally, for the water footprint of fruit production, we found a mean value of almost 0.45 m^3 per kg (apricots, peaches, nectarines and plums); a value that is quite similar to the one cited by El-Gafy (2017) for Egyptian peach orchards.

The third main finding of this study implies that even though profitability and water productivity of livestock are limited in comparison to orchards, in this specific climate context, with a rainy season that lasts almost six months a year, livestock mainly adds value thanks to rainfall, as is the case for rain-fed crops, and does not contribute to further groundwater depletion. At the opposite end of the scale, orchard and summer vegetable outputs depend almost entirely on groundwater resources, as it represents from 50% (like in the case of fruits) to 100% of the total water used for summer vegetable production (as calculated for onions, tomatoes, beans, etc.). If such crops are adopted by the majority of farmers in the region, who might be tempted by their profitability, the rate of groundwater drawdown would rapidly increase, leading to the decline of the agricultural economy based on groundwater exploitation (Berbel et al., 2013).

The results obtained in this study should, however, be interpreted with caution. First, they were obtained in a favorable climatic year, as rainfall levels were above average, and rainfall distribution was very stable from late November to mid-May. Additional observations for at least three consecutive years will be needed to assess the real effects of climate variability on water productivity for mixed crops-livestock systems to account for yield variations, water volumes used and their origins, in addition to the use of inputs and their effects on crops and livestock profitability. Another reason to interpret these results with caution is the nature of the sample we selected. In fact, our sample did not include the recently emerging very large farms (more than 200 ha) that are highly specialized in fruit tree production and benefitted from state incentives.

These incentives encouraged investors to plant orchards, to dig boreholes, and to install drip-irrigation systems and anti-hail nets. The aquifers have consequently been declining and many farmers have seen their wells run dry and have been forced to quit the groundwater economy, which has increased social exclusion and frustration. As there are still no effective regulations to control groundwater use, if no immediate action is taken, this resource may disappear in the coming decades. Altogether, the assessment of the current situation of water uses, shows that the intensification of groundwater access is increasing risks of water scarcity. In practice, the vast majority of farmers could be excluded from the groundwater economy, due to the limited capital or land titles that can be mortgaged, etc. (Kalpakian et al., 2014). The absence of regulation of groundwater use may trigger the collapse of the whole irrigation sector in the near future (Petit et al., 2017) if appropriate measures are not adopted.

Conclusion

The present study focused on the water productivity of several water resources (rainfall, surface or groundwater irrigation and virtual water) in mixed crop-livestock farms in a semi-arid area. Our results show that farmers are fully aware of the range of water sources in the water mix they use to reach their production goals. However, water is not the only limiting factor, as financial means may also explain why some farms are not able to invest in more water intensive uses, such as the access to groundwater, which requires considerable financial investments to drill boreholes or wells and to purchase drip irrigation equipment. Most farms that use groundwater benefited from state incentives and usually aim for high-value cash crops, such as orchards (peaches, plums, etc.) and vegetables (bell peppers, onions, tomatoes, etc.). However, intensification in the Mediterranean context appears to depend increasingly on more use of groundwater, which is already highly overexploited. This may jeopardize the sustainability of irrigated agriculture in the near future, as well as amplifying the socio-economic inequalities between farms. There is therefore an urgent need for innovative agricultural policies that promote the efficiency and integration of water uses rather than encouraging a mining exploitation of groundwater, sometimes entirely destined to exporting water from a semi-arid area to more water-endowed environments. If not, the collapse of the whole groundwater economy may be imminent, threatening the sustainability of the entire agricultural regional sector and putting the future of several high value investments, particularly fruit trees and groundwater irrigation infrastructure at risk.

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