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*Original*

Ever-increasing agricultural land and water productivity: A global multi-crop analysis / Tuninetti, M.; Ridolfi, L.; Laio, F.. -  
In: ENVIRONMENTAL RESEARCH LETTERS. - ISSN 1748-9326. - ELETTRONICO. - 15:9(2020), p. 0940a2.  
[10.1088/1748-9326/abacf8]

*Availability:*

This version is available at: 11583/2971925 since: 2022-09-30T19:39:12Z

*Publisher:*

IOP Publishing Ltd

*Published*

DOI:10.1088/1748-9326/abacf8

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To cite this article: Marta Tuninetti *et al* 2020 *Environ. Res. Lett.* **15** 0940a2

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# Environmental Research Letters



## LETTER

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### OPEN ACCESS

RECEIVED  
1 June 2020

REVISED  
14 July 2020

ACCEPTED FOR PUBLICATION  
6 August 2020

PUBLISHED  
4 September 2020

Marta Tuninetti , Luca Ridolfi and Francesco Laio

Department of Environmental, Land, and Infrastructure Engineering, Politecnico di Torino, Turin, Italy.

E-mail: [marta.tuninetti@polito.it](mailto:marta.tuninetti@polito.it)

**Keywords:** land productivity, nutrition security, water productivity, water footprint, agricultural production

Supplementary material for this article is available [online](#)

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## Abstract

Producing more nutritious food with less resources, while preserving the natural ecosystems, is a key challenge of our society. In this paper we propose a macronutrient-based indicator of productivity, the *nutrient land productivity (NLP)*, to measure the amount of calories, proteins, and fats produced per hectare of cropland. Over the period 1961–2016, we find that the global *NLP* has increased by 2.7–2.9% per year for calories and proteins, and between 2.1 and 4.6% for fats. However, such rates exhibit significant spatial patterns throughout the world depending on whether farmers adopted intensification (e.g. Eastern and South Asia, North America) or extensification (e.g. Sub-Saharan Africa) practices to boost nutrients production. Our outcomes, based on a production basket including 144 crops, show that cereals and pulses cultivations have been dominated by intensification practices coupled with a stable or decreasing harvested area. Conversely, for fruits and nuts cultivations extensification prevailed over intensification, while for oil crops most cultivations experienced a coupled action of the two practises. Finally, by coupling the *NLP* indicator with its *nutrient water productivity (NWP)* counterpart, we find that *NWP* has mainly changed following land patterns, with the exception of locations having undergone significant crop substitutions, namely from less toward more water demanding crops. Indeed, the transition toward perennial crops has increased the evapotranspiration demand over cultivated land by 14% on a global average.

## 1. Introduction

Increasing human population and food demand, larger biofuel consumption, and changing diets toward larger proportion of meat products have driven agricultural production increase over the past decades [1] and will probably push it in the upcoming years [2–4]. The analysis of the agricultural production growth is at the centre of the international debate since the Malthusian prediction of exponentially growing population outstripping linearly increasing production [5–7]. Since then, economists and environmental scientists [8–10] have investigated the history and geography of agricultural production to understand if there is and there will be enough food to feed a global increasing population.

The rate of agricultural production growth is influenced by aspects pertaining to (i) agriculture *intensification* that happens through yield

enhancements [1, 11], and (ii) agricultural *extensification* through croplands expansion over natural vegetation [12]. Depending on economic, climatic, cultural and social factors, land intensification and extensification have been heterogeneously adopted worldwide. As a result, in some areas major gains of crop yield are yet to be accomplished [13], while in other locations yields seem to be more stable in time [14, 15]. Literature includes several contributions analysing the twin role of intensification and extensification [16–19]. For instance, the study by Burney *et al* [20] has suggested that the climatic impacts of historical agricultural intensification were lower than those pertaining to a system with lower inputs that instead would have expanded cropland to meet global demand for food. This is particularly important considering that across the tropics, between 1980 and 2000, more than 55% of new agricultural land came at the expense of primary forests, and another

28% came from disturbed forests [21]. Many studies have pointed out that a sustainable intensification can drive a progressive reduction or stabilization of the extensification process with important land sparing. Indeed, according to the Borlaug hypothesis when agricultural yield increases, prices drop and cultivated area declines [22]. However, it has been shown [16] that cropland intensification over 1990–2005 was hardly accompanied by declines or stasis in cropland area, with a pattern recalling the Jevons Paradox, i.e. when technological progress increases the efficiency with which a resource is used, but the rate of consumption of that resource rises due to increasing demand. To date, a major gap exists on whether the nutritional content of crops has been a driver of preferentially adopting the intensification or the extensification practise. Indeed, most studies have used crop yields and harvested areas as proxy of these processes, while only few studies have combined these processes with the nutritional density of the crop. Analysing such relation is mandatory to monitor how far is the current production system from achieving the nutrition security [23].

Recent studies have introduced new indicators to monitor the agricultural evolution under the perspective of nutrition security [10, 24, 25]. The study by DeFries *et al* [26] introduced the concept of *nutritional yield* in order to quantify the number of people that can be fed (obtaining a 100% of the daily reference dietary intake) by a hectare of cultivated land. Cassidy *et al* [27] have redefined crop yield as the number of people fed per hectare of cultivated land. However, it remains unclear whether countries have adopted intensification or extensification processes depending on the nutritional density of the cultivated product. Moreover, it is not clear whether countries are still increasing the nutritional productivity of their lands, through structural change of their basket composition, despite clear signs of yield stabilization and decrease.

In this study we propose a macronutrient-based indicator of nutrient land productivity, *NLP*, that quantifies the amount of calories, proteins, and fats supplied per hectare of harvested area. The indicator merges the crop yield, quantifying the the metric tonne of crop produced per hectare of land, with the nutrients content specific of the crop. Hence, it levels-off the dichotomy between production and the corresponding nutritional load. We integrate the analysis with a twin macronutrient-based water productivity, *NWP*, based on the study by [28], to critically address whether land has always been a driver of water use [29, 30], or if a particular composition of the production basket (i.e. annual versus perennial crops) have caused water use to increase faster/slower than land. We focus on the following research questions: (i) did nutrient land productivity keep increasing over the past decades despite crop-specific yield

stabilizing or slowing down?, (ii) what is the relation between intensification and extensification practises and the nutritional content of crops?, and (iii) what role does the production basket composition play when water and land use evolve with different patterns? We address these questions on a global and regional scale through a data-based and multi-crops analysis encompassing 144 crops, including cereals, tubers, vegetables, fruits, oil crops, sugar crops, pulses, nuts, and stimulants and spices, and ranging between year 1961 and year 2016.

## 2. Materials and methods

### 2.1. Nutrient land productivity and land footprint

Land productivity measures the annual amount of calories ( $NLP_c$ ), or fats ( $NLP_f$ ), or proteins ( $NLP_p$ ) supplied by a hectare of harvested land in a year  $t$ .  $NLP$  is defined as

$$NLP_{c,f,p}(t) = \frac{\sum_i P(i, t) \cdot k_{c,f,p}(i)}{\sum_i LF(i, t)}, \quad (1)$$

where,  $P(i, t)$  is the annual production of crop  $i$  expressed in tons in year  $t$ ,  $k_{c,f,p}(i)$  is the calorie (kcal/ton), or fat (g/ton), or protein (g/ton) content per unit production typical of each crop, and  $LF(i, t)$  is the annual crop-specific harvested area expressed in hectares, or Land Footprint. The agricultural parameters ( $P$  and  $LF$ ) are derived from the FAOSTAT database [31], while the macro-nutrient contents are provided by the FAO ‘Nutritive Factors’ database [32]. Equation (1) is applied both at the global and regional level to explore spatial heterogeneities. Notice that the  $NLP$  indicator can be applied to production baskets of different size. For production baskets consisting of one crop,  $NLP$  coincides with the crop yield re-scaled by the nutritional factor  $k$ . For production baskets including two or more crops,  $NLP$  quantifies the average nutritional productivity of the whole basket. Accordingly, a country can witness an increase of the land productivity regardless a stabilization or decrease in the yield of some crops. Indeed, countries can perform crop substitution based on the nutritive contents in order to produce more nutrients, without modifying neither the land footprint nor the crop yield. Hence, a proper diversification and optimization of the national production basket may play a crucial role in altering the  $NLP$  value.

### 2.2. Nutrient water productivity and water footprint

Similarly, we calculate a nutrient-based water productivity, expressing the amount of nutrients obtained per cubic meter of water (see also [28]).

$$NWP_{c,f,p}(t) = \frac{\sum_i P(i, t) \cdot k_{c,f,p}(i)}{\sum_i WF(i, t)}. \quad (2)$$

Equation (2) is the analogous for water of equation (1). Hence, in this case we quantify the macronutrients production compared to the total water use, or Water Footprint (*WF*). Water footprint quantifies the volume of water (rainfall plus irrigation) required to produce a given crop under certain climatic conditions and agricultural practises [33, 34]. So far, most studies in literature have provided a static measure of the crop water footprint. In order to assess the annual *WF*, we adopt the Fast Track approach introduced and validated in the study by Tuninetti *et al* [35] and recently adopted by Gao *et al* to estimate the water use efficiency in China over 2004–2013 [36]. According to this approach, the water footprint per-unit product [ $\text{m}^3 \cdot \text{ton}^{-1}$ ] varies in time as a function of the crop yield, while evapotranspiration can be assumed to be constant and equal to a long-term average (see [35] for further details). Indeed, it has been shown that the uncertainty associated with the Fast Track methodology is low with a standard deviation of the error around 10%, which is three times smaller than the variability of the models used to estimate the crop water footprint. Accordingly, the annual *WF* is defined as

$$WF(i, t) = \frac{Y(i, T)}{Y(i, t)} \cdot uWF(i, T) \cdot P(i, t), \quad (3)$$

where the annual yield values,  $Y(i, t)$ , are provided by the FAO [31] for each crop over the period 1961–2016,  $Y(i, T)$  is the ten-year average yield calculated over the period  $T = 1996–2005$ ,  $uWF(i, T)$  is the average unit water footprint typical of the period  $T$  provided by Mekonnen *et al* [37], and  $P(i, t)$  is the annual crop production. In the present study, we assess the total water footprint without disentangling the role of green and blue water [37] due to uncertainties in the quantification of annual blue water. Indeed, crop-specific areas equipped for irrigation are not available in the literature, except for year 2000 [38]. Most studies and open databases provide irrigated areas as an aggregated number that accounts for the total cropland (e.g. see AQUASTAT [39]).

## 3. Results

### 3.1. History and geography of macronutrients production

#### 3.1.1. Nutrient land and water productivity to explore agricultural intensification

$NLP_c$  and  $NLP_p$  show a linear increase over time at an average rate of 2.7% and 2.9% per year, respectively (figure 1). Conversely,  $NLP_f$  shows a super-linear rise in time, with an average annual rate increasing from 2.1% to 4.6% per year. Nowadays, global average *NLP* is around 10.7 million of calories, 370 kg of proteins, and 214 kg of fats per hectare of harvested area. Namely, current *NLPs* have exceeded by 2.5, 2.7 and 3.5 times their values in 1961. The top-three crops

in terms of calories and proteins supplies- i.e. wheat, maize, and rice- have remained constant in time, in spite of the remarkable rise of proteins supplied by soybean that has overcome that of the other staple crops. For fat supply, the picture is different: maize, wheat, and groundnuts dominated the past supply, while soybean, palm oil, and, to a lower extent, rapeseed, dominate the present one.

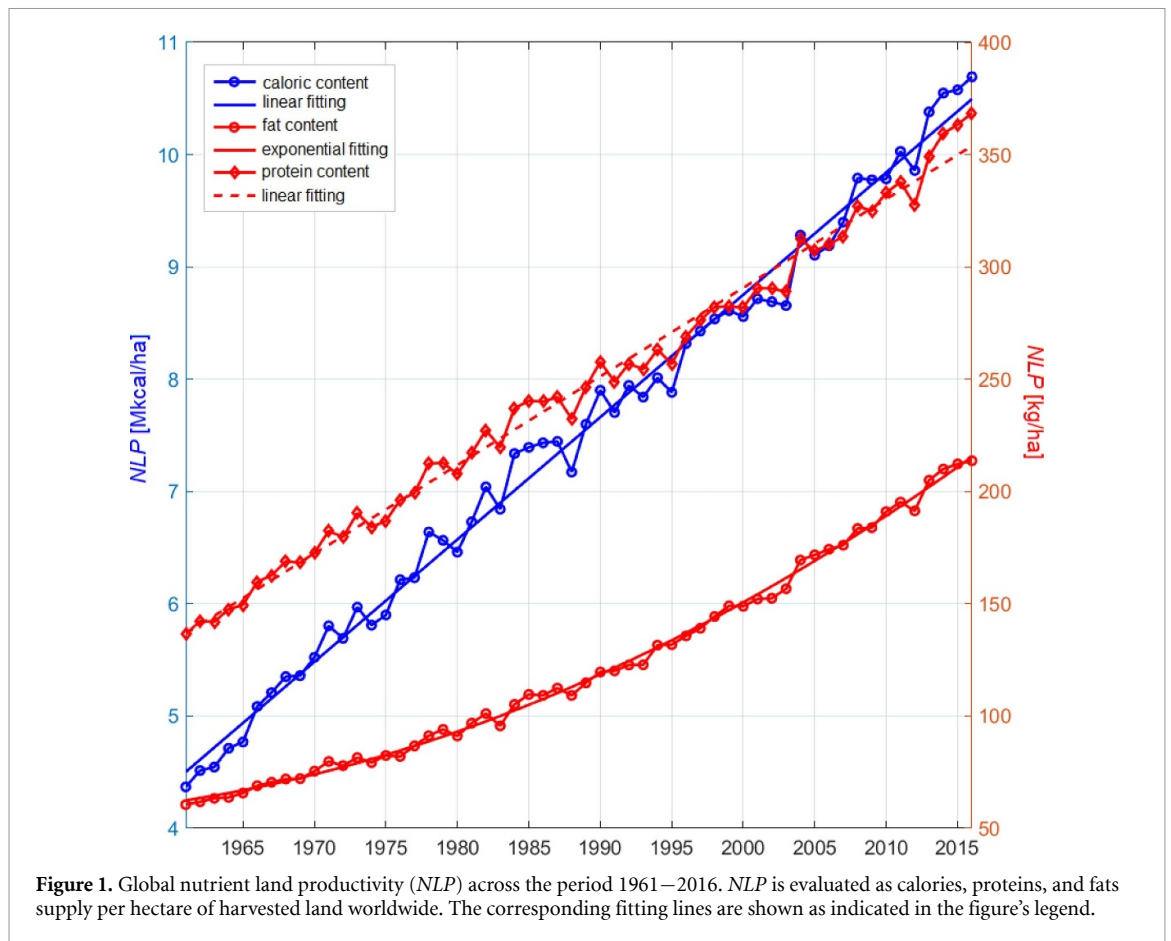
At the global scale, the growth of  $NLP_c$  and  $NLP_p$  has been mostly driven by crop yield's positive trends [1], while  $NLP_f$  has been boosted also as a consequence of a change in the fat content typical of the global basket of products: i.e. on global average, we produce more fatty products (e.g. through oil palm, rapeseed) than in the past. Hence, while a kilogram of crop still provides an average of 1700 calories and 55 g of proteins on global average, it provides 60% more fats than in the past. Important heterogeneities appear when regional patterns are considered, and the role of basket composition becomes crucial also for calorie- and protein- based productivity.

Looking at water productivity we find similar temporal patterns at the global level as shown in figure S1 and S2 (<https://stacks.iop.org/ERL/15/0940a2/0/mmedia>) where the global temporal series of the *NLP* and *NWP* growth rates are shown to highlight the divergence between the fat productivity growth rate (4.5% per year in 2016) and the calorie (2.4% per year) and protein (3.0% per year) growth rates that has been reached in 2016.

#### 3.1.2. Agricultural intensification and extensification compared to the nutritive content

In this section we examine the history and geography of the dynamics of agricultural intensification compared to extensification across nine major regions (figure 2). Importantly, we relate such variations to the nutritive content of 144 crops to shed light on what has been the dominant practise depending on the nutritional load. The geography of the dominant practises is quite heterogeneous along the period 1961–2016 (figure 2) and shows peculiar links to the crop category (figure 3).

Globally, the increase of agricultural production has been driven by the enhancement of land productivity, whose value in the Sixties was 40% of the current one (figure 2(b)). Similarly to the global picture, South Asia (orange line), Eastern Asia and Pacific Islands (yellow line), the Americas (dark red and red lines), and Europe (bluish lines) show an increase of the agricultural production mostly driven by *NLP* boosting (figures 2(b) and (c)). Particularly, South and Eastern Asia show marked trends of *NLP* growth. Differently, Africa (black dotted line) mostly incremented its production through area expansion: i.e. in 1961 only 40% of the current area was cultivated, while the land productivity was already at the 70% of the current value. Both the Middle East and Northern Africa (MENA) region and Europe present



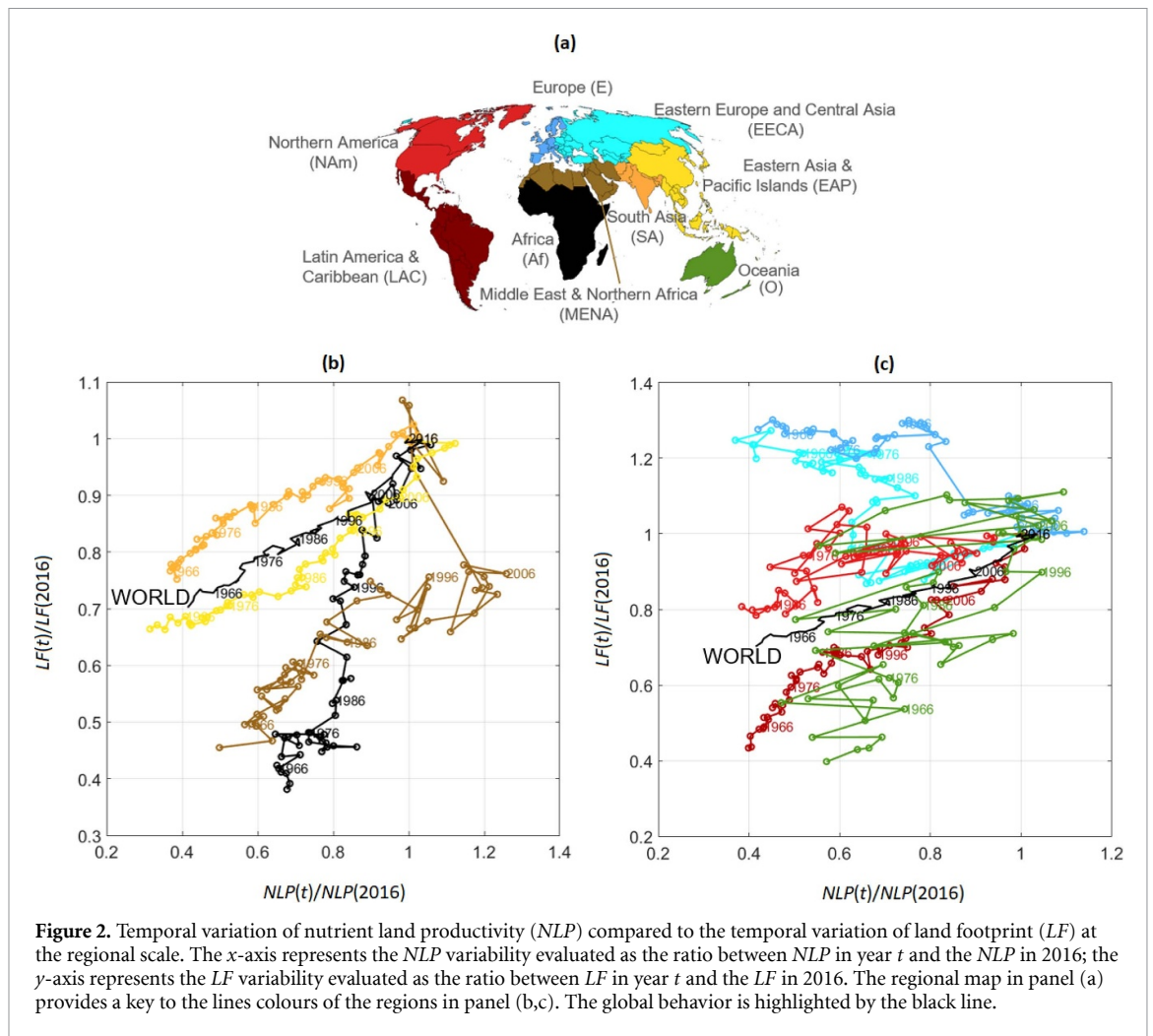
a recent stabilization of the agricultural production, which has been compensated by increased imports from the rest of the world ([31]). Indeed, Europe (figure 2(c), blue) shows a peculiar contraction of the harvested area in time, which is compensated by NLP growth at rates similar to those found in North America (red line), despite exhibiting a less regular trend than South and East Asia. Finally, Oceania shows the most irregular temporal pattern, but it seems clear that most of the production growth has been favoured by cropland expansion.

On a global average, cereals and pulses have been dominated by the intensification process over the period 1961–2016 (figure 3(b)), which has been generally associated with a stable (e.g. sorghum and peas dry) or decreasing land footprint (e.g. oats and rye, broad beans) with few exceptions for maize, cow peas, and lentils exhibiting a 100% to 400% increase of their LF (figure 3(a)). Hence, the agricultural patterns of staple crops can be interpreted through the Borlaug hypothesis of increasing productivity driving land sparing. Tubers show a variegated dynamic for extensification (with positive and significant changes for cassava and yams and slightly negative changes for potatoes and sweet potatoes), but a nearly uniform NLP increase, which is generally lower than that of other crop varieties. Vegetables and fruits have the most heterogeneous dynamics highlighting the peculiar agricultural practises

and the variegated species composing these categories. On a global average, we observe an opposite behaviour with respect to other categories with a number of fruit crops (e.g. persimmon, cashew apple, plums) showing a decreasing NLP and increasing LF. Oil crops show increasing land footprint and productivity, but LF shows larger increase than NLP (see soybean and rapeseed in particular). The top-production of nuts and sugar products (i.e. groundnuts and coconuts, sugar beet and sugar cane) show opposite trends of NLP and LF in accordance with the Borlaug hypothesis. Similarly to some vegetables, also the NLPs of nut products have decreased in time accompanied by LF increases (e.g. karite nuts, Brazil nuts).

### 3.2. The Malthusian trap: agricultural production and population growth rates

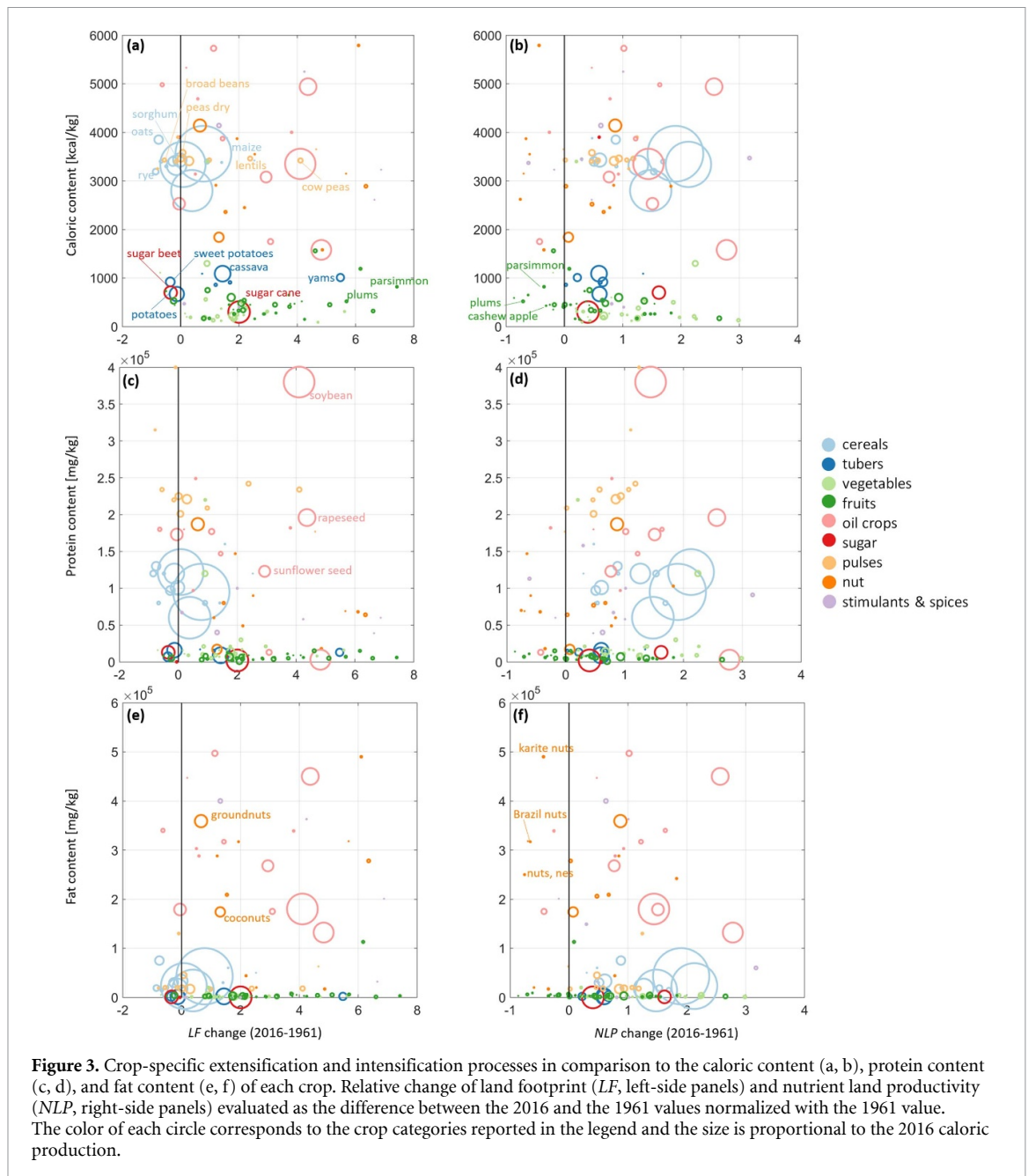
Due to the joint effect of cropland expansion, land intensification, and changes in the crop mix typical of each production basket, the global production of calories and proteins have increased by 3.5 and 3.9 times since 1961; conversely, fats production has increased by 5 times. These increases are smoothed when we look at the corresponding per-capita values due to population growth [31]: i.e. per-capita production of calories increased from 3711 to 5351 kcal/day (+44%) over the observed period, the per-capita production of protein from 115 to



184 g/day (+60%), and the per-capita fat production from 51 to 106 g/day (+108%). According to these variations, humans have been able to improve their productive regime on a global average and to increase agricultural production at a faster rate than that of population growth. However, important heterogeneities and peculiar dynamics appear at the regional scale when we consider the per-capita  $NLP$  trends (figure 4). Notice that the results always refer to the gross primary production, without neither specific distinctions across sectors, e.g. supply to the food, feed, and bio-fuels sectors, nor accounting for the portion that is wasted along the supply chain, for which further analyses and additional databases would be required.

Eastern Asia and Pacific islands (EAP) exceptionally tripled its per-capita  $NLP_c$  over 1961–2016 (reaching 38 000 kcal/ha/day in 2016), but without reaching neither North America nor Europe, which remain the most productive regions over the entire period, despite a stabilization of the European  $NLP_c$  around 45 000 kcal/ha/day. Until the Ninety the EAP's  $NLP_c$  mainly grows following population dynamics and allowing an average per-capita production of 3000 kcal/cap/day, similarly to South Asia and

Africa. However, in the Ninety production growth rate exceptionally outpaced population growth rate, hence allowing an acceleration of the productivity regime that has recently reached 5000 kcal/cap/day. This caloric transition of the productive regime brings EAP closer to the caloric regime of the Western economies. In figure 4, the transition is clearly represented by an inflection point around 1990, which looks similar to that found for Latin America and the Caribbean (LAC), where the  $NLP_c$  also consistently increased (i.e. 2.5 fold). Latin America and Caribbean exceptionally exceeded a production of 8000 kcal/cap/day in 2016, similarly to Eastern Europe and Central Asia. We interpret these inflection points as markers of technological development and consistent investments to boost production over a *basal* threshold where production growth is constantly levelled-off by population growth (i.e. the Malthusian trap). In a broad sense, crossing the basal threshold means escaping from the Malthusian trap. We find similar transition for the  $NWP_c$  (figure S5), however the gain was less marked than in the case of land. Indeed, in 2016 EAP produced 6 kcal  $m^{-3}$  while Europe reached 12 kcal  $m^{-3}$ . This is due to a transition of the Eastern Asian production toward crops



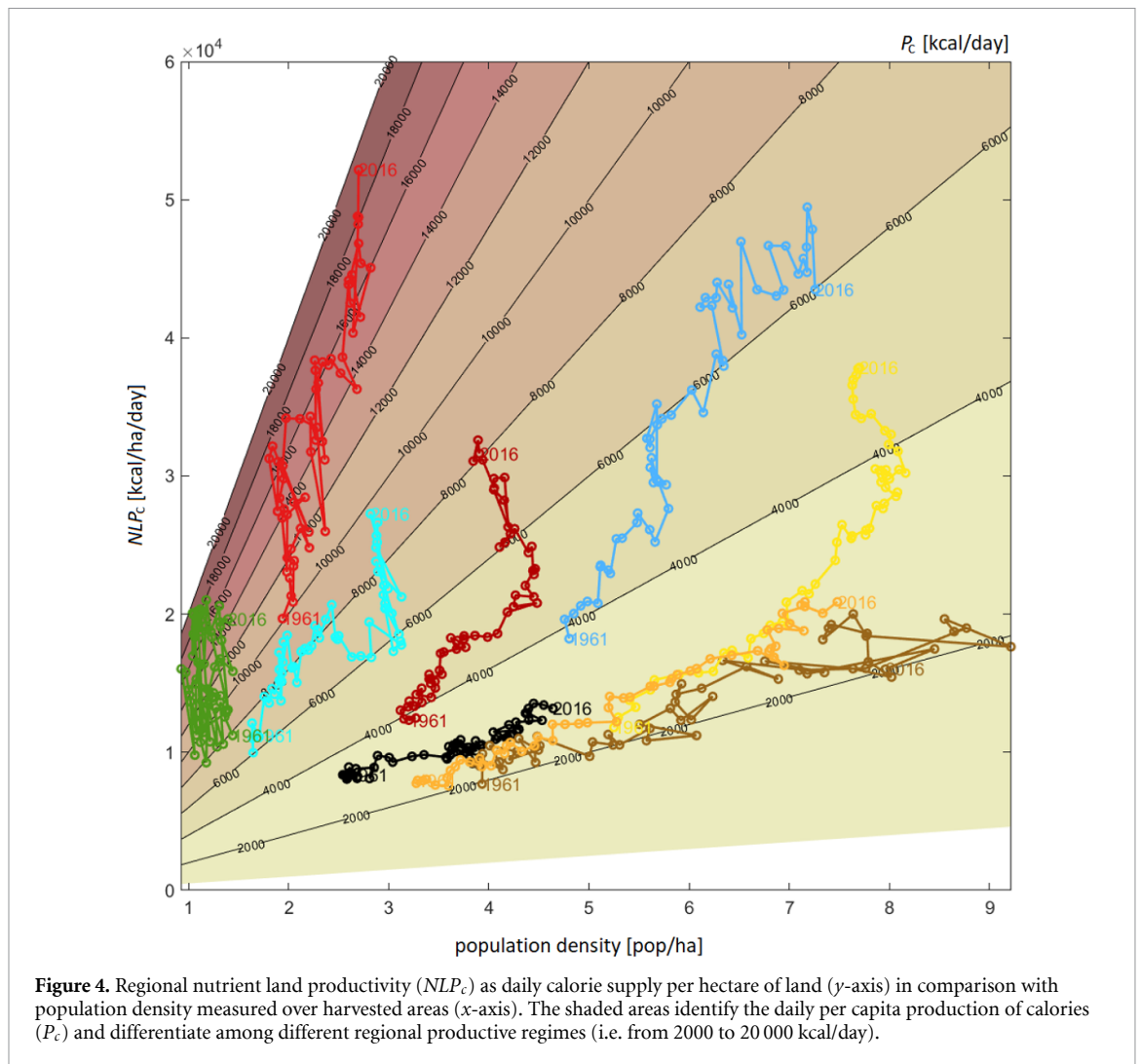
requiring more water along the growing period, such as palm oil whose cropping period extends over the whole year (i.e. perennial crop) differently from an annual crop having shorter cropping period.

The caloric transition in EAP has been accompanied by an important fat transition (figure S4), but a less significant protein transition that has been greater in LAC (figure S3). Interestingly, while  $NLP_f$  of EAP reached the LAC's one and even overtook the European one, in the case of land (figure S4), the  $NLP_p$  remained far from that of the Western economies, but close to the one of Eastern Europe and Central Asia for land (figure S3) and to South Asia for water (figure S6). Notably, while the caloric and protein transition of EECA did not show any specific inflection points, a clear transition in the fat productive regime happened after year 2000 mostly due

to the intensification of rapeseed production (i.e. 6 fold increase), half of which is exported in the global market [31]. Interestingly, Latin America always outperforms EECA for *NLP*, but in the case of *NWP* EECA outperforms LAC being able to extract more calories per unit water (figure S5), while the amount of proteins and fats produced by a cubic meter of water is similar in the two regions.

The largest protein transition happened in Latin America and the Caribbean, where daily production increased from 100 g/cap to more than 400 g/cap. Nowadays, LAC is the region with the largest protein and fat production per calorie produced; this could happen thanks to the significant investments devoted to increase soybean production. Conversely, back in the Sixties the largest fat production per calorie is found in Africa (9 g/kcal), while it was between 3





and 6 g/kcal in all the other regions. Indeed, Africa was the only region that used to produce consistent amount of groundnuts and palm oil already. Looking at the proteins, Africa did not increase the amount of protein per kcal, which remained constant around 8 g/kcal. Notably, while the 2.6 fold increase in the Northern American  $NLP$  allowed a significant increase of the per capita production, the same relative rise of  $NLP$  in South Asia did not allow any caloric transition, but it seems likely that the  $NLP$  growth has been constantly levelled off by population growth (figure 4). Indeed, South Asia, together with Africa and the Middle East and Northern Africa, seems to be still halted in the Malthusian trap, with the same caloric, fat and protein productive regimes (figures 4 B, S2, S3). Especially in Sub-Saharan Africa and South Asia the level of productivity is strongly impacted by the fact that land consolidation has not yet occurred [40]: indeed, small farms ( $\leq 20$  ha) produce more than 75% of most food commodities [41]. This has implications in terms of what is produced, how it is produced, and the level of productivity. Finally, Oceania consistently increased its productive

regimes for all macro-nutrients, despite strong fluctuations over years.

### 3.3. Decoupling land and water footprint: the role of crop evapotranspiration

Cropland area increased by 43% over the observed period, and reached 1360 Mha in 2016. Such increase in the cultivated land implies a proportionally larger use of water resources to sustain production. We find that the total  $WF$  has increased by 50% worldwide since 1961, reaching an annual volume of 7100 km<sup>3</sup> in 2016. Notice that this global estimate compares well with the study by Mekonnen *et al* ([37]), which has estimated a global  $WF$  of 7404 km<sup>3</sup> around year 2000 for 126 crops. The faster increase of  $WF$  compared to  $LF$  resulted in an increase of the water use per hectare of cultivated land (or water intensity), i.e. from 4700 m<sup>3</sup> · ha<sup>-1</sup> in 1961 to 5300 m<sup>3</sup> · ha<sup>-1</sup> in 2016 (relative increase of +14%).

Hence, Water Footprint and Land Footprint (or harvested area), despite being tightly connected when considering one crop at a time, show

peculiar temporal dynamics when all crops composing the production basket are considered together (see table 1). In the following, we will show the role of crop-specific evapotranspiration in decoupling the two footprints. When one considers a single crop at a time this role can be neglected, however when all crops are considered together the different transpiration demand of each species can be an important driver of the total water footprint associated with the production basket. We find that some regions (i.e. Africa, Middle East and Northern Africa, Eastern Europe and Central Asia, North America, and Latin America and the Caribbean) show coupled trends of *WF* and *LF*, namely an increase in cultivated area causes a nearly proportional increase in the water use (table 1). In particular, Africa increases its *WF* and *LF* by 160% over the period 1961–2016, North America by 23%, and Latin America and Caribbean by 130%. The annual rate of increase varies from region to region and from decade to decade depending on the cropland expansion (figure 2). Particularly, while Africa shows the largest rate of agricultural expansion in recent years (i.e. from 100 Mha in 1990 to 150 Mha in 2013), North America presents the largest increase from the 1970 s to the 1980 s and then it shows a stabilization around 125 Mha. Conversely, Latin America and Caribbean is keeping expanding with a marked acceleration from the Ninety. This suggests that *WF* has grown driven by area expansion mostly, while average crop evapotranspiration remained stable, despite some changes in the structural composition of the production basket (figure 5(a)). For instance, in Latin America and Caribbean despite soybean production more than tripled its average water intensity (i.e. evaluated as *WF* divided by *LF*) remains nearly constant at  $6000 \text{ m}^3 \cdot \text{ha}^{-1}$ . Indeed, soybean evapotranspiration is very similar to the evapotranspiration rates of the other dominant crops. As opposite to those areas where *WF* and *LF* have increased at very similar rates, Eastern Asia and Pacific islands, South Asia, Europe, and Oceania show very different patterns for the two variables (table 1). Eastern Asia and Pacific islands is the most emblematic case: while the harvested area increased by 51%, the *WF* increases by 88% reaching  $1850 \text{ km}^3$  in 2016. Hence, an average hectare of land in EAP required around 500 mm of water in 1961, while it requires nearly 630 mm nowadays (figure 5(b)). This peculiar outcome is due to a transition of the EAP's production toward more water-demanding crops, particularly palm oil fruit. As a permanent crop, palm oil has an average evapotranspiration demand of 1500 mm, which is much larger than that typical of other annual crops such as rice or maize. Oceania also shows different trends in water and land use, but in the opposite directions: while the *LF* has increased by 151% over the past decades, *WF* has increased by 131%. This is probably a sign

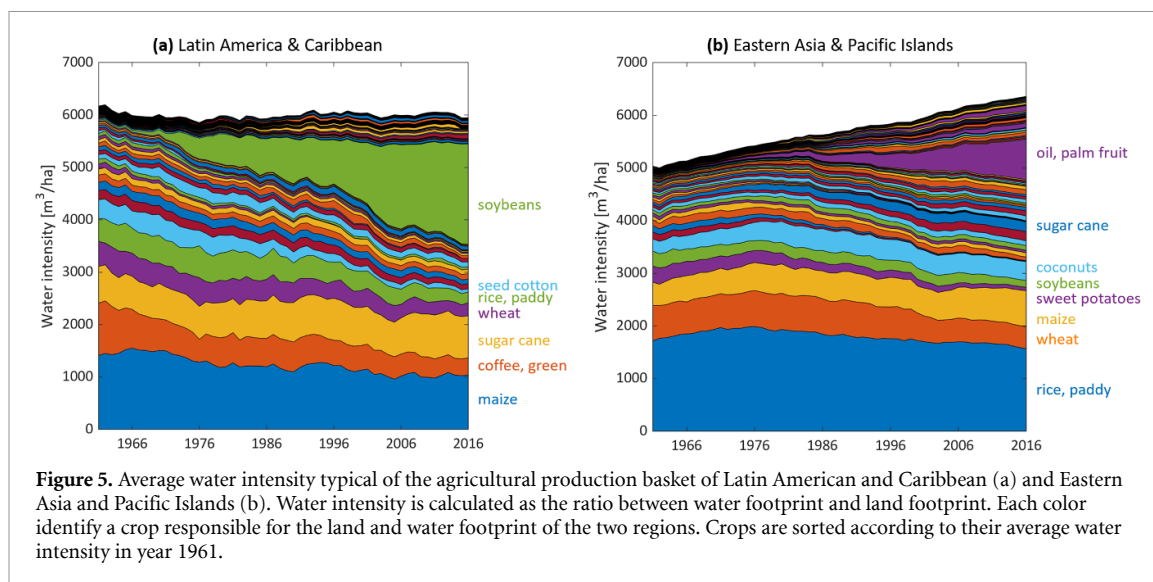
**Table 1.** Relative variation of harvested area or land footprint (*LF*) and total water footprint (*WF*) in year 2016 with respect to 1961 at the regional scale. The key to the acronyms of the regions' names is provided in figure 2(a).

region	<i>LF</i>	<i>WF</i>
Sub-Saharan Africa	1.62	1.63
Middle East and Northern Africa	1.20	1.14
Eastern Asia and Pacific islands	0.51	0.88
South Asia	0.33	0.46
Eastern Europe and Central Asia	−0.17	−0.15
Europe	−0.22	−0.58
Northern America	0.24	0.23
Latin America and Caribbean	1.31	1.25
Oceania	1.51	1.31

of the transition toward less water-demanding crops. Finally, Europe shows a decreasing trend in both *WF* and *LF*, suggesting a lessening of the pressure on both the natural resources. However, the pressure release is more important for water resources (−58% for total *WF*) than for lands (−22%).

#### 4. Conclusions

Future demand of calories and proteins is expected to more than double by 2050 [2] due to population growth, urbanization expansion, per capita increases in income, and changing diet habits. Producing more nutrients with less resources, while preserving the natural ecosystems, is a key challenge for the future [40, 42] also in accordance with the Sustainable Development Goals (in particular, SDGs 2, 6, 15 [43]). In this study, we show that agricultural productivity has kept increasing over the past decades, despite the slowdown or stabilization of the yield of some crops (e.g. [14]). We find that the global nutrient land productivity has increased by 2.7–2.9% per year for calories and proteins, and between 2.1% and 4.6% for fats. On a global average, we found that humans can rely on larger amounts of calories (+1640 kcal/cap/day), proteins (+70 g/cap/day), and fats (+55 g/cap/day) production. The adoption of intensification and extensification processes have been heterogeneous across the regions. In Sub-Saharan Africa and Middle East and North Africa cropland expansion over natural vegetation and savanna was the dominant practise. Conversely, in other regions intensification through the adoption of agricultural inputs and high-yielding crop varieties played a major role in rising the macronutrient production, while in Latin American and Caribbean there has been a twin adoption of the two practises. Importantly, we have shown that cereals and pulses cultivation have been dominated by an intensification process generally associated with a stable or decreasing land footprint with few exceptions for, e.g. maize and lentils. Conversely, fruit and nut crops mostly shown an increased land



**Figure 5.** Average water intensity typical of the agricultural production basket of Latin American and Caribbean (a) and Eastern Asia and Pacific Islands (b). Water intensity is calculated as the ratio between water footprint and land footprint. Each color identify a crop responsible for the land and water footprint of the two regions. Crops are sorted according to their average water intensity in year 1961.

footprint generally accompanied by a decreased land productivity. Finally, oil crops have undergone to a coupled increase of both productivity and footprint.

This outcome confirms important patterns in the temporal variability of the productive regime, whose rate of variations has also been levelled-off by population growth rate in developing regions (e.g. in Sub-Saharan Africa and South Asia), where the daily productive regime has remained stable around a supply of 3000 kcal/day/cap *versus* the 5000 and 8000 kcal/day/cap reached in Eastern Asia and Pacific islands and Latin America and Caribbean.

Finally, our findings suggest that past production growth has been responsible for increasing the Water Footprint by 50% worldwide, either following the pattern of land footprint in some regions (e.g. Sub-Saharan Africa, Latin America and Caribbean) or departing from them in other ones (e.g. Eastern Asia, Europe, Oceania) due to a transition from less water demanding crops to more water demanding crops in the agricultural production basket. On average, we found that the water footprint per hectare (or water intensity) has increased by 14%. This analysis has provided preliminary insights on the importance of the production basket composition in determining a different average water intensity over the cultivated land of a certain region. Such outcomes provide ground to deal with climate change issues impacting crop transpiration demand and water availability patterns, hence confirming the benefits of a proper optimization of the production basket in terms of water saving and nutrient supply [44, 45].

Our study provides evidence of the complex framework surrounding agriculture, where the Bourlaug hypothesis, stating that improvements in agricultural technology enable farmers to produce more food from a given piece of land without leading to increased deforestation, does not hold true for all crops (e.g. soybean, rapeseed) and regions (e.g.

Latin America and Caribbean). This could be partially explained by the Jevons paradox suggesting that the consumption of a resource, land or water in our study, can increase despite the enhanced productivity. Future analyses may explore with greater details on sub-national level the existence of synergies and trade-off between land and water, intensification and extensification, in order to find thresholds limiting the impacts of agriculture on the natural ecosystem.

## Acknowledgment

Authors acknowledge funding support provided by the European Research Council (ERC) through the project ‘Coping with water scarcity in a globalized world’ (ERC-2014-CoG, project 647473)

## ORCID iD

Marta Tuninetti  <https://orcid.org/0000-0003-2619-8783>

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