Trading off natural resources and rural livelihoods. A framework for sustainability assessment of small-scale food production in water-limited regions

Francesca Recanati[a], Andrea Castelletti[a], Giovanni Dotelli[b], Paco Melià[a]*

[a] Dipartimento di Elettronica, Informazione e Bioingegneria, Politecnico di Milano, via Ponzio 34/5, 20133, Milano, Italy

[b] Dipartimento di Chimica, Materiali e Ingegneria Chimica "G. Natta", Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milano, Italy

* Corresponding author. Tel.: +390223993680; fax: +390223993412

E-mail address: paco.melia@polimi.it (P. Melià).

Recanati F., Castelletti A., Dotelli G., Melià P. (2017) Trading off natural resources and rural livelihoods. A framework for sustainability assessment of small-scale food production in water-limited regions. *Advances in Water Resources* 110: 484-493.
DOI: 10.1016/j.advwatres.2017.04.024
http://www.sciencedirect.com/science/article/pii/S0309170817304396

Abstract

Enhancing local production is key to promoting food security, especially in rural households of low-income countries, but may conflict with limited natural resources and ecosystems preservation. We propose a framework integrating the water-food nexus and a sustainable livelihoods perspective to assess small-scale food production in water-poor regions. We demonstrate it by assessing alternative production scenarios in the Gaza Strip at different spatial scales. At the scale of a single farm, there is a clear conflict among objectives: while cash crops ensure good incomes but contribute scarcely to domestic protein supply, crops performing well from the nutritional and environmental viewpoint are among the worst from the economic one. At the regional scale, domestic production might cover an important fraction of nutritional needs while contributing to household income, but water scarcity impairs the satisfaction of food demand by domestic production alone. Pursuing food security under multiple constraints thus requires a holistic perspective: we discuss how a multidimensional approach can promote the engagement of different stakeholders and allow the exploration of trade-offs between food security, sustainable exploitation of natural resources and economic viability.

Keywords

Domestic food production; environmental impact indicators; food security; sustainable agriculture; water footprint; water-food nexus

1. Introduction

Small-scale agriculture is the principal source of food and income for rural households in developing economies (Byerlee et al., 2008; FAO et al., 2014). People living in rural areas are also among the poorest and hungriest in the world (FAO et al., 2015). Growth in agricultural productivity is argued to be key to close current and projected yield gaps and improve food security (FAO and WFP, 2007; OECD and FAO, 2015), as long as the yields currently realized in high-income countries are attained globally (Mueller et al., 2012; Rulli and D'Odorico, 2014; West et al., 2014). However, the unsustainable intensification of agricultural production can lead to overexploitation of natural resources and degradation of ecosystems (Bonsch et al., 2015; Godfray et al., 2010; Tilman et al., 2001), ultimately affecting agricultural productivity due to loss of supporting ecosystem services (Power, 2010).

Undergoing global change exacerbates this conflict (Gerland et al., 2014; Iglesias and Garrote, 2015): the combined action of climate change and ecosystem degradation is expected to reduce the availability of freshwater and productive land, while food demand will increase due to projected population growth. This is further aggravated by the heterogeneous distribution of natural resources, which can cause mismatches between demand and availability, affecting in particular rural households in warmer regions (Butler et al., 2014; Krishnamurthy et al., 2014). Although at the global scale freshwater and land requirements by current agricultural practices might be compatible with reserves (Rost et al., 2008; Siebert and Döll, 2010), at the regional scale shortages are common and will have serious impacts on food security (Mclaughlin and Kinzelbach, 2015).

The spatial decoupling of food production and consumption driven by increasingly globalized international trade is expected to mitigate the effects of spatiotemporal variation in food availability worldwide (Allan, 2001; Fader et al., 2013; Gilmont, 2015). Nevertheless, the ultimate impact of trade intensification on global food security is difficult to evaluate (Marchand et al., 2016). In addition, low-income populations and, in particular, rural households in developing economies are still mostly dependent upon subsistence agriculture and local resources (World Bank, 2008), taking little or no advantage from global trading (IFAD, 2011; Ortiz and Cummins, 2011; Mclaughlin and Kinzelbach, 2015). Indeed, recent analyses suggest that globalization may have reduced the social resilience to water limitations by favouring the propagation of water crises (e.g. D'Odorico et al., 2010). For these reasons, solutions that both enhance rural livelihoods and preserve ecosystems and natural resources are key to pursuing food security along sustainable pathways (Biggs et al., 2015; Peng et al., 2015; UN, 2015).

Understanding the inextricable link between water and food security requires a nexus approach, i.e. a holistic perspective integrating the different facets of the problem within a common conceptual framework. During the last fifteen years, a large body of literature has flourished around the central concept of water-food nexus, in most cases extended to include also energy (Finley and Seiber, 2014) and, sometimes, encompassing additional environmental components such as land (e.g. Kumar et al., 2012; Ringler et al., 2013; Rulli et al., 2016), climate (Beck and Villarroel Walker, 2013), and ecosystems (de Strasser et al., 2016; Karabulut et al., 2016).

In this work, we adapt and integrate existing assessment frameworks into a nexus approach with the aim of investigating the potential of agricultural systems to ensure food security and enhance rural livelihoods in a sustainable manner (Biggs et al., 2015; UNEP, 2013), with particular reference to contexts characterized by limited availability of natural resources. We specifically focus on domestic production, intended here as the fraction of small-scale agricultural production which is directly consumed on site by households. Based on a set of quantitative indicators, we comparatively assess alternative production scenarios in terms of their contribution to (i) food supply and (ii) economic conditions of rural households, as well as (iii) their impact on natural resources.

We demonstrate the approach on the sustainability assessment of domestic food production in the rural Gaza Strip. This region provides an extreme, yet paradigmatic case study in this respect: agricultural production is strongly constrained by the scarcity of freshwater resources and severely limited trading possibilities (Butterfield et al., 2000; EWASH, 2011). The geopolitical situation with the blockade imposed by Israeli and Egyptian authorities (OCHA, 2015) is a further pressure element. The United Nations have identified food insecurity and freshwater scarcity as the most critical issues in the Gaza Strip (UNDP, 2011). In this context, a quantitative assessment of alternative food production scenarios from an integrated perspective is a crucial step to inform policy making in the region. In our analysis, we compare a set of food production scenarios (combining horticulture, animal husbandry and aquaculture) that exemplify some of the most widely implemented small-scale practices in the Gaza Strip. First, we assess the selected scenarios at the scale of a single farm in terms of protein supply, freshwater consumption, and income. Then, we broaden the perspective of the analysis to the regional scale and use those scenarios to appraise the potential contribution of domestic food production to rural livelihoods (food supply and income) and evaluate the environmental balance between demand and supply of water for food production.

2. Materials and methods

2.1. Methodological framework

To assess the sustainability of domestic food production and its potential contribution to fostering food security of rural households, we evaluate the consequences of alternative production scenarios along the three basic dimensions of sustainability (environmental, social and economic) through a set of quantitative indicators defined over two spatial scales (farm level and regional level). The conceptual framework in which the indicators are organized (Fig. 1) integrates the water-food nexus (FAO, 2014a) through the environmental dimension, with a specific focus on the impacts of food production on freshwater resources, and the social dimension, by looking at the nutritional aspects. The framework incorporates also a sustainable livelihoods perspective (Biggs et al., 2015) through the economic dimension, focusing in particular on the local scale (FAO, 2014b). The last two dimensions are directly linked to food availability and access to food (FAO, 2014a), two major premises to food security that are inextricably linked in rural areas where agricultural production, besides being a major source of income, is still the major source of food. The proposed approach is novel in that it integrates aspects that have never been included in a single framework before. In fact, nutrition has usually been excluded from assessments of agricultural sustainability, which have made use of a wide range of environmental indicators but of a much narrower set of economic and social indicators (Latrouffe et al., 2016). In addition, where social aspects have been considered, these have mainly included labour conditions, psychological well-being or health (e.g. FAO, 2014b; Horrigan et al., 2002; Lebacq et al., 2013), without linking well-being directly to food security. On the contrary, dietary assessments have mainly focused on nutritional aspects (Donini et al., 2016), while putting less emphasis on the sustainability of the production process (but see, for instance, Gustafson et al., 2016). In the present framework, nutrition is put in the foreground together with the environmental and economic aspects.

The specific indicators used for the analysis at the two different scales are described in detail in sections 2.4 and 2.5. Here, we delineate the general framework that supports the choice of the indicators. According to ISO standards (ISO, 2006), environmental sustainability assessments should encompass both natural resources appropriation and environmental impacts caused by emissions into air, water and soil. Focusing primarily on the water dimension, we use the water footprint concept (Hoekstra et al., 2011) to include both water consumption and impacts on water quality (Pellicer-Martínez and Martínez-Paz, 2016). After quantifying the water footprint of alternative food production scenarios at the farm scale, we compare water appropriation for household production with freshwater supply at the regional scale. To broaden the scope of the analysis, we assess food production scenarios also in terms of land appropriation (another key aspect of human pressure on natural resources) and contrast the results with the current availability of agricultural land. We describe the analysis on land appropriation only in the supplementary material (sections S1.2.2 and S2.3.2), because the main focus of the work is on the water-food nexus.

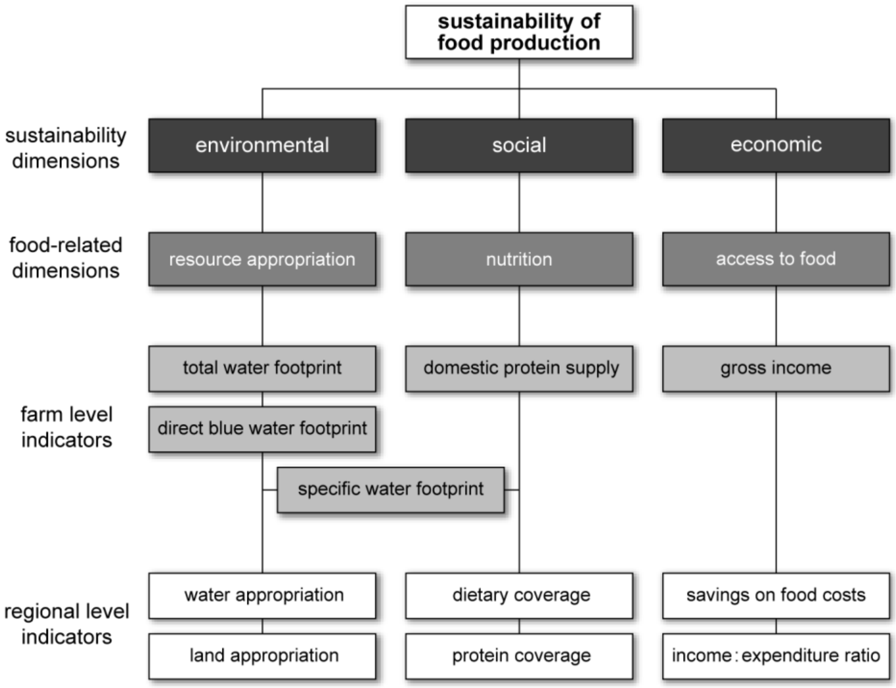

Fig. 1: Framework for the sustainability assessment of alternative food production scenarios. The achievement of the general objective (sustainable food production) is measured along three basic dimensions: environmental, social and economic. These, in turn, are directly associated with specific components of both the water-food nexus and food security.

As for nutrition, we consider both the dietary coverage of different food categories, and the intake of specific nutrients such as proteins, as suggested by Gibson (2005). Domestic production is then compared among scenarios and contrasted with national consumption statistics and nutritional guidelines. The economic benefits of domestic food production comprise both the opportunity to reduce household expenditures on food and the income deriving from selling the production that is not directly consumed by the household (Singh et al., 2009). Savings on food and incomes from crop sale under different production scenarios can eventually be compared with national statistics.

2.2. Case study

The Gaza Strip is a small, self-governing portion of the Palestinian territories along the eastern coast of the Mediterranean Sea, with an overall area of 365 km^2. Despite its small dimensions, almost two million people live in the area, making it one of the most densely populated regions in the world. Limited land and freshwater availability are crucial: population density is greater than 5000 person/km^2, and overall freshwater supply is far below the water resources available in other countries of the Near East. In 2005, the total amount of renewable water resources was on average 51 m^3/yr per person (while it ranged between a minimum of 161 m^3/yr in Jordan and a maximum of 1259 m^3/yr in Lebanon; FAO, 2017). During the last decade, however, the deterioration (in terms of both quantity and quality) of water resources, paralleled by the continuous increase in water demand caused by population growth, has further decreased water availability in the Gaza Strip to just 33 m^3/yr per person (PWA, 2014). Resource scarcity strongly constrains internal food production, and high population density further aggravates the imbalance between food demand and supply. Agriculture is a key sector in the region, with smallholder farms providing a major contribution to the regional food supply (FAO, 2005). However, wages in the agricultural sector are below the average of all economic sectors (PCBS et al., 2013). In addition, restricted access to fertile land, freshwater and markets limits production and exports (FAO, 2005). As a consequence, the commercial balance of the Palestinian territories is strongly shifted toward imports, with a value of exports amounting to only 17% of that of imports (PCBS, 2015a). Despite the fact that farmers have direct access to food through domestic production, during the last decade more than 50% of the rural population has been affected by food insecurity (PCBS et al., 2013). The main causes are restrictions to movement of people and goods, impairing physical access to food (FAO, 2003), and the lack of economic access to food due to unemployment and low income (FAO and WFP, 2007). This last aspect is especially critical in the region: in 2012, Palestinian households spent 50% of their cash income on food, with a proportion attaining 55% among food insecure people (PCBS et al., 2013). Economic constraints impair, in particular, access to expensive animal products, making it difficult to achieve safe levels of protein intake for the rural population (FAO, 2003).

Enhancing domestic food production through sustainable agricultural techniques, which do not exacerbate the scarcity of natural resources affecting the region, is thus crucial to alleviate food insecurity in rural areas of the Gaza Strip. We applied our assessment framework (Fig. 1) to evaluate how domestic food production can contribute to secure food for the local rural population, while concurrently addressing the environmental and economic sustainability of different production scenarios. The reference unit of the assessment is an average agricultural holding in the Gaza Strip, as described in the following section.

2.3. The farm model

A model describing an "average" farm of the Gaza Strip has been built with the help of the Italian NGO Overseas (www.overseas-onlus.org), which has been active in the area since 2009. A survey conducted by Overseas among 30 farmers was used to gather information about the implementation of small-scale agriculture. Local agronomists of the Union of Agricultural Work Committees (UAWC; uawc-pal.org) supported the development of the farm model and of food production scenarios providing field data and helping validate the literature data used to fill main knowledge gaps. The representativeness of the farm model for the whole region was then verified through an extensive review of the institutional reports periodically released by the Palestinian Central Bureau of Statistics (PCBS; www.pcbs.gov.ps).

The general features of the reference farm are the following:

1. the extension is equal to 9000 m^2 (9 dunum), which is the average size of agricultural holdings in the Gaza Strip (PCBS, 2005), 8,500 of which are dedicated to agriculture;
2. the farm includes three family units, composed of six people each (the average size of rural households in the Gaza Strip ranged, with a decreasing trend, from 6.9 to 5.7 during the last 2 decades, PCBS, 2015b);

3. food production in the farm is based on horticulture, animal husbandry, and aquaculture.

Horticulture is a major income source for rural households in the Gaza Strip (68% of the agricultural holdings in the area; PCBS and PNA, 2012). The crops considered in the analysis were selected by local agronomists and Overseas operators as the most representative of the region. They include both cash crops, i.e. export-oriented crops, like tomatoes and cucumbers, and crops intended mainly for domestic consumption, such as lentils. Collectively, they represent ca. 70% in weight (PCBS, 2012b) and 75% in monetary value (PCBS, 2012a) of the overall vegetable production of the Gaza Strip. The different crops are combined in rotation systems; among these, we have considered five that are illustrative of actually implemented agricultural practices.

Livestock raising also contributes significantly to the rural economy of the region. The most commonly reared species include poultry, sheep and goats (PCBS, 2012a). According to data gathered from local farmers and agronomists, we consider an average animal asset of 15 hens (providing eggs and meat) and 7 sheep (providing milk and meat). Animals graze in the courtyard, which is assumed to cover an area of about 200 m^2, and occasionally in the restricted area running along the Israeli border. Fish production of Nile tilapia (*Oreochromis niloticus*) from small-scale aquaculture is also included in the scenarios. The expansion of small-scale aquaculture in the Palestinian territories is fostered by aid institutions and NGOs, with the aim to compensate the decreased availability of fish proteins caused by the restrictions Palestinian fishers are subjected to. *O. niloticus* is native to the Nile basin and coastal rivers of Israel and occurs in a wide variety of freshwater habitats, but tolerates brackish water and a wide temperature range; for these reasons, and thanks to its high reproductive potential, it is widely used for farming in tropical countries, although it can cause adverse ecological impacts outside its original distribution range. Nile tilapia farming can take place in irrigation ponds; in accordance with data provided by agronomists and Overseas operators, each pond has, on average, a surface area of 50 m^2, is 1.6 m deep, serves an irrigated area of 3,000 m^2 and produces 400 fish per year.

We consider five alternative food production scenarios (Fig. 2), obtained by combining the five crop rotation systems with animal production (husbandry plus aquaculture) for domestic consumption. Further details about the farm model are given in the supplementary material (section S1.1).

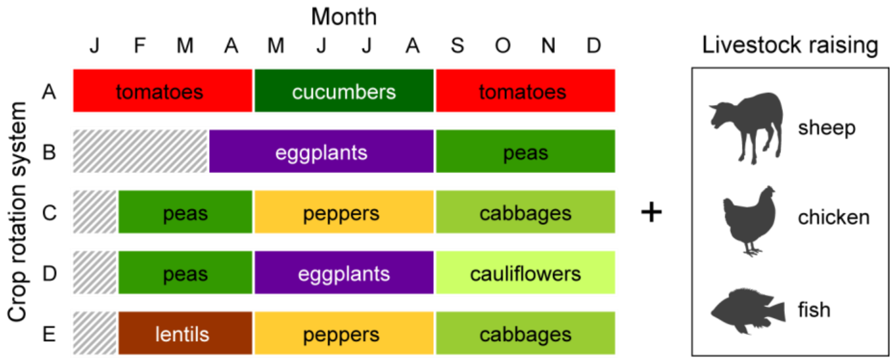

Fig. 2: Food production scenarios are composed by alternative crop rotation systems (A–E) plus animal production from husbandry and aquaculture (the same for all scenarios). Crops included in system A (tomatoes and cucumbers) are grown in greenhouse, while the others are grown in the open field. Hatched bars indicate fallow periods.

2.4. Analysis at the farm scale

In the first part of the analysis, we contrast alternative food production scenarios at the scale of a single farm. Following the methodological framework described in section 2.1, we assess the performance of each scenario with the following indicators (Table 1, *Farm scale*): *domestic protein supply*, *total water footprint*, *direct blue water footprint* and *gross income*. In addition, we compare protein-rich food products in terms of *specific water footprint* (i.e. water footprint per kilogram of protein produced). The reference time frame for the assessment is one year.

Domestic protein supply measures the contribution of domestic production to household nutrition. Proteins play a crucial role with respect to nutritional aspects (Latham, 1997), and the minimum safe level of protein intake is difficult to achieve in the Gaza Strip (FAO, 2003): for this reason, protein intake is considered a key indicator of food security.

Water footprint (Hoekstra et al., 2011) is chosen as a comprehensive measure of water resources appropriation. Its value is the sum of three terms: (i) blue water footprint (surface- and groundwater), (ii) green water footprint (rainwater), and (iii) grey water footprint (freshwater required to dilute the pollutant load to meet water quality standards). In our analysis, we use the *total water footprint* (sum of the freshwater used on site, and of that used along the life cycle of all production inputs), as well as the *direct blue water footprint*, to specifically focus on freshwater withdrawn and consumed for food production within the Gaza Strip.

Then, we combine nutritional and environmental aspects by calculating the *specific water footprint* of protein-rich food products (characterized by protein content >5%, hence animal products and legumes). As sheep and chicken provide more than one product (milk and meat, eggs and meat, respectively), water consumption is allocated according to a mass criterion.

Gross income provides a measure of the importance of domestic food production for the household economy. It is calculated as the income deriving from the sale of vegetables produced within the farm, i.e. the fraction which is not directly consumed by the household, on the basis of market prices provided by the Palestinian Central Bureau of Statistics. A detailed description of how the different indicators used for the assessment at the farm scale were calculated is provided in the supplementary material (section S1.2).

2.5. From the single farm to the regional scale

In the second part, we broaden the perspective to the regional scale and assess the potential contribution of domestic food production to secure food to the rural population of the whole Gaza Strip, along with its impact on natural resources. Indicators calculated at the farm scale are transformed into values per capita by dividing them by the number of persons living in the farm (18, i.e. 3 families × 6 people per family). According to the proposed framework (section 2.1), we use the following indicators encompassing the three dimensions of the analysis (Table 1, *Regional* *scale*): *dietary coverage*, *protein coverage*, *water appropriation*, *savings on food costs* and *income-to-expenditure ratio*.

As regards the nutritional dimension, *dietary coverage* contrasts the fraction of domestic production allocated to household consumption, disaggregated by food category, with average consumption patterns in the Gaza Strip (PCBS, 2011), while *protein coverage* compares domestic protein supply with minimum safe levels of protein intake recommended by international agencies (FAO et al., 1991; SINU, 2014). As for the environmental dimension, *water appropriation* is used to compare requirements of water to the availability in the region. This indicator is measured as the direct blue water footprint per capita for domestic food production, and is contrasted with the availability of renewable freshwater in the Gaza Strip (PWA, 2014). Regarding the economic dimension, *savings on food costs* are calculated as the difference between average expenditures on food in the Gaza Strip (PCBS, 2011) and the monetary value of domestic production that is consumed by the household, while the *income-to-expenditure ratio* is the ratio between gross income, obtained by selling the production not consumed by the household on local markets, and the residual expenditure on food, net of savings guaranteed by domestic production. Details about the estimation of the indicators used for the assessment at the regional scale are given in the supplementary material (section S1.2).

Table 1: Indicators used for the analysis at the farm scale and at the regional scale

Indicator (units)	Short description	Data (source: see notes)
Farm scale		
Domestic protein supply (kg/year)	annual production of proteins from domestic horticulture and husbandry	crop yield[1]; protein content[2]
Total water footprint (m^3/year)	total water consumption for domestic food production (including the life cycle of external inputs)	water consumption[1]; water footprint of products[3]
Direct blue water footprint (m^3/year)	annual withdrawal from local surface and groundwater sources for domestic food production	water consumption[1]; water footprint of products[3]
Specific water footprint (m^3/kg)	water footprint per unit of protein	domestic protein supply[1,2]; total water footprint[1,3]
Gross income (USD/year)	annual income from crop sale (net of the portion consumed by the household)	crop yield[1]; price of food commodities[4]
Regional scale		
Dietary coverage (%)	proportion of dietary needs covered by domestic production	crop yield[1]; average consumption per food type[5]
Protein coverage (%)	proportion of protein requirement covered by domestic production	domestic protein supply[1,2]; recommended protein intake[6]
Water appropriation (m^3 per capita)	per capita water footprint for domestic food production	water footprint[1,3]
Savings on food costs (USD/year)	difference between average expenditure on food and value of domestic production	price of food commodities[4]; average expenditure on food[5]
Income-to-expenditure ratio (%)	ratio between gross income and expenditure on food	gross income[1,4]; average expenditure on food[5]

[1] (Overseas and UAWC agronomists)

[2] (FAO and USDA, 1982)

[3] (Mekonnen and Hoekstra, 2011)

[4] (PCBS, 2016a, 2016b)

[5] (PCBS, 2011)

[6] (FAO et al., 1991; SINU, 2014)

3. Results

3.1. Comparing food production scenarios at the farm scale

The results of comparing alternative food production scenarios are summarized in Fig. 3, and presented in further details in section S2.2 of the supplementary material. In the parallel coordinate plot, each axis represents a different objective, and each scenario is indicated by a line: the intersection between an axis and the line identifying a specific scenario indicates the relative performance of that scenario with respect to the objective represented by the axis. Performances are normalized, i.e. the original values of each indicator are mapped between 0 and 1. The normalized value of an indicator is hence calculated as $z = (x - x_{\text{worst}}) / (x_{\text{best}} - x_{\text{worst}})$, where x is the raw value of the indicator for the specific scenario, while x_{worst} and x_{best} are the raw values corresponding to the worst and best-performing scenarios, respectively. Thus, the best value is the maximum one for economic income and protein supply, while it is the minimum one for the two water footprints. In this way, the direction of preference for each indicator is always upward (i.e. the ideal solution would be a horizontal line running along the top of all the axes).

Fig. 3 points out a clear conflict emerging among nutritional, environmental and economic domains. For instance, scenario A, a greenhouse crop rotation of tomatoes and cucumbers, combined with animal production, is the best in economic terms, due to the high yield of cucumbers and tomatoes. It performs very well also in terms of total water footprint, being only slightly worse than scenario E (lentils, peppers and cabbages). However, it provides by far the lowest domestic protein supply due to the absence of legumes. On the contrary, scenario E is the best alternative in terms of water footprint and is second only to scenario D (peas, eggplants and cauliflowers) in terms of protein supply, but the associated income is among the lowest. Finally, while scenario B (rotation between eggplants and peas) performs very well with respect to blue water footprint, it is the worst in terms of gross income.

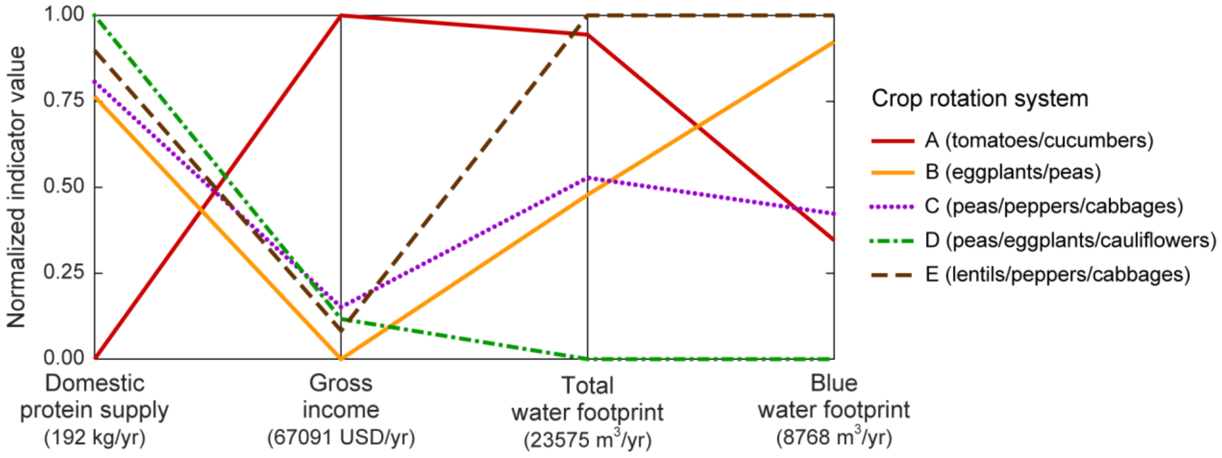

Fig. 3: Comparison of five alternative food production scenarios (see Fig. 2). Indicators (see Table 1 for more details) are normalized over their minimum-maximum range, with 0 corresponding to the worst scenario and 1 corresponding to the best one. The best raw value of each indicator is indicated below the corresponding label.

Looking at the specific water footprint of each protein-rich food product (Fig. 4), it emerges that fish proteins have the highest blue water footprint, due to the large amount of water evaporating from ponds (estimated to be about 125 m^3 per year per pond). Proteins from peas also have a high blue water footprint, due to irrigation, and a relatively high grey water footprint caused by the use of fertilizers. Sheep proteins have the highest green water footprint, which is associated to rainwater falling on grazing grounds. In terms of total direct water footprint, proteins from sheep milk and peas have the highest environmental impacts, while proteins from chicken and lentils have the lowest.

The inclusion of the indirect footprint allows accounting for water consumption associated to products used as inputs to the production process. They are all imported from outside the Gaza Strip, so their production does not have a direct impact on local water resources. The indirect water footprint is relevant for chicken and fish products (ranging between ca. 20 and 40 m^3 of water per kg of protein), due to the use of concentrate feeds, while it is negligible for sheep products and legumes.

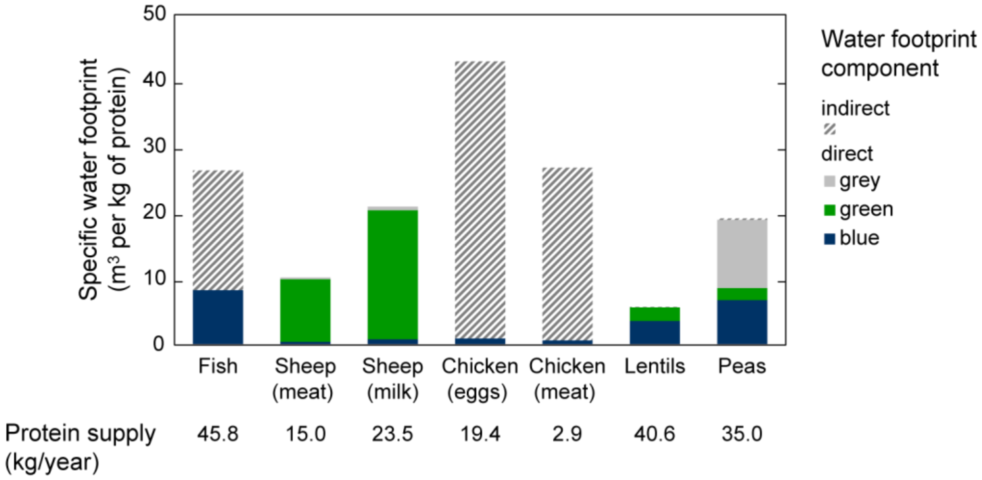

Fig. 4: Comparison between specific water footprints (disaggregated by component) of protein-rich food products. The total contribution of each product to protein supply is also indicated.

3.2. Food production vs. resource scarcity from a regional perspective

Table 2 compares dietary coverage under the different production scenarios considered, i.e. the fraction of the main food groups covered by domestic production, with average food consumption patterns in the Gaza Strip. Results highlight that rural households could potentially rely on domestic production for the supply of some major food groups (eggs, dairy, vegetables and legumes), while the demand for meat and fish would not be entirely satisfied. Note that some components of the diet, such as fruits, cereals, fats and tubers, were not included in the analysis. Cereals, in particular, were not considered, despite being an important source of proteins in many Mediterranean countries (Halkjaer et al., 2009), because in the Gaza Strip they are generally imported from abroad (FAO, 2005).

Results regarding protein coverage are reported in Table 3, which shows that domestic production would guarantee about half of the recommended intake, with most of the proteins being of animal origin (from 55% to 81%, depending on the scenario). The main contributions come from fish (25–35% of the total supply) and legumes, whose inclusion into the crop rotation allows a remarkable increase of domestic protein supply with respect to scenario A (between 36% and 47%, depending on the scenario) that includes only cash crops.

Table 2: Comparison between estimated domestic production of the model farm and average consumption patterns of selected food groups in the Gaza Strip (PCBS, 2011).

Food group	Estimated domestic production per capita (kg/year)	Average consumption per capita in the Gaza Strip (kg/year)	Dietary coverage (%)
Meat and Fish	21.0	50.4	42
Eggs	8.9	8.6	103
Dairy[1]	22.1	15.2	145
Fresh vegetables	146.0	131.1	111
Fresh legumes[2]	27.4	2.0	1337
Dried legumes[3]	9.1	5.7	161

[1] Estimated domestic production includes only sheep milk, while the classification used by PCBS and PNA (PCBS, 2011) includes milk (>80%), cheese and yoghurt from different sources (cow, goat, sheep).

[2] Included only in scenarios B, C and D.

[3] Included only in scenario E.

As concerns environmental sustainability, results outline a critical picture with respect to freshwater in the Gaza Strip (Fig. 5). Water appropriation, i.e. freshwater demand for food production, would be higher than supply (33 m^3/year per capita; PWA, 2014) under all production scenarios. The amount of freshwater used to self-produce the vegetables and to raise animals and fish consumed by one person would, in fact, exceed (by 15% up to 163%) the average availability in the region (Fig. 5a).

Table 3: Estimated domestic protein supply compared with the recommended protein intake (50 g per person per day).

Crop rotation system	Per-capita protein supply (g/day)	Protein coverage (%)	Protein source animal (%)	vegetal (%)
A	20.0	40	81	19
B	27.1	54	60	40
C	27.5	55	59	41
D	29.3	59	55	45
E	28.4	57	57	43

As for the economic dimension, domestic production has the potential to guarantee savings on food costs from about 52 USD/month per capita reported by PCBS reports, to about 33 USD/month. The main savings are those related to meat and fish (about −40%, from 16.4 to about 9.6 USD/month per capita), dairy and eggs (no expenditure, instead of 3.9 USD/month per capita), and vegetables and legumes (depending on the crop rotation considered, from 9.7 to about 1.7–2.0 USD/month per capita, with an average saving of about 80%). Overall, the income-to-expenditure ratio for food ranges between a minimum of 11% (scenario A) and a maximum of 47% (scenario B). More detailed results are reported in section S2.3.3.

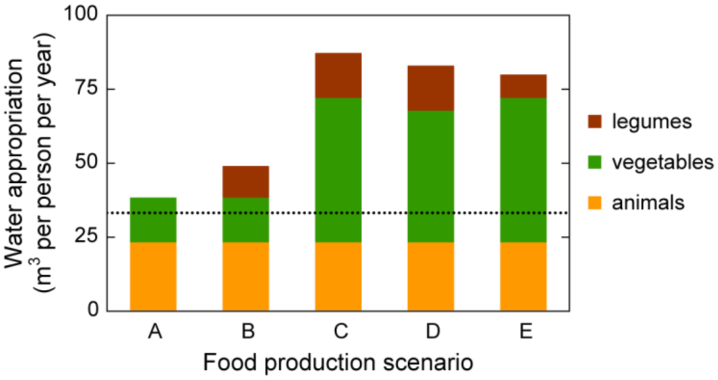

Fig. 5: Water appropriation for domestic food production. Letters indicate the different production scenarios (see Fig. 1). The dotted horizontal line indicates current water availability in the Gaza Strip (33 m^3 per person per year).

4. Discussion

4.1. Case study

The application of the assessment framework presented in section 2.1 to the Gaza Strip case study allowed us to perform a sustainability assessment of domestic food production at two different scales. The comparison of food production scenarios at the farm scale highlights a critical, multidimensional nexus between preserving natural resources and enhancing rural livelihoods. The choice to grow high-yield cash crops has the potential to improve incomes, but performs poorly, at least in relative terms, when assessed from an environmental or a nutritional perspective, while other crop rotation systems have lower economic performance but show lower impacts on freshwater demand and higher performance from a nutritional viewpoint. With specific reference to protein-rich food products (i.e. animal products and legumes), it is interesting to point out their different impacts on water resources at different geographic levels. For instance, legumes have a direct water footprint (hence affecting local water resources) related to irrigation (blue footprint) and the use of fertilizers (grey footprint), sheep products (meat and milk) have a relevant green footprint associated to grazing, while aquaculture has a direct blue footprint due to water evaporating from ponds, where a minimum water level must be maintained to ensure fish survival. On the contrary, the use of imported concentrate feeds contributes to the indirect water footprint (thus resting on alien water resources) of both aquaculture and poultry rearing.

When the scope of the analysis is broadened to the regional scale, results suggest that domestic production has the potential to provide a considerable contribution to rural livelihoods in the Gaza Strip, benefitting both food availability (by enhancing dietary coverage) and access to food (by increasing income and reducing expenditures on food). In particular, locally produced food would completely cover the current demand for vegetables, legumes, eggs and dairy, and a significant fraction of the demand for meat and fish. Between 40 and 60% of the recommended protein intake (depending on the considered production scenario) would be guaranteed by protein-rich food produced on site. From the economic viewpoint, besides providing an important source of income, domestic food production may reduce expenditures for food by about 35% compared to current expenditures in rural households. However, while pursuing food security in the region appears to be economically viable, the environmental balance is critical with respect to the current availability of freshwater. The annual withdrawal needed to provide Gazan people with the food products listed in Table 2 alone would largely exceed, by up to 160%, the total freshwater availability, making the unbalance between demand and supply severe. A similar conclusion can be reached with respect to agricultural land, since most scenarios would require the appropriation of an area larger than the one actually available in the region (see results reported and discussed in section S2.3.2, supplementary material).

It is important to note that our assessment is based on several simplifying assumptions. The food production scenarios considered in the analysis exemplify agricultural and husbandry practices that are actually and widely implemented in the Gaza Strip, but their extension to the regional scale is merely illustrative. Given the relatively limited number of food products involved, our results should be considered as an underestimate of the actual burden that the pursuit of food security through domestic production would impose on the natural resources of the Gaza Strip. In addition, there are other competing uses of water (domestic and industrial) that are not accounted for in the analysis, hence the actual amount of freshwater available for agricultural uses would necessarily be lower than our reference point set to 33 m^3/yr per person. Nevertheless, even if all the available water were allocated to agriculture, it would not be sufficient to cover the entire demand. In addition, data regarding the productivity of crops and animals, their water demand, as well as their economic value, albeit realistic and based on local knowledge and evidence from the literature, may be subject to variation over space and time that could affect results significantly. In particular, uncertainty affecting yield and price dynamics might influence the robustness of our conclusions. Extensive changes in the composition of the crop mix on a wide geographical scale may lead to changes in market prices and a different economic equilibrium; the analysis of the socio-economic consequences of these changes, however, is outside the scope of this work.

Despite all these caveats, the picture emerging from the analysis clearly points out the complexity of the food-water nexus in the region, and shows that there is no single optimal solution for this multi-constrained problem. Moreover, the present geopolitical context makes it impossible to guarantee food security through the import of food and/or resources from abroad. If the current situation does not change toward improved mobility of goods and people, and enhanced access to water resources and agricultural land of good quality, there are very little chances to achieve food security in the Gaza Strip. Projected future scenarios of sustained population growth, rapid urbanization, resource depletion and ecosystem degradation will further exacerbate the problem (Al-Yaqubi et al., 2007).

Expanding the current water capacity (e.g. via seawater or brackish water desalination, or through water transfer) would contribute to fill the significant gap between the overall freshwater demand and its availability in the region, but appears extremely difficult in the short term given the geopolitical context and the financial investments required (Hilles and Al-Najar, 2011). For this reason, at least in the short term, the annual availability of renewable freshwater represents a critically limiting factor for any human activity in the Gaza Strip. Water scarcity strongly limits the enhancement of food security and the reduction of the dependence on imports. The internal production of basic inputs to food production processes, such as fertilizers and concentrate feeds, as well as that of other food commodities like cereals, would further contribute to fostering food security and self-sufficiency, but would cause an additional pressure on freshwater resources in the area.

4.2. General remarks and conclusions

Enhancing self-sufficient food production in rural households is crucial to guarantee food availability and direct access to food, which are major conditions for food security (FAO et al., 2014; Godfray et al., 2010). However, rural households often experience a controversial situation in regions characterized by scarce natural resources and/or constrained trading possibilities. Although farmers have direct access to their domestic food production, the majority is affected by food insecurity due to impaired access to natural and/or economic resources. Hence, a nexus approach is needed to explore the trade-offs between food security, sustainable exploitation of natural resources and economic viability.

Our analysis allows pinpointing two key aspects that are common to a range of situations where natural resource scarcity is a major constraint to food security. First, the need to look at the problem from a multidimensional perspective in order to take properly into account conflicts emerging between different objectives. In fact, while techniques such as cost-benefit analysis can be effective when objectives can be expressed in monetary terms and reduced to maximizing economic efficiency alone, multi-criteria approaches can be more appropriate when the social implications and the environmental impacts of decisions are also important to decision makers (Castelletti and Soncini-Sessa, 2006; Gatto and De_Leo, 2000; Gregory and Slovic, 1997). Multi-criteria analysis [see Köksalan (2013) for an historical perspective, and Cinelli et al. (2014) for a critical review of the potentials of multi-criteria analysis to support sustainability assessment] provides decision makers with a set of instruments to explore the range of effective choices and assess their expected consequences with respect to several viewpoints at a time, promoting the engagement of stakeholders and usually generating a wider range of alternatives than those produced by single-objective analyses.

Second, the need to investigate the water-food nexus at different spatial scales. Assessments at the micro-scale allow small-scale food producers to compare alternative agricultural practices with respect to their contribution to household livelihoods, and provide them with useful information to take decisions. For instance, the choice of the most appropriate allocation of agricultural land between cash-oriented crops and those aimed to satisfy basic dietary needs, or the opportunity to increase the number of animals raised to ensure a wider coverage of protein requirements. However, land use planning at the regional scale must also rely on a wider knowledge base, allowing decision makers to allocate limited natural resources such as freshwater and land from a sustainability perspective, and to trade off among possibly conflicting objectives.

Although the geopolitical context makes the Gaza Strip a peculiar and extreme example of the water-food nexus, we believe that the case study has a general interest. The proposed approach is flexible and can be adapted to assess the sustainability of strategies aimed to foster food security in different contexts. Since the Gaza Strip suffers from particularly stringent limitations in both freshwater availability and trade opportunities, we specifically focused on the local water balance. However, in regions where trade is less severely constrained, direct and indirect flows of natural resources among countries may become relevant. In those situations, the virtual displacement of water through trade can be effectively investigated by virtual water analysis. Such an assessment is crucial to evaluate the possible global effects of local water crises. For example, some studies (e.g. Gilmont, 2015) indicate that water resources decoupling (i.e. the substitution of domestic food production for increasing food imports) is an effective measure to reduce pressure on scarce water resources, while other studies (e.g. Tamea et al., 2016) pointed out that global vulnerability to water crises has increased over the last decades and that countries with low food (and water) availability suffer most from water crises.

The indicator set used to conduct the analysis has to be tailored to the specific case study while remaining general enough to allow comparisons. Indicators are a vital component of sustainability assessments, and the selection of the indicator set is a critical step of the assessment process (Niemeijer and de Groot, 2008). Several selection criteria have been proposed in the literature (see e.g. Lebacq et al., 2013; Niemeijer and de Groot, 2008; Pires et al., 2017; van Oudenhoven et al., 2012), but no general consensus has been reached up to now on the guiding principles for the selection process.

In our analysis, we developed an assessment framework built around the food-water nexus and encompassing the three major dimensions of sustainability. We selected two relatively small sets of indicators, one for each level of the analysis, that we deemed suitable to capture the key aspects of the problem in comparison with available data. Comprehensive assessments will greatly benefit from the availability of more detailed data (accounting explicitly for spatial heterogeneity and/or temporal variability of the processes under investigation) that would support the evaluation of a wider range of indicators (which may include, in addition to those proposed in the present work, economic indicators such as net income and environmental impact categories such as climate change) and future scenarios (such as demographic and climatic projections).

Acknowledgements

We thank Roberto Cerrina, Rosella Bonarrigo, Giulia Campigotto and Adriana Zega (Overseas) for providing general information and specific data regarding their international cooperation activities in the Gaza Strip, as well as valuable links with local people. We are grateful to Mohammed El-Bakri and Khaldoun Shanti (UAWC) for providing the valuable data necessary to build the farm model and to Husam Al-Najar and Jamal Al-Dadah (Islamic University of Gaza) for helping us fill knowledge gaps. The constructive comments of three anonymous reviewers helped us improve the manuscript. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

Allan, T., 2001. The Middle East water question: hydropolitics and the global economy. I. B. Tauris, London.

Al-Yaqubi, A., Aliewi, A., Mimi, Z., 2007. Bridging the Domestic Water Demand Gap in Gaza Strip-Palestine. Water Int. 32, 219–229. doi:10.1080/02508060708692202

Beck, M.B., Villarroel Walker, R., 2013. On water security, sustainability, and the water-food-energy-climate nexus. Front. Environ. Sci. Eng. 7, 626–639. doi:10.1007/s11783-013-0548-6

Biggs, E.M., Bruce, E., Boruff, B., Duncan, J.M.A., Horsley, J., Pauli, N., McNeill, K., Neef, A., Van Ogtrop, F., Curnow, J., Haworth, B., Duce, S., Imanari, Y., 2015. Sustainable development and the water–energy–food nexus: A perspective on livelihoods. Environ. Sci. Policy 54, 389–397. doi:10.1016/j.envsci.2015.08.002

Bonsch, M., Popp, A., Biewald, A., Rolinski, S., Schmitz, C., Weindl, I., Stevanovic, M., Högner, K., Heinke, J., Ostberg, S., Dietrich, J.P., Bodirsky, B., Lotze-Campen, H., Humpenöder, F., 2015. Environmental flow provision: Implications for agricultural water and land-use at the global scale. Glob. Environ. Chang. 30, 113–132. doi:10.1016/j.gloenvcha.2014.10.015

Butler, J.R.A., Suadnya, W., Puspadi, K., Sutaryono, Y., Wise, R.M., Skewes, T.D., Kirono, D., Bohensky, E.L., Handayani, T., Habibi, P., Kisman, M., Suharto, I., Hanartani, Supartarningsih, S., Ripaldi, A., Fachry, A., Yanuartati, Y., Abbas, G., Duggan, K., Ash, A., 2014. Framing the application of adaptation pathways for rural livelihoods and global change in eastern Indonesian islands. Glob. Environ. Chang. 28, 368–382. doi:10.1016/j.gloenvcha.2013.12.004

Butterfield, D., Isaac, J., Kubursi, A., Spencer, S., 2000. Agriculture in Palestine: impacts of water and export market restrictions on Palestinian agriculture. https://goo.gl/FbgdII (last accessed 04/07/2016).

Byerlee, D., De Janvry, A., Sadoulet, E., Townsend, R., Klytchnikova, I., 2008. World development report 2008 : agriculture for development 1–390.

Castelletti, A., Soncini-Sessa, R., 2006. A procedural approach to strengthening integration and participation in water resource planning. Environ. Model. Softw. 21, 1455–1470. doi:10.1016/j.envsoft.2005.07.013

Cinelli, M., Coles, S.R., Kirwan, K., 2014. Analysis of the potentials of multi criteria decision analysis methods to conduct sustainability assessment. Ecol. Indic. 46, 138–148. doi:10.1016/j.ecolind.2014.06.011

D'Odorico, P., Laio, F., Ridolfi, L., 2010. Does globalization of water reduce societal resilience to drought? Geophys. Res. Lett. 37, L13403. doi:10.1029/2010GL043167

de Strasser, L., Lipponen, A., Howells, M., Stec, S., Bréthaut, C., 2016. A Methodology to Assess the Water Energy Food Ecosystems Nexus in Transboundary River Basins. Water 8, 59. doi:10.3390/w8020059

Donini, L.M., Dernini, S., Lairon, D., Serra-Majem, L., Amiot, M.-J., del Balzo, V., Giusti, A.-M., Burlingame, B., Belahsen, R., Maiani, G., Polito, A., Turrini, A., Intorre, F., Trichopoulou, A., Berry, M.E., 2016. A consensus proposal for nutritional indicators to assess the sustainability of a healthy diet: the Mediterranean diet as a case study. Front. Nutr. 3, 37. doi:10.3389/fnut.2016.00037

EWASH, 2011. Water for agriculture and food security in Gaza. EWASH Advocacy Task Force Fact Sheet no. 6. http://goo.gl/PhMsDj (last accessed 04/07/2016).

Fader, M., Gerten, D., Krause, M., Lucht, W., Cramer, W., 2013. Spatial decoupling of agricultural production and consumption: quantifying dependences of countries on food imports due to domestic land and water constraints. Environ. Res. Lett. 8, 14046. doi:10.1088/1748-9326/8/1/014046

FAO, 2003. Executive report of the food security assessment - West Bank and Gaza Strip. FAO, Rome.

FAO, 2005. Nutrition Country Profile - Palestine. FAO, Rome.

FAO, 2014a. The Water-Energy-Food Nexus. A new approach in support of food security and sustainable agriculture. FAO, Rome.

FAO, 2014b. SAFA (Sustainability assessment of food and agriculture systems) Guidelines. Version 3.0. FAO, Rome.

FAO, 2017. AQUASTAT - FAO's Information System on Water and Agriculture. http://www.fao.org/nr/water/aquastat/water_res/ (last accessed 31/01/2017).

FAO, IFAD, WFP, 2014. The State of Food Insecurity in the World 2014. Strengthening the enabling environment for food security and nutrition. FAO, Rome.

FAO, IFAD, WFP, 2015. The State of Food Insecurity in the World 2015.

FAO, USDA, 1982. Food composition tables for the Near East. FAO, Rome.

FAO, WFP, 2007. West Bank and gaza Strip. Comprehensive Food Security and Vulnerability Analysis (CFSVA). FAO, Rome.

FAO, WHO, UN, 1991. Energy and protein requirements. WHO, Geneva.

Finley, J.W., Seiber, J.N., 2014. The Nexus of Food, Energy, and Water. J. Agric. Food Chem. 62, 6255–6262. doi:10.1021/jf501496r

Gatto, M., De_Leo, G.A., 2000. Pricing biodiversity and ecosystem services: the never-ending story. Bioscience 50, 347–355.

Gerland, P., Raftery, A.E., Sevčíková, H., Li, N., Gu, D., Spoorenberg, T., Alkema, L., Fosdick, B.K., Chunn, J., Lalic, N., Bay, G., Buettner, T., Heilig, G.K., Wilmoth, J., 2014. World population stabilization unlikely this century. Science 346, 234–237. doi:10.1126/science.1257469

Gibson, R.S., 2005. Principles of Nutritional Assessment, 2nd ed. Oxford University Press, Oxford, UK.

Gilmont, M., 2015. Water resource decoupling in the MENA through food trade as a mechanism for circumventing national water scarcity. Food Secur. 7, 1113–1131. doi:10.1007/s12571-015-0513-2

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., Toulmin, C., 2010. Food security: the challenge of feeding 9 billion people. Science 327, 812–818. doi:10.1126/science.1185383

Gregory, R., Slovic, P., 1997. A constructive approach to environmental valuation. Ecol. Econ. 21, 175–181.

Gustafson, D., Gutman, A., Leet, W., Drewnowski, A., Fanzo, J., Ingram, J., 2016. Seven food system metrics of sustainable nutrition security. Sustainability 8, 196. doi:10.3390/su8030196

Halkjaer, J., Olsen, A., Bjerregaard, L.J., Deharveng, G., Tjønneland, A., Welch, A.A., Crowe, F.L., Wirfält, E., Hellstrom, V., Niravong, M., Touvier, M., Linseisen, J., Steffen, A., Ocké, M.C., Peeters, P.H.M., Chirlaque, M.D., Larrañaga, N., Ferrari, P., Contiero, P., Frasca, G., Engeset, D., Lund, E., Misirli, G., Kosti, M., Riboli, E., Slimani, N., Bingham, S., 2009. Intake of total, animal and plant proteins, and their food sources in 10 countries in the European Prospective Investigation into Cancer and Nutrition. Eur. J. Clin. Nutr. 63 Suppl 4, S16–S36. doi:10.1038/ejcn.2009.73

Hilles, A.H., Al-Najar, H., 2011. Brackish water desalination is the merely potable water potential in the Gaza Strip: Prospective and limitations. J. Environ. Sci. Technol. 4, 158–171. doi:10.3923/jest.2011.158.171

Hoekstra, A.Y., Chapagain, A.K., Aldaya, M.M., Mekonnen, M.M., 2011. The Water Footprint Assessment Manual. Earthscan, London and Washington.

Horrigan, L., Lawrence, R.S., Walker, P. 2002. How sustainable agriculture can address the environmental and human health harms of industrial agriculture. Environ. Health Perspect. 110, 445–456.

IFAD, 2010. Rural Poverty Report 2011. Quintily, Rome.

Iglesias, A., Garrote, L., 2015. Adaptation strategies for agricultural water management under climate change in Europe. Agric. Water Manag. 155, 113–124. doi:10.1016/j.agwat.2015.03.014

ISO, 2006. ISO 14044:2006 – Environmental management – Life cycle assessment – Requirements and guidelines. ISO, Geneva.

Latrouffe, L., Diazabakana, A., Bockstaller, C., Desjeux, Y., Finn, J., Kelly, E., Ryan, M., Uthes, S., 2016. Measurement of sustainability in agriculture: a review of indicators. Stud. Agr. Econ. 118, 123–130. doi:10.7896/j.1624.

Karabulut, A., Egoh, B.N., Lanzanova, D., Grizzetti, B., Bidoglio, G., Pagliero, L., Bouraoui, F., Aloe, A., Reynaud, A., Maes, J., Vandecasteele, I., Mubareka, S., 2016. Mapping water provisioning services to support the ecosystem–water–food–energy nexus in the Danube river basin. Ecosyst. Serv. 17, 278–292. doi:10.1016/j.ecoser.2015.08.002

Köksalan, M., Wallenius, J., Zionts, S., 2013. An early history of multiple criteria decision making. J. Multi-Criteria Decis. Anal. 20, 87–94. doi:10.1002/mcda.1481

Krishnamurthy, P.K., Lewis, K., Choularton, R.J., 2014. A methodological framework for rapidly assessing the impacts of climate risk on national-level food security through a vulnerability index. Glob. Environ. Chang. 25, 121–132. doi:10.1016/j.gloenvcha.2013.11.004

Kumar, M.D., Sivamohan, M.V.K., Narayanamoorthy, A., 2012. The food security challenge of the food-land-water nexus in India. Food Secur. 4, 539–556. doi:10.1007/s12571-012-0204-1

Latham, M.C., 1997. Human nutrition in the developing world. FAO, Rome.

Lebacq, T., Baret, P. V., Stilmant, D., 2013. Sustainability indicators for livestock farming. A review. Agron. Sustain. Dev. 33, 311–327. doi:10.1007/s13593-012-0121-x

Marchand, P., Carr, J.A., Dell'Angelo, J., Fader, M., Gephart, J.A., Kummu, M., Magliocca, N.R., Porkka, M., Puma, M.J., Ratajczak, Z., Rulli, M.C., Seekell, D.A., Suweis, S., Tavoni, A., D'Odorico, P., 2016. Reserves and trade jointly determine exposure to food supply shocks. Environ. Res. Lett. 11, 95009. doi:10.1088/1748-9326/11/9/095009

Mclaughlin, D., Kinzelbach, W., 2015. Food security and sustainable resource management. Water Resour. Res. 51, 4966–4985. doi:10.1002/2015WR017053

Mekonnen, Hoekstra, 2011. The green, blue and grey water footprint of crops and derived crop products. Hydrol. Earth Syst. Sci. 15, 1577–1600. doi:10.5194/hess-15-1577-2011

Mueller, N.D., Gerber, J.S., Johnston, M., Ray, D.K., Ramankutty, N., Foley, J.A., 2012. Closing yield gaps through nutrient and water management. Nature 490, 254–257. doi:10.1038/nature11420

Niemeijer, D., de Groot, R.S., 2008. A conceptual framework for selecting environmental indicator sets. Ecol. Indic. 8, 14–25. doi:10.1016/j.ecolind.2006.11.012

OCHA, 2015. The Gaza Strip: The humanitarian impact of the blockade. OCHA oPt, East Jerusalem. https://goo.gl/FRUxni (last accessed 04/07/2016).

OECD, FAO, 2015. OECD-FAO Agricultural Outlook 2015. OECD Publishing, Paris.

Ortiz, I., Cummins, M., 2011. Global inequality: beyond the bottom billion – A rapid review of income distribution in 141 countries. UNICEF, New York.

PCBS, 2005. Farm structure survey 2004/2005: Main findings. PCBS, Ramallah.

PCBS, 2011. Living standards in the Palestinian Territory. Final report (January 2010-January 2011). PCBS, Ramallah.

PCBS, 2012a. Agriculture statistics survey 2010/2011: Main results. PCBS, Ramallah.

PCBS, 2012b. Agricultural Statistics - Various Data, 2011. PCBS, Ramallah.

PCBS, 2015a. Registered foreign trade statistics. Goods and services, 2014. Main results. PCBS, Ramallah.

PCBS, 2015b. Palestinians at the end of 2015. PCBS, Ramallah.

PCBS, 2016a. Consumer Price Index. http://www.pcbs.gov.ps/site/lang__en/695/default.aspx (last accessed 04/07/2016), Ramallah.

PCBS, 2016b. Producer Price Index. http://www.pcbs.gov.ps/site/lang__en/747/default.aspx (last accessed 04/07/2016).

PCBS, WFP, FAO, UNRWA, 2013. Socio-economic and food security survey 2012. West Bank and Gaza Strip, Palestine. WFP, Rome.

Pellicer-Martínez, F., Martínez-Paz, J.M., 2016. The Water Footprint as an indicator of environmental sustainability in water use at the river basin level. Sci. Total Environ. doi:10.1016/j.scitotenv.2016.07.022

Peng, J., Liu, Z., Liu, Y., Hu, X., Wang, A., 2015. Multifunctionality assessment of urban agriculture in Beijing City, China. Sci. Total Environ. 537, 343–351.

Pires, A., Morato, J., Peixoto, H., Botero, V., Zuluaga, L., Figueroa, A., 2017. Sustainability Assessment of indicators for integrated water resources management. Sci. Total Environ. 578, 139–147. doi:10.1016/j.scitotenv.2016.10.217

Postel, S.L., Daily, G.C., Ehrlich, P.R., 1996. Human appropriation of renewable fresh water. Science 271, 785–788. doi:10.1126/science.271.5250.785

Power, A.G., 2010. Ecosystem services and agriculture: tradeoffs and synergies. Philos. Trans. R. Soc. Lond. B. Biol. Sci. 365, 2959–2971. doi:10.1098/rstb.2010.0143

PWA, 2014. Gaza Water Resources Status Report, 2013/2014. PWA, Ramallah.

Ringler, C., Badhuri, A., Lawford, R., 2013. The nexus across water, energy, land and food (WELF): potential for improved resource use efficiency? Curr. Opin. Environ. Sustain. 5, 617–624. doi:10.1016/j.cosust.2013.11.002

Rost, S., Gerten, D., Bondeau, A., Lucht, W., Rohwer, J., Schaphoff, S., 2008. Agricultural green and blue water consumption and its influence on the global water system. Water Resour. Res. 44. doi:10.1029/2007WR006331

Rulli, M.C., Bellomi, D., Cazzoli, A., De Carolis, G., D'Odorico, P., 2016. The water-land-food nexus of first-generation biofuels. Sci. Rep. 6, 22521. doi:10.1038/srep22521

Rulli, M.C., D'Odorico, P., 2014. Food appropriation through large scale land acquisitions.

Environ. Res. Lett. 9, 64030. doi:10.1088/1748-9326/9/6/064030

Shiklomanov, I.A., 2000. Appraisal and assessment of world water resources. Water Int. 25, 11–32. doi:10.1080/02508060008686794

Siebert, S., Döll, P., 2010. Quantifying blue and green virtual water contents in global crop production as well as potential production losses without irrigation. J. Hydrol. 384, 198–217. doi:10.1016/j.jhydrol.2009.07.031

Singh, R.K., Murty, H.R., Gupta, S.K., Dikshit, A.K., 2009. An overview of sustainability assessment methodologies. Ecol. Indic. 9, 189–212. doi:10.1016/j.ecolind.2008.05.011

SINU, 2014. Livelli di assunzione di riferimento di nutrienti ed energia per la popolazione italiana. IV revisione. SINU, Firenze.

Tamea, S., Laio, F., Ridolfi, L., 2016. Global effects of local food-production crises: a virtual water perspective. Sci. Rep. 6, 18803. doi:10.1038/srep18803

Tilman, D., Fargione, J., Wolff, B., D'Antonio, C., Dobson, A., Howarth, R., Schindler, D., Schlesinger, W.H., Simberloff, D., Swackhamer, D., 2001. Forecasting agriculturally driven global environmental change. Science 292, 281–284. doi:10.1126/science.1057544

UN, 2015. Transforming our world: the 2030 Agenda for Sustainable Development. UN General Assembly resolution A/RES/70/1. UN, Geneva.

UNDP, 2011. Programme of Assistance to the Palestinian People - MDGs in the oPt. UNDP, New York. http://www.undp.ps/en/mdgs/mdgopt.html (last accessed 04/07/2016).

UNEP, 2013. Embedding the Environment in Sustainable Development Goals. UNEP Post-2015 Discussion Paper 1. UNEP, Nairobi.

van Oudenhoven, A.P.E., Petz, K., Alkemade, R., Hein, L., de Groot, R.S., 2012. Framework for systematic indicator selection to assess effects of land management on ecosystem services. Ecol. Indic. 21, 110–122. doi:10.1016/j.ecolind.2012.01.012

West, P.C., Gerber, J.S., Engstrom, P.M., Mueller, N.D., Brauman, K.A., Carlson, K.M., Cassidy, E.S., Johnston, M., MacDonald, G.K., Ray, D.K., Siebert, S., 2014. Leverage points for improving global food security and the environment. Science 345, 325–328. doi:10.1126/science.1246067

World Bank, 2008. World development report 2008: Agriculture for development. World Bank, Washington DC.

S1. Supplementary materials

S1.1. The farm model

The farm model (main text, section 2.3) was built by integrating information supplied by local farmers, local agronomists and operators of Overseas (an Italian NGO involved in cooperation projects in the Gaza Strip) with data from the literature. Here we provide further details regarding data sources and modelling assumptions that were omitted from the main text for the sake of brevity.

S1.1.1. *Horticulture*

Data about the considered crop rotation systems (main text, Fig. 2) and the yield of each crop were provided by local agronomists and are reported in Table S1, along with basic statistics about their production in the Gaza Strip and the corresponding economic value (from PCBS, 2009).

Table S1. Annual yield of different crops, total production in the Gaza Strip and corresponding economic value. Letters between parentheses indicate the rotation system (for crops considered in more than one).

Crop	**Yield** (kg/ha)	**Production** (t/year)	**Value** (10^3 USD)
cabbage	45,000	7,951	4,569
cauliflower	25,000	6,209	4,504
cucumber	90,000	37,117	24,740
eggplant (B)	60,000	10,668	6,508
eggplant (D)	40,000		
pepper	20,000	4,197	4,197
tomato	150,000	89,912	59,766
lentil	1,800	34	30
peas (B)	10,000	712	560
peas (C and D)	7,000		

S1.1.2. *Sheep*

Sheep are assumed to graze in the farm courtyard and occasionally in the restricted area running along the Israeli border. The considered breed is the Awassi sheep, which is the most common in south-west Asia and in the arid and semi-arid areas of Asia. On the basis of the information provided by local agronomists and data gathered from the literature (Epstein, 1982; FAO, 1989), the following assumptions are made:

- the flock is composed of 7 ewes (female sheep), while the ram (male sheep) needed for mating is borrowed from outside the farm;
- ewes deliver 8 lambs every year. Tex ratio at birth is equal to 1:1;
- male lambs are slaughtered during their first year of life; female lambs are raised and slaughtered after their first (25%) or second (75%) lambing. No animal dies before slaughter;
- overall, four male lambs, one ewe aged 2, and three ewes aged 3 are slaughtered every year. Their average weight (total and carcass) is reported in Table S2.

Table S2. Total and carcass weight of sheep at slaughter.

Age class	**Total weight** (kg)	**Carcass weight** (kg)	**Animals slaughtered per year**
male lamb (age <1)	22.0	11.0	4
ewe (age ≤ 2 years)	40.0	18.0	1
ewe (age ≤ 3 years)	45.0	20.2	3

Summing up the amount of meat obtained from each age class, the total annual meat production is ca. 123 kg. Awassi sheep have a high milk production potential, up to 230 kg per year (Epstein, 1982). In this work, we considered an annual yield of 103 kg per ewe (obtained by averaging FAOSTAT data for the Palestinian territories from 2000 to 2013). Considering that about one-third of the milk is consumed by lambs (Epstein, 1982) and assuming that ewes produce between 70%

and 100% of their potential production (depending on their age), we estimated an overall amount of 398 kg of milk per year available for the household.

S1.1.3. *Poultry*

Fifteen hens are assumed to graze in the farm courtyard to provide eggs and meat for household consumption. According to the information gathered from local agronomists and farmers, chickens are fed with concentrates (100 g per day per animal), and each animal produces 1 kg of meat and 10.8 kg of eggs (60 g each) per year. We assumed that the whole stock is renewed every year.

S1.1.4. *Aquaculture*

Small-scale aquaculture takes place within irrigation ponds. According to local agronomists, each pond produces 400 fish (Nile tilapia, *Oreochromis niloticus*) per year; as the farm includes 3 ponds, the overall fish production corresponds to 1,200 fish per year. Overseas data (gathered through a survey among ca. 30 farms) indicate an annual demand of 0.45 kg per fish of concentrate feed and a total production of edible fish equal to 240 kg.

A fundamental requirement for guaranteeing fish survival is the maintenance of a minimum water level in the ponds. Overseas operators reported a requirement of 1 m^3 of water per kilogram of fish, which corresponds to a minimum water depth of 1.60 m. Due to the high evaporation rates characterizing the climate of the study area (Martens et al., 2016; Miralles et al, 2011), freshwater must be pumped from the aquifer when rainfall is not sufficient to guarantee this condition.

S1.2. Indicator definition and assessment

The methodological assessment framework is presented in section 2.1 and summarized in Fig. 1 (main text). The motivations of the choice of the two sets of indicators used for the analyses at the farm scale and at the regional scale are explained in sections 2.4 and 2.5, respectively (see Table 1 for the complete list and a synthetic description). At the farm scale, we compared alternative scenarios of vegetal and animal food production in terms of domestic protein supply, water appropriation and gross income; at the regional scale, benefits and impacts of domestic food production were compared with the current situation of the Gaza Strip in terms of nutritional, environmental and economic sustainability. The following sections provide additional details to those given in the main text on methods and data sources.

S1.2.1. *Nutritional analysis*

The contribution of domestic production to household food supply was evaluated by assuming the following consumption patterns:

- as vegetable production widely exceeds household needs, domestic consumption was set to 400 g per day per capita (excluding legumes), which is the minimum portion suggested by WHO & FAO guidelines for fruits and vegetables (FAO and WHO, 2005). For the sake of simplicity, we assumed that the entire portion is covered by vegetables;
- legumes were differentiated between fresh (peas) and dried (lentils). Recommended serving portions are 150 g and 50 g, respectively (SINU, 2014). Since different nutritional guidelines suggest a weekly consumption between 3 and 4 portions (HHS and USDA, 2015; INRAN, 2003), we assumed an average consumption of 3.5 portions per week per capita;
- animal production (i.e. chicken and sheep meat, eggs, sheep milk, and fish) was considered to be entirely consumed by the household.

In the first part of the analysis, we compared alternative food production scenarios in terms of domestic protein supply. Each production scenario includes the totality of animal production plus a portion of vegetables and legumes (see above) depending on the crop rotation system considered (Fig. 2, main text). The achievement of safe levels of protein intake is a priority for the rural population of the region (FAO, 2003). To assess protein intake, we used protein contents for different food items, as reported by FAO and USDA (1982) specifically for the Near East (Table S3).

Then, we used the results of the first part of the analysis to calculate the potential contribution of domestic food production to food security in the Gaza Strip. For each scenario, we calculated the fraction of domestic production per capita destined for household consumption and compared it with average consumption levels of major food groups in the whole Gaza Strip. In addition, we compared domestic protein supply per capita with the minimum safe intake level of proteins recommended by international agencies (FAO, WHO, and UN 1991; SINU 2014;).

Table S3. Protein content of considered products.

Product	Protein content (%)	FAO data name
fish	19.1%	Nile tilapia, raw
sheep meat	12.2%	carcass, raw
sheep milk	5.9%	milk sheep, fluid, whole
chicken egg	12.1%	whole, raw
chicken meat	19.4%	whole, raw
cabbage	1.6%	leaves, raw
cauliflower	2.5%	flower, raw
cucumber	0.8%	fruit, unpeeled, raw
eggplant	1.4%	fruit, peeled, raw
pepper	1.4%	pepper sweet, fruit, raw
tomato	1.1%	fruit, raw
lentil	24.7%	mature seed, raw
pea	7.1%	immature seed, raw

S1.2.2. *Environmental analysis*

The Gaza Strip is strongly affected by water and land scarcity; we mainly focused on water appropriation, but we also carried out a simple, exploratory assessment of land appropriation to broaden the discussion regarding the environmental sphere.

Water appropriation

The water footprint is a comprehensive indicator of freshwater resources appropriation, accounting for both water consumption and water pollution along the whole supply chain of products. Despite the recent release of a specific International Standard (ISO, 2014), a unique methodology for assessing water footprint does not exist yet (Bayart et al., 2010; Hoekstra et al., 2011). The most widely used methodology is the one proposed by the Water Footprint Network, which calculates the total water footprint (WF_{tot}) as the sum of three terms (Hoekstra et al., 2011):

$$WF_{\text{tot}} = WF_{\text{blue}} + WF_{\text{green}} + WF_{\text{grey}} \qquad \text{(eq. S1)}$$

where

- WF_{blue} is the blue water footprint and measures the consumption of surface- and groundwater;
- WF_{green}, the green water footprint, refers to the consumption of rainwater;
- WF_{grey}, the grey water footprint, accounts for the amount of water consumed due to pollution.

In this study, we considered both the direct (associated to local water consumption) and the indirect (associated to imported input materials) water footprint.

The water footprint of crops was assessed following Mekonnen and Hoekstra (2011). The blue water footprint accounts for the groundwater evaporated during the cultivation period and for that incorporated into products. We estimated the blue water component on the basis of data on water demand (groundwater pumped from the aquifer for irrigation) of each crop, as provided by Overseas operators (Table S4). A fraction of groundwater recharge equal to 20% (Dentoni, 2013) was subtracted from the amount of withdrawn water: since this flows back into the same catchment, it is not considered as an actual consumption.

Table S4. Water demand for irrigation of the different crops.

Crop	**Water demand** (m^3/year)
cabbage	3,060
cauliflower	4,080
cucumber	5,100
eggplant	6,800
lentil	1,700
pea	4,250
pepper	5,950
tomato	8,500

The green water footprint accounts for rainwater evaporated or incorporated into products. The footprint of crops was estimated from monthly precipitation data (2000–2010 average, from Al-Najar, 2011). The reference area for the calculation of the green water component encompasses fields (8,500 m^2) and water ponds (150 m^2) for open field crops, while for greenhouse crops only the surface of ponds was considered. Rainwater evaporating from the ponds (where fish are also raised) was allocated to crops, since the primary purpose of ponds is to collect rainfall for crop irrigation. Similarly to what was done for the blue contribution, a 20% groundwater recharge was subtracted from precipitation (Dentoni, 2013).

The grey water footprint is defined as the volume of freshwater that is required to dilute the load of pollutants to meet existing water quality standards (c_{max}, kg/m^3) given the natural background concentration (c_{nat}, kg/m^3). The pollutant load (L) is calculated by multiplying the application rate (AR) of fertilizers applied to the reference unit (e.g. 1 ha of field surface) by the leaching/run-off fraction α, which represents the fraction of chemicals reaching freshwater bodies (Hoekstra et al., 2011):

$$WF_{\mathrm{grey}} = L/(c_{\mathrm{max}} - c_{\mathrm{nat}}) = (AR \cdot \alpha)/(c_{\mathrm{max}} - c_{\mathrm{nat}}) \qquad \text{(eq. S2)}$$

Application rates of fertilizers were provided by local agronomists (Table S5). As specific data for the estimation of the other parameters of the equation were not available, α was set to 10% for all fertilizers (Hoekstra et al., 2011), while for $c_{\max}$ and c_{nat} we used default values proposed by Mekonnen and Hoekstra (2011), reported in Table S5.

Finally, the indirect water footprint (related to imported input materials) associated with the production of seeds, fertilizers and pesticides was calculated with the software SimaPRO 8.0 based on data from the Ecoinvent 3.0 database (Weidema et al., 2013).

Table S5. Application rates (per unit area) of fertilizers applied to the different crops and corresponding water quality standards ($c_{\max}$ and c_{nat}).

Crop	**Application rate** (kg/ha)			
	N	K	P	Mg
cabbage (B and E)	150	120	120	–
cauliflower	150	120	120	–
cucumber	700	450	–	450
eggplant (B and E)	860	250	600	–
lentil	–	–	–	–
pea (C and D)	25	500	50	–
pepper (C and E)	580	260	240	–
tomato	1,000	230	125	–
$c_{\max}$ (mg/l)	50	10	5	150
c_{nat} (mg/l)	0	0	0	0

To estimate the water footprint of animal products, we followed the approach proposed by Mekonnen and Hoekstra (2012), according to which the total water footprint is calculated as the sum of three terms:

$$WF_{\text{tot}} = WF_{\text{feed}} + WF_{\text{drink}} + WF_{\text{services}} \quad \text{(eq. S3)}$$

where

- WF_{feed} is the water consumed for the production of animal feed;
- WF_{drink} is the water drunk by the animals;
- $WF_{services}$ is the water consumed for different services, like cleaning the farmyard, washing the animals and carrying out the activities necessary to maintain the environment.

According to Mekonnen and Hoekstra (2012), 98% of the total water footprint is associated to feed production, and only 2% is consumed for drink and services. For this reason, we calculated the water footprint of fish and poultry by taking into account the footprint of the main feed ingredients (Mekonnen & Hoekstra, 2011).

The ingredients composing concentrates for poultry (Daghir, 2008) and their associated water footprint (Mekonnen & Hoekstra, 2011) are reported in Table S6. We assumed that feed is imported from Israel (since Israel is the main source of imported products in the Gaza Strip; PCBS, 2015). However, according to FAOSTAT the necessary ingredients are imported by Israel from other countries (food balance sheet and trade matrix from FAO, 2016): barley is mainly imported from Switzerland (80% of the total import), sesame seeds are mainly imported from Ethiopia (70%), while sunflower seeds are mainly produced in Israel (86%). Therefore, for each ingredient we used the water footprint value regarding the main country of origin. Since two different products are obtained from poultry (meat and eggs), the total water footprint of chicken was split according to a mass criterion: given an annual production of 15 kg of chicken meat and 160 kg of eggs, the corresponding allocation factors were set to 9% and 91%, respectively. The direct contribution of chicken was set to 2% of the total water footprint, as suggested by Mekonnen and Hoekstra (2012).

Table S6. Ingredients of concentrated feed for poultry and associated water footprint.

Ingredient	Origin	Proportion (%)	Water footprint (m^3/kg)		
			green	blue	grey
barley	Switzerland	76	0.38	–	0.18
sunflower seeds	Israel	15	0.57	3.37	0.26
sesame seeds	Ethiopia	9	6.36	0.02	–
total			0.95	0.51	0.17

As for fish, concentrated feed used in aquaculture was assumed to be imported from Israel. Concerning the main ingredients, the FAOSTAT database reports that 70% of yellow corn is imported from Switzerland, 70% of soybean meal from the U.S.A. and 55% of corn oil from Argentina (FAO, 2016). Feed ingredients (Aquamax, 2008), along with their associated water footprints (Mekonnen & Hoekstra, 2011) are reported in Table S7. Minor ingredients (accounting for ca. 15% of the feed mass) were not included in the analysis due to the difficulty of retrieving reliable data. Besides the contribution of concentrate feeds, the water footprint of fish includes a further contribution due to water pumped from the aquifer to maintain the required minimum water level in the ponds. This contribution is estimated from monthly precipitation and evaporation data (2000–2010 average, from Al-Najar, 2011; Martens et al., 2016; Miralles et al, 2011) considering a minimum water requirement of 1 m^3 of water per 1 kg of living fish.

Table S7. Ingredients of concentrated feed for fish and associated water footprint.

Ingredient	**Origin**	**Composition** (%)	**Water footprint** (m^3/kg)		
			green	blue	grey
yellow corn	Switzerland	15	0.44	0.00	0.20
soy bean meal	U.S.A.	50	1.84	0.11	0.01
corn oil	Argentina	20	2.16	0.03	0.16
others	–	15	not considered		
total			1.40	0.06	0.07

Unlike fish and poultry, sheep consume a negligible amount of feed: in West Asia and North Africa, feed concentrates account only for 4% of sheep diet, with an even lower share (1.1%) in grazing systems (Mekonnen & Hoekstra, 2012). The remaining fraction of the diet is represented by grass growing in the grazing area, crop residues, and hay produced during the rest period of crop cultivation. The water footprint of sheep was estimated on the basis of the figure reported by Mekonnen & Hoekstra (2012) for a tonne of live sheep at the end of life, equal to 4,519 m^3/t (grazing systems, global average). To calculate the water footprint on an annual basis, we considered that consumption by lambs (through milking) is already included in that of their mothers, and that, of the 7 adult ewes, 3 are kept alive throughout the year, while 4 (1 aged 16 months and 3 aged 28 months) are slaughtered and replaced by the 4 female lambs born in the same year. Assuming an average weight of 42.5 kg per animal (as reported in section S1.1.2) and a lifespan of 2.1 years (average of 1 ewe living 16 months and 6 ewes living 28 months), we obtain an overall footprint of 91.5 m^3/yr per sheep.

To disaggregate the total water footprint value into its three components (Table S8), we assumed that 94% of the total footprint is associated with the green contribution, while the blue and grey components contribute to 3.6% and 2.4%, respectively (Mekonnen and Hoekstra, 2012). Like for poultry, the water footprint of sheep was allocated to the obtained products on the basis of a mass allocation criterion (76.4% to milk and 23.6% to meat).

Table S8. Water footprint of a sheep.

Water footprint component	Share (%)	Estimate (m^3/yr)
green	94.0	86.0
blue	3.6	3.3
grey	2.4	2.2

After estimating the water footprints of single food items, we aggregated them to calculate the water footprint of each production scenario. Then, we compared alternative scenarios at the farm scale in terms of blue and total water footprint. In the second part of the analysis, we compared water appropriation with available freshwater resources in the Gaza Strip (Table S9) as reported by PWA (2014). For each scenario, per capita water appropriation was obtained by dividing water footprints at the farm scale by the average household size (18 people). As in this second analysis we focused specifically on the water resources of the Gaza Strip, only the direct component of water footprints (i.e., local consumptions) was considered.

Table S9. Water availability in the Gaza Strip.

Average aquifer recharge	57,500,000 m^3/year
Population (2013)	1,730,737
Water availability per capita	33.22 m^3/year

Land appropriation

To complement the analysis of the water balance at the regional scale, we assessed land requirements for domestic food production, to be compared with the current availability of agricultural land. Only direct land appropriation was considered (i.e. we excluded land use associated with the production of imported products). Land appropriation for domestic production of vegetables was estimated on the basis of crop productivity (see Table S1) and household consumption (see section S1.2.1) following the approach of Goedkoop et al. (2009). The area occupied by irrigation ponds (150 m^2) was allocated to crops. As for animal production, we allocated the area dedicated to grazing (200 m^2) to poultry and sheep. For each scenario, per capita land appropriation was obtained by summing up land appropriated for crops and land for grazing and by dividing the total by the average household size. Results were then compared with per capita availability of agricultural land in the Gaza Strip (Table S10; data from PCBS, 2011).

Table S10. Land availability in the Gaza Strip.

Total area	365 km^2
Cultivated area (2011)	88 km^2
Population (2013)	1,730,737
Total area per capita	210.9 m^2
Cultivated area per capita	50.8 m^2

S1.2.3. *Economic analysis*

With respect to the economic dimension, we estimated the contribution of domestic production to economic access to food, both in terms of decreased expenditures on food and in terms of increased household income. To this end, we used price data reported by the Palestinian Central Bureau of Statistics (PCBS, 2016a, 2016b), averaged over the period 2008–2013. While in PCBS reports consumer prices (necessary to assess the benefits on expenditures for food) are provided separately for the Gaza Strip and the West Bank, producer prices (used to assess incomes) are provided only as averages for the whole Palestinian territories and for selected food commodities. To estimate producer prices specific to the Gaza Strip, we calculated the average ratio between producer and consumer prices in Palestine (equal to 44%) and used it to derive producer prices from consumer prices in the Gaza Strip (Table S11). Prices, originally reported in New Israeli Shekels (NIS), were converted into US dollars (USD) using an average exchange rate of 1 NIS = 0.257 USD calculated over the last decade. Note that our analysis does not include the costs related to food production (neither capital investments nor operational costs), so it provides only an estimate of the gross contribution of domestic production to the income of rural households.

Table S11. Prices of food commodities in the occupied Palestinian territories and in the Gaza Strip.

	Palestinian territories			**Gaza Strip**	
	Consumer price (NIS/kg)	**Producer price** (NIS/kg)	**PP:CP ratio** (%)	**Consumer price** (NIS/kg)	**Producer price** (NIS/kg)
greenhouse tomato	3.41	2.35	46	2.32	1.25
greenhouse cucumber	3.15	2.40	32	2.00	1.37
eggplant	3.18	2.10	52	2.23	0.60
cauliflower	3.54	2.72	30	2.56	2.15
cabbage	3.15	2.01	58	2.39	0.97
average			44		
lentil				6.58	3.69
pepper				3.82	2.14
pea	5.60			5.10	3.48

S2. Supplementary results

S2.1. Water footprint assessment

S2.1.1. *Crops*

The water footprints of the crops included in the alternative rotation systems are reported in Table S12.

Table S12. Direct (by component) and indirect water footprint of crops. Letters between parentheses indicate crop rotation systems.

Crop	**Blue** (m^3/t)	**Green** (m^3/t)	**Grey** (m^3/t)	**Indirect** (m^3/t)
cabbage	62.4	28.7	86.7	2.9
cauliflower	149.8	51.6	156.0	6.1
cucumber	52.0	0.0	68.9	2.3
eggplant (B)	104.0	1.0	270.3	4.0
eggplant (D)	156.0	0.0	405.5	6.0
lentil	866.7	507.0	0.0	22.0
pea (B)	390.0	129.0	605.0	17.0
pea (C and D)	557.1	130.4	864.3	16.6
pepper	273.0	0.0	428.0	11.8
tomato	52.0	0.06	45.3	2.14

Lentils are the crop with the highest blue and green water footprint per tonne of product. However, a comparison between lentils and the other crops on a weight basis can be misleading, because they are weighed dry, while all the other products are weighed wet. On the other hand, lentils have no grey footprint, as they do not require fertilizers nor pesticides. Peas have also high green and blue footprints (note that their water content is <80%, while that of most vegetables is >90%), but have a high grey footprint too. Summer crops (cucumbers, eggplants and peppers) have a green footprint equal or close to zero, as they are cultivated in the dry season. In contrast, their grey footprint is among the highest, due to the use of fertilizers and pesticides. Tomatoes have also a negligible green water contribution, as they are grown in greenhouses (the small amount of green footprint is due to the use of rainwater collected in the irrigation ponds).

S2.1.2. *Animals*

Table S13 summarizes the results of the water footprint assessment of animal products. The water footprint of poultry and fish is mainly due to concentrate feed (indirect contribution), while for sheep it is due to the direct green water footprint (rainfall over the grazing area). The direct blue water footprint contribution of fish (about 30% of the total) is due to the water evaporated from the pond.

Table S13. Water footprint of animal products.

Product	**Water footprint** (m^3/kg)				
	green	blue	grey	indirect	total
fish	0.00	1.50	0.00	3.50	5.00
chicken eggs	0.00	0.10	0.00	5.10	5.20
chicken meat	0.00	0.10	0.00	5.10	5.20
sheep meat	1.16	0.04	0.03	0.00	1.23
sheep milk	1.16	0.04	0.03	0.00	1.23

S2.2. Comparison of food production scenarios at the farm scale

Table S14 shows the annual productivity of the different crop rotation systems. A fraction of the annual production is considered to be consumed directly by the household (see section S1.2.1), while the rest can be sold. Domestic consumption covers a small share of the production (between 1 and 5%), confirming the trade-oriented nature of horticulture in the Gaza Strip**.**

Table S15 compares different food production scenarios in terms of protein supply (assuming the consumption patterns defined in section S1.2.1), gross income, and water footprint (blue and total). Production scenarios including legumes (B–E) contribute the most to protein supply. On the other hand, scenario A (which does not include legumes) provides a much lower contribution, but guarantees the highest gross income, as it is based on the production of cash crops (tomatoes and cucumbers). Finally, Table S16 shows the specific water footprint (expressed in m^3 of water consumed per kilogram of protein produced) of the different protein-rich food products (animal products and legumes) included in the production scenarios.

Table S14. Total production of vegetables and legumes for the model farm (as obtained with different crop rotation systems, see Fig. 2 in the main text), fraction potentially consumed by the household and fraction available for sale.

Crop rotation system	**Total production** (kg/year)	**Domestic consumption** (%)	**Available for sale** (%)
A	204,000	1	99
B	59,500	3	97
C	61,200	5	95
D	61,200	5	95
E	56,780	5	95

Table S15. Comparison of food production scenarios in terms of protein supply, annual income, water footprint (blue and total). Indicators are calculated over a time horizon of one year.

Crop rotation system	**Protein supply** (kg/year)	**Gross income** (USD/year)	**Total water footprint** (m^3/year)	**Blue water footprint** (m^3/year)
A	131.6	67,091	24,419	11,022
B	178.4	14,786	31,456	9,033
C	181.0	22,700	30,706	10,757
D	192.8	20,897	38,675	12,215
E	186.6	19,117	23,575	8,768

Table S16. Specific water footprint (direct contribution only) for protein-rich food products.

Product	**Specific water footprint** (m^3/kg)			
	blue	green	grey	total
Fish	7.90	–	–	7. 90
Sheep meat	0.36	9.47	0.24	10.07
Sheep milk	0.75	19.58	0.50	20.83
Chicken eggs	0.84	–	–	0.84
Chicken meat	0.52	–	–	0.52
Lentils[1]	3.51	2.05	–	5.56
Peas[2]	6.67	1.83	10.35	18.85

[1] Only scenario E. [2] Average of the values obtained for scenario B (cultivation in autumn) and scenarios C and D (cultivation in late winter-early spring).

S2.3. Contribution of domestic production to food security in the Gaza Strip

S2.3.1. *Nutritional analysis*

Per capita food supply (total and proteins) covered by domestic production, classified by food group, is reported in Table S17.

Table S17. Contribution of domestic production to food supply on a daily basis. Animal products (meat, fish, eggs and milk) and vegetables are produced in all the considered production scenarios, while legumes are included only in some (indicated between parentheses).

Food group	**Supply** (g day^{-1} person^{-1})	**Protein supply** (g day^{-1} person^{-1})
meat	21.0	2.7
fish	36.5	7.0
eggs	24.4	2.9
milk	60.6	3.6
vegetables	400.0	3.8 – 9.5
fresh legumes (B, C and D)	50.0	3.55
dried legumes (E)	15.0	3.7

S2.3.2. *Environmental sustainability*

Per capita water appropriation for the different production scenarios, estimated in terms of direct blue water footprint, is reported in the main text (Fig. 5).

Per capita land appropriation for domestic food production is shown in Table S18 separately for the different crops. Results for the different production scenarios are summarized in Fig. S1, which shows that the area available for agriculture (ca. 51 m^2 per capita) would not be sufficient in the majority of the analysed scenarios, with land appropriation ranging between 89% (scenario A, which, however, does not include legumes and guarantees, therefore, a lower protein supply) and 345% of the corresponding availability.

Table S18. Land appropriation for domestic production of different crops.

Product	**Area** (m^2 per capita)
cabbage	36.3
cauliflower	62.2
cucumber	19.0
eggplant (B)	31.4
eggplant (D)	40.3
pepper (C and E)	76.8
tomato	15.3
lentil	50.9
pea (B)	28.7
pea (C and D)	39.8
sheep and poultry	11.1
fish	0.0

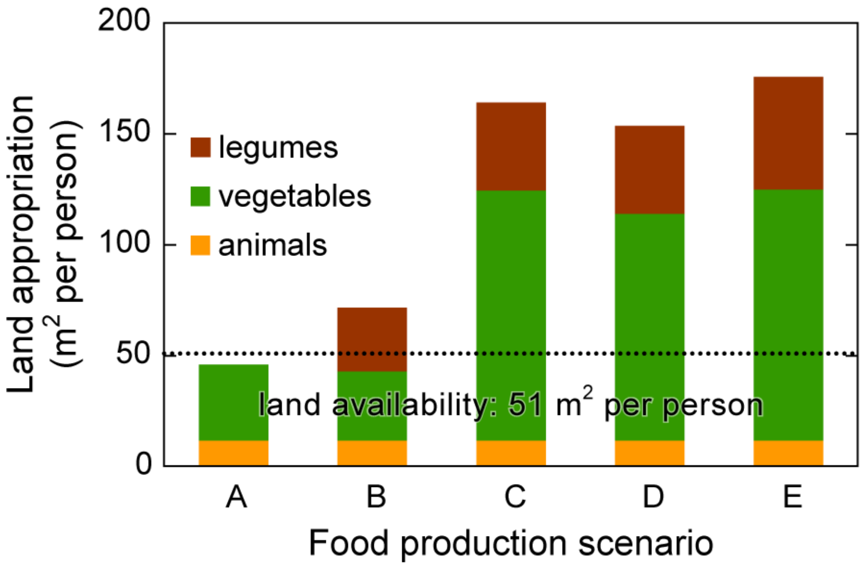

Fig. S1. Per capita land appropriation for domestic food production.

S2.3.3. *Economic analysis*

Table S19 compares the average monthly expenditure on food in the Gaza Strip with the economic value of domestic food production (estimated in terms of savings on food costs thanks to household production). Results show that domestic production allows a reduction of expenditures on food from 51.6 to about 33 USD per month per capita. In particular, domestic production of vegetables and legumes allows to save ca. 80% of the expenditures on this food group. Animal production has also a relevant importance for household economy, as it allows covering more than half the requirement of meat and fish, and 100% of the requirement of dairy products and eggs.

Table S19. Comparison between average monthly expenditure on food in the Gaza Strip and the economic value of domestic food production.

Food group	**Average expenditure** (USD per capita)	**Domestic production** (USD per capita)
meat and fish	16.4	6.8
dairy and eggs	3.9	3.9
vegetables, legumes and tubers	9.7	7.7 – 8.0[1]
fruits and nuts	5.2	0.0[2]
bread and cereals	9.6	0.0
oils and fats	3.0	0.0
sugar and confectionery	3. 9	0.0
total	51.6	18.4 – 18.7

[1] Depending on the specific crop rotation system adopted.

[2] This category is included even if the recommended portion of fruits and vegetables (400 g per day per capita) is considered to be fully covered by vegetables.

Table S20 compares the residual monthly expenditure on food (calculated as the difference between the average expenditure on food in Gaza and the economic value of domestic production) and the gross income deriving from selling the production that is not dedicated to domestic consumption.

Depending on the crop rotation system included in the production scenario, the ratio between residual expenditure and gross income varies between 11% (for scenario A, based on the cultivation of cash crops) and 47% (for scenario B, which is based on the less remunerative crop rotation system).

Table S20. Comparison between monthly expenditure on food (net of the economic value of domestic production) and gross income.

Crop rotation system	**Expenditure on food** (USD per capita)	**Gross income** (USD per capita)	**Expenditure-to-income ratio** (%)
A	33.2	310.6	11
B	32.8	69.2	47
C	32.8	105.7	31
D	32.8	97.4	34
E	33.1	88.8	37

S3. Supplementary references

Al-Najar, H., 2011. The integration of FAO-CropWat model and GIS techniques for estimating irrigation water requirement and its application in the Gaza Strip. Nat. Resour. 2, 146–154. doi:10.4236/nr.2011.23020

Aquamax, 2008. Sustainable alternatives to fishmeal and fish oil to produce fish feeds. Aquamax News, August 2008, No. 3.

Bayart, J.-B., Bulle, C., Deschênes, L., Margni, M., Pfister, S., Vince, F., Koehler, A., 2010. A framework for assessing off-stream freshwater use in LCA. Int. J. Life Cycle Assess. 15, 439–453. doi:10.1007/s11367-010-0172-7

Daghir, N. (Ed.), 2008. Poultry production in hot climates, 2nd ed. CABI, Wallingford.

Dentoni, M., 2013. Risk analysis and mitigation of seawater intrusion for the Gaza Strip coastal aquifer under climate induced changes. PhD Thesis, Università degli Studi di Cagliari, Cagliari.

Epstein, H., 1982. Awassi sheep. World Anim. Rev. 44, 11–27.

FAO, 1989. Small ruminants in the Near East. FAO, Rome.

FAO, 2003. Executive report of the food security assessment - West Bank and Gaza Strip. FAO, Rome.

FAO, 2016. FAOSTAT. http://faostat3.fao.org/home/E (last accessed 04/07/2016).

FAO, USDA, 1982. Food composition tables for the Near East. FAO, Rome.

FAO, WHO, 2005. Fruits and vegetables for health. Report of a join FAO/WHO Workshop, 1–3 September 2004, Kobe, Japan. WHO, Geneva.

FAO, WHO, UN, 1991. Energy and protein requirements. WHO, Geneva.

Goedkoop, M., Heijungs, R., Huijbregts, M., Schryver, A. De, Struijs, J., Zelm, R. Van, 2009. ReCiPe 2008. A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. First Edition. Report 1: Characterization. Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieu, Den Haag.

HHS, USDA, 2015. Dietary guidelines for Americans 2015–2020, 8th ed. U.S. Government Printing Office, Washington.

Hoekstra, A.Y., Chapagain, A.K., Aldaya, M.M., Mekonnen, M.M., 2011. The Water Footprint Assessment Manual. Earthscan, London and Washington.

INRAN, 2003. Linee guida per una sana alimentazione italiana. INRAN, Rome.

ISO, 2014. ISO 14046:2014 – Environmental management – Water footprint – Principles, requirements and guidelines. ISO, Geneva.

Martens, B., Miralles, D.G., Lievens, H., van der Schalie, R., de Jeu, R.A.M., Fernández-Prieto, D., Beck, H.E., Dorigo, W.A., and Verhoest, N.E.C.: GLEAM v3: satellite-based land evaporation and root-zone soil moisture, Geosci. Model Dev. Discuss. 1–36. doi: 10.5194/gmd-2016-162, 2016

Mekonnen, Hoekstra, 2011. The green, blue and grey water footprint of crops and derived crop products. Hydrol. Earth Syst. Sci. 15, 1577–1600. doi:10.5194/hess-15-1577-2011

Mekonnen, M.M., Hoekstra, A.Y., 2012. A global assessment of the water footprint of farm animal products. Ecosystems 15, 401–415. doi:10.1007/s10021-011-9517-8

Miralles, D.G., Holmes, T.R.H., de Jeu, R.A.M., Gash, J.H., Meesters, A.G.C.A., Dolman, A.J., 2011. Global land-surface evaporation estimated from satellite-based observations. Hydrol. Earth Syst. Sci. 15, 453–469. doi: 10.5194/hess-15-453-2011

PCBS, 2009. Agricultural Statistics 2007/2008. PCBS, Ramallah.

PCBS, 2011. Land-use statistics. http://www.pcbs.gov.ps/site/lang__en/733/default.aspx (last accessed 04/07/2016).

PCBS, 2012. Agriculture statistics survey 2010/2011: Main results. PCBS, Ramallah.

PCBS, 2015. Registered foreign trade statistics. Goods and services, 2014. Main results. PCBS, Ramallah.

PCBS, 2016a. Consumer Price Index. http://www.pcbs.gov.ps/site/lang__en/695/default.aspx (last accessed 04/07/2016).

PCBS, 2016b. Producer Price Index. http://www.pcbs.gov.ps/site/lang__en/747/default.aspx (last accessed 04/07/2016).

Pfister, S., Koehler, A., Hellweg, S., 2009. Assessing the environental impact of freshwater consumption in life cycle assessment. Environ. Sci. Technol. 43, 4098–4104. doi:10.1021/es802423e

PWA, 2014. Gaza Water Resources Status Report, 2013/2014. PWA, Ramallah.

SINU, 2014. Livelli di assunzione di riferimento di nutrienti ed energia per la popolazione italiana. IV revisione. SINU, Firenze.

Weidema, B.P., Bauer, C., Hischier, R., Mutel, C., Nemecek, T., Reinhard, J., Vadenbo, C.O., Wernet, G., 2013. Overview and methodology. Data quality guideline for the ecoinvent database version 3. Ecoinvent report 1(v3). The ecoinvent Centre, St. Gallen.