Sustainability **2014**, *6*, 1729-1746; doi:10.3390/su6041729

OPEN ACCESS

sustainability

ISSN 2071-1050

www.mdpi.com/journal/sustainability

Article

Combining Satellite Data and Models to Assess Vulnerability to Climate Change and Its Impact on Food Security in Morocco

Saloua Rochdane [1], Lahouari Bounoua [2,*], Ping Zhang [2,3], Marc L. Imhoff [4], Mohammed Messouli [1] and Mohammed Yacoubi-Khebiza [1]

[1] Department of Environmental Sciences, Faculty of Sciences Semlalia, Cadi Ayyad University, B.P. 2390, Boulevard Prince My Abdellah, Marrakesh 40000, Morocco; E-Mails: rochdane@yahoo.fr (S.R.); messouli@ucam.ac.ma (M.M.); yacoubi@ucam.ac.ma (M.Y.-K.)

[2] Biospheric Sciences Laboratory, Code 618, NASA Goddard Space Flight Center, Code 618, Greenbelt, MD 20771, USA; E-Mail: ping.zhang@nasa.gov

[3] Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD 20742, USA

[4] Joint Global Change Research Institute 5825 University Research Court, Suite 1200, College Park, MD 20742, USA; E-Mail: Marc.Imhoff@pnnl.gov

* Author to whom correspondence should be addressed; E-Mail: lahouari.bounoua@nasa.gov; Tel.: +1-301-614-6631; Fax: +1-301-614-112-6695.

Received: 31 January 2014; in revised form: 18 March 2014 / Accepted: 19 March 2014 / Published: 3 April 2014

Abstract: This work analyzes satellite and socioeconomic data to explore the relationship between food and wood demand and supply, expressed in terms of net primary production (NPP), in Morocco. A vulnerability index is defined as the ratio of demand to supply as influenced by population, affluence, technology and climate indicators. The present situation (1995–2007), as well as projections of demand and supply, following the Intergovernmental Panel on Climate Change, Scenarios A2 and B2, are analyzed for a 2025 horizon. We find that the food NPP demand increased by 34.5%, whereas the wood consumption NPP demand decreased by 19.3% between 1995 and 2007. The annual NPP required to support the population's food and wood appropriation was 29.73 million tons of carbon (MTC) in 2007, while the landscape NPP production for the same year was 60.24 MTC; indicating that the population appropriates about 50% of the total NPP resources. Both scenarios show increases in demand and decreases in supply. Under A2, it would take more than 1.25 years for terrestrial ecosystems in Morocco to produce the NPP appropriated by populations in one

year. This number is 0.70 years under B2. This already high vulnerability for food and wood products is likely to be exacerbated with climate changes and population increase.

Keywords: satellite; model; vulnerability index; climate change; food security; Morocco

1. Introduction

Warming of the climate system is unequivocal and is associated with surface climate variability [1]. Inter-annual variability in precipitation has important consequences on ecosystem functioning and may have predictable impacts on plant's net primary production (NPP) and crop yields. In the middle and high latitudes, increases in temperature and precipitation associated with increases in the atmospheric CO_2 concentration may have some beneficial impacts on plant growth [2,3], while in arid and semi-arid regions, even small temperature increases may have negative impacts [4]. If these climate trends continue in the future, they may alter local food production [5–7] and increase the vulnerability of local populations, especially in developing countries, where nearly 70% of people live off agricultural products in rural areas and where the livelihoods of roughly 450 million of the world's poorest people are entirely dependent on managed ecosystem services [8].

North African countries are expected to be more exposed to future climate change adverse effects [1]. It is projected that precipitation will decrease and temperature will increase in the entire Mediterranean region, including northern Africa. With a total population of about 31 million in 2007, Morocco—a North African country—counts about 1.6 million undernourished people, about 5% of its population [9]. Although agricultural production has been rising in the past few years, the continuously growing need for food, compounded by adverse climate conditions, has brought food security to the forefront as a concern for government and land owners alike. In the near future, Morocco's population is expected to increase and so is its food demand for a finite land resource and the same or decreasing amount of precipitation water.

The human demand for the products of photosynthesis (NPP) is a powerful measure of the aggregate footprint of human action on the biosphere [10] and an indicator of food security and the vulnerability of the population to climate variability and changes. Assessments of food security and vulnerability are central to the survival and sustainability of population livelihoods and social structure. Investments are therefore needed to improve our ability to understand, predict, mitigate or otherwise adapt to the multifaceted impacts of climate change, demographic evolution and technological advances. Better use of climate information in assessing risks and vulnerability and developing safety nets and insurance products as an effective and practical response is already being piloted in some areas with fairly positive results [11].

In this paper, we use a methodology similar to that developed in Imhoff *et al.* [10] to estimate the fraction of terrestrial NPP appropriated to produce the food and wood products required to support local populations in Morocco. This approach allows a comparison of the rate of NPP required to support human appropriation (NPP demand) as influenced by demographic and technological changes with the rate of terrestrial NPP production (NPP supply) as influenced by climate changes. While based on Imhoff *et al.* [10], our methodology is distinctly different from it in the sense that it explicitly:

(1) Discriminates between urban and rural populations,
(2) Performs the estimates at a fine horizontal scale (5 km × 5 km) compatible with regional agro-ecological zones in Morocco, and most importantly,
(3) Considers climate change indicators as drivers of the NPP supply component.

This work presents the first detailed study using a unique combination of satellite, socioeconomic and field data to explore the relationship between food and wood demand and supply and projected near future climate change in Morocco. The study is carried out at a spatial scale fine enough to provide guidance on regional and local policies on food security given our current knowledge of impending climate change, socio-economic statistics, technological advances and resource constraints.

2. Materials and Methods

2.1. Model Formulation

In order to focus on the impact of changes in climate and socio-economic issues on food security, we developed a model that strikes a realistic balance between the complexity of the issue of demand and supply, the availability of data and the simplicity of the formulation. A vulnerability index (VI) was defined as the simple ratio between the NPP required to support the human appropriation for food and wood products, including fiber and paper, hereafter referred to as NPP demand, and the total terrestrial NPP produced by the landscape, referred to as the NPP supply, both expressed in grams of carbon as,

$$VI\ (D, S) = D\ (Pt, Pd, Te, Af)/S\ (T, P) \quad (1)$$

where D represents the demand and S the supply; Pt is the population total, Pd the population distribution (urban *versus* rural) and Te a technological development indicator representing the efficiency with which the supply is produced and includes harvest and processing efficiencies and transport and crop residue losses. Af is the Affluence represented by the average per capita consumption. S is the supply and represents the net primary production at the landscape level, with T and P representing the temperature and precipitation indicators of changes in the climate. As defined, VI allows us to map vulnerable regions where the demand approaches or exceeds the supply and represents the footprint of these two commodities (food and wood) appropriated from productive landscapes. VI is not defined over non-productive regions, such as desert areas, where the NPP is null.

We use this formulation to assess the current situation *ca*. 2007 and explore how variations in population, affluence, technology and climate will affect VI and, consequently, the future of food security and livelihood sustainability in Morocco by the year 2025. We regard the annual integral of the component of VI induced by the demand for food products as an indicator for food security.

2.2. Data

We use the United Nations Food and Agriculture Organization (UNFAO) consumption data on food and wood products reported by country on an annual basis. We developed a methodology similar to Imhoff *et al.* [10] to estimate the amount of NPP demand, at the landscape level, to generate the various food and wood products consumed in Morocco.

On the other hand, we use down-scaled climate projections for Morocco from Babqiqi [12], who used 30-year climatological daily mean, maximum and minimum temperatures, as well as precipitation recorded at 20 stations over the period 1961–2000 to reduce the scale of climate projection outputs from climate models used in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) for Scenarios A2 and B2. Although the down-scaling data is difficult, especially in arid regions, the Statistical Downscaling Model used in [12] performed relatively well across a variety of stations over Morocco. Using the root mean square error (RMSE) as a standard metric to evaluate the power of the downscaling and including the downscaling of the extreme, the downscaled temperature RMSE is less than 0.8 °C. This degree of accuracy is generally acceptable for the assessment of the water and energy exchanges in most climate projections models. This provides some assurance, but not absolute confidence, in the robustness of the model and the accuracy of its outputs.

The A2 scenario represents a heterogeneous world based on self-reliance and preservation of local identities, favoring high population growth and slow technological advances. In the B2 scenario, an emphasis on food self-reliance contributes to changes in affluence represented by a shift in dietary patterns towards local products, with relatively low meat consumption. The scenario assumes local solutions to economic, social and environmental sustainability with moderate population growth, intermediate levels of economic development and important improvements of technologies [13]. These two scenarios are the closest to bracket the trajectory of the evolution of society in Morocco and the associated changes in climate indicators [14].

3. Estimating NPP Demand and Supply

3.1. NPP Demand

As in Imhoff *et al.* [10], we define NPP demand as the total amount of terrestrial NPP required for generating the food products consumed by humans and the wood products appropriated for their own use by including the total organic matter lost into the end products. The process consists of recursively adding mass to the reported consumed product, taking into account losses due to harvesting, transportation and processing, as well as the root system of the whole plant, thereby rebuilding the total amount of NPP required to derive the consumed product. Starting with products consumed on an annual basis in Morocco, including vegetal foods and crop-fiber, meat, milk and eggs, as well as wood products (building and fuel), including paper and wood fiber, we have reconstructed the amount of NPP demand on the landscape to generate these products.

We have applied technological efficiency factors [15] considering Morocco as a developing country. We also estimated the below-ground allocation of carbon to data on consumed products to restore the total amount of NPP at the landscape level. Food products, such as grains, also used for livestock feed, have been accounted for separately and added to the total NPP demand. We define *in situ* consumption as the (local production + imports − exports) to constrain the country's total products consumed locally [15].

The NPP demand was calculated per capita and then applied to a gridded population map at 5 km × 5 km horizontal resolution to capture the spatial heterogeneities of the distribution of the NPP demand on the landscape. The UNFAO data does not differentiate between urban and rural population

consumption. Unlike Imhoff *et al.* [15], who considered a homogenous in-country consumption rate, this study makes an explicit distinction between urban and rural population consumption based on a 5 km × 5 km population map discriminating urban *versus* rural cells [16] to resample the NPP demand. The urban *versus* rural relative consumption of products considered in this study was determined through a field survey conducted in 39 regions (19 urban and 20 rural areas) in Morocco (Table 1).

Table 1. The percentage of urban and rural consumption for the different products. We used a distribution of 50/50 for crop fibers and wood fibers, as these product categories were not answered properly in the survey.

	Vegetal	Eggs	Milk	Meat	Wood	Paper
Urban	64	56	57	60	12	80
Rural	36	44	43	40	88	20

The consumption total reported by the UNFAO at the country level was then split into urban and rural consumption fractions using the survey results. This allowed us to estimate distinct per capita consumption rates for urban and rural populations. Finally, using a gridded population map at 5 km × 5 km, also discriminating urban *versus* rural pixels [16], it was possible to redistribute the NPP demand taking into account urban and rural regions separately.

3.2. NPP Supply

For this study, we use the NPP values generated by Zhao and Running [17]. These data were obtained from National Aeronautics and Space Agency (NASA) Moderate Resolution Imaging Spectroradiometer (MODIS) at 1 km × 1 km and spanned the period 2000–2011. We aggregated these global NPP to 5 km × 5 km and then precisely co-registered them to the land cover map over Morocco. We have used multiyear values to compute the rates of change in NPP during the last 10 years for specific vegetation classes and used the year 2007 NPP as a comparison for the most recent 2007 UNFAO consumption data and as a starting year for future projection scenarios.

4. Results and Discussion

4.1. Evaluation of the Current Situation

We have mined the UNFAO data for different product categories, including vegetal foods, meat, milk, eggs, crop-fiber, wood, paper and wood-fiber and estimated the total NPP demand expressed in million metric tons of carbon (MTC) for five different time periods between 1995 and 2007 (Table 2). Except for crop-fiber, which shows a substantial decrease from 1995 to 2007, NPP demand increased for all other food products. The largest relative increase was associated with milk, which almost doubled between 1995 and 2007, followed by meat and then vegetal food, which increased by about 27.30%. The increase in milk consumption is believed to be associated with extensive government efforts granted for the importation of improved breeds, the extension of breeding techniques and the fight against animal diseases, which have made the dairy products more readily available in Morocco [18]. On the other hand, an improved standard of living in both urban and rural households promoted the consumption of dairy products during the period [19]. Overall, the NPP demand for food

products has increased by 6.17 MTC or 34.5% between 1995 and 2007, primarily reflecting a 16.5% increase in population (Table 2) and an implicit improvement of living conditions in Morocco [19].

Table 2. Net primary production (NPP) demand (million metric tons of carbon (MTC)) and absolute and relative changes between 1995 and 2007.

	Population (million)	Vegetal	Eggs	Meat	Milk	Crop Fiber	Total Food Products	Wood	Paper	Wood Fiber	Total Wood Products	Total Appropriation
1995	27.21	11.91	0.64	4.83	0.38	0.15	17.91	6.35	0.30	0.11	6.75	24.66
2000	29.14	13.10	0.77	5.74	0.51	0.11	20.24	4.46	0.34	0.08	4.87	25.11
2003	30.21	13.94	0.76	6.26	0.54	0.11	21.61	4.57	0.38	0.20	5.15	26.76
2005	30.93	14.54	0.63	7.10	0.60	0.005	22.88	6.18	0.44	0.11	6.73	29.61
2007	31.70	15.16	0.67	7.56	0.69	0.01	24.08	5.12	0.44	0.09	5.65	29.73
Absolute change	4.49	3.25	0.03	2.73	0.31	−0.15	6.17	−1.23	0.14	−0.02	−1.10	5.07
Relative change (%)	16.50	27.30	4.56	56.54	80.37	−96.71	34.45	−19.33	48.66	−18.08	−16.33	20.54

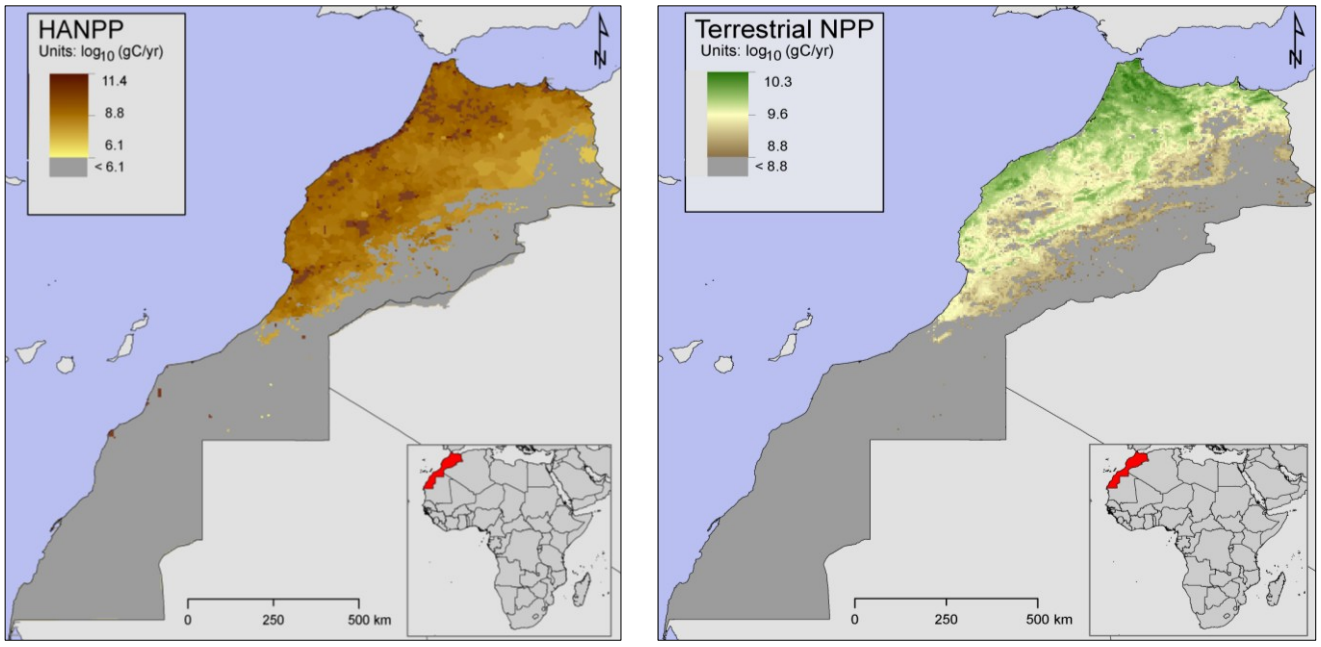
The NPP demand associated with wood has neatly decreased in 2000 and 2003 compared to the 1995. A subsequent increase has been observed in 2005 and is believed to be linked to the global recession at the start of the century and the consequent increase in fuel cost in Morocco during late 2002 [20]. Overall, however, the NPP demand for wood consumption has decreased by 19.3% over the study period. Our analysis shows that NPP appropriation for paper has increased by 48.7% or about 0.14 MTC compared to 1995, corresponding to an increase in actual paper consumption of 0.4 kg per capita per year. This is an important rate of increase for a country with an annual average per capita consumption of 13.16 kg, an increasing rate of use of electronic media [21] and an increase in the recycling rate [22]. However, it is not an alarming rate considering neighboring industrialized countries, such as Spain, which consumes about 150 kg per capita per year, and a developing country, such as Tunisia, with a yearly per capita consumption of 35 kg [23]. The constant appropriation of paper between 2005 and 2007 is probably a reflection of the recycling program introduced in 2005 [22]. The NPP demand for wood-fiber is small and indicates a decrease of about 18.1% over the period of analysis. Overall, the appropriation of total wood products (wood, paper and wood-fiber) shows substantial interannual variation around an average value of 5.83+/−0.88 MTC and a decrease of about 16.3% in 2007 compared to the 1995 baseline.

Based on our field survey, the urban population in Morocco *ca*. 2010 represents only 55.9% of the total population, yet it appropriates a substantial fraction, nearly 70%, of the total NPP demand. Except for wood, the urban population has larger appropriation than the rural one for all other products. The consumption of wood in urban settings is mainly for use as fuel in the traditional public communal bathhouses 'Hammams', which are still in use in many modern cities of Morocco. At the country level, the total NPP demand for all products increased by about 5.1 MTC or 20.5% between 1995 and 2007 (Table 2). The division of crop and wood fibers with equal weight between the urban and rural populations was assumed and not based on survey results, which were the basis for all other results.

While this may affect the appropriation distribution between urban and rural populations, it does not affect the total appropriation from which the fiber represents only a small portion (~3%).

The distribution of the total NPP required for human appropriation (NPP demand), as well as the total NPP generated on the landscape (NPP supply) is shown in Figure 1. We estimate the spatially integrated total annual amount of NPP demand required to support the Moroccan population to be 29.73 MTC in 2007 (Figure 1A) when the total NPP produced and available on the landscape (supply) for the same year was 60.24 MTC (Figure 1B). This NPP demand value is at the lower end of the range of regional estimates found in Imhoff and Bounoua [10] and indicates that the population appropriated about 50% of the country's natural NPP resources in 2007. As expected, and as reported in Imhoff and Bounoua [10], the NPP appropriation is mostly centered on large populated urban centers.

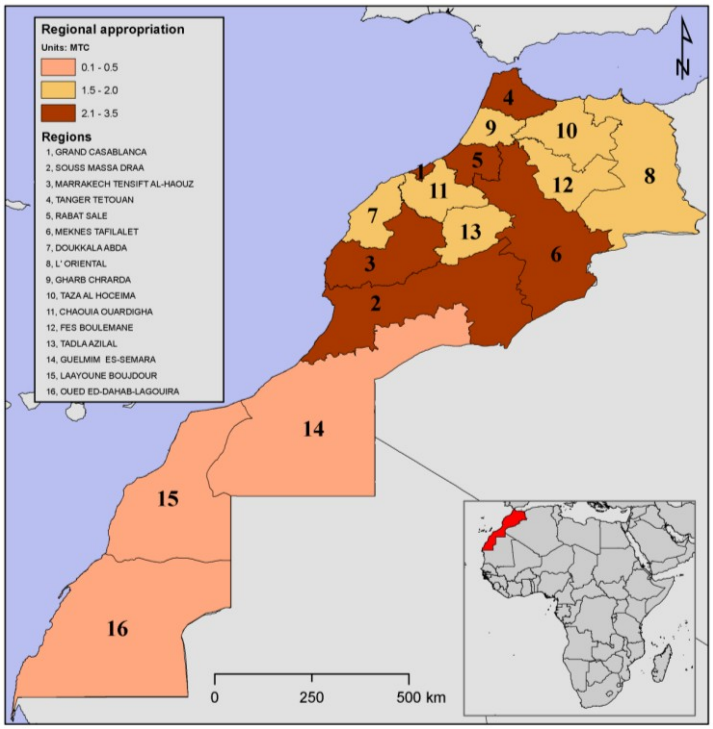
Figure 1. Distribution of annual total: (**A**) NPP demand for human appropriation (**B**) NPP supply (see the text for details).



(**A**) (**B**)

The distribution of the total NPP demand shows three broad groups of regions (Figure 2). A group with an annual appropriation ranging from about 2.1–3.5 MTC, which includes large urban regions, such as the Grand Casablanca, Marrakech Al-Haouz, Tanger-Tetouan and the region of Meknes Tafilalet. A second group with appropriation ranging from 1.5–2.0 MTC includes other large agricultural regions, such as Doukkala, l'oriental, le gharb, Fez and Tadla-Azilal; and a third group with the smallest annual appropriation from 0.1–0.5 MTC, including the arid regions of Es-Semara, Laayoune and Oued Ed-Dahab.

Figure 2. Regional distribution of total NPP demand in MTC for the year 2007.



In order to assess the vulnerability in food and wood products separately, we conducted a detailed analysis, whereby NPP demand for food products is compared directly to NPP supply generated on agricultural lands and the NPP demand for wood products is compared to NPP supply generated on forests and woodlands. For the computation of the NPP demand for food products, we separated the fraction of meat produced using pasture lands [24,25] and included only the component that used grain for feed, so that the total NPP demand for food products can be compared to the NPP generated from agricultural lands. Similarly, in the computation of the NPP supply for wood products, we partitioned the MODIS woody savannahs class into wooded and savannah components using fractions provided by [26,27] and included only the wooded part in the computation.

The NPP supplies from agricultural and wooded lands were estimated from satellite data and aggregated over the corresponding land cover classes. We considered food products to be supplied by classes labeled cropland and cropland/natural vegetation mosaic, including cereals in the MODIS classification scheme [27], while the NPP for wood products is supplied by forests and other wooded classes. We have computed these requirements from 2000 to 2007, as the supply part from MODIS is only available starting in 2000 [28].

Table 3 indicates that the NPP demand for food as a percent of the supply is more than 80% for all years, but does not exceed 100%, except for 2005, when it reached 103.7%. It is generally known that 2005 was a drought year over Morocco, and the national cereal production was reduced by about half [29]. This is also captured in the MODIS data, which shows an average NPP value of about 22.73 MTC for 2000, 2003 and 2007 and a low value of only 19.50 MTC in 2005. Had 2005 been a normal year with an average supply value, the demand would have been only 89.0% of it. These results indicate that in Morocco, as of 2007, the NPP supply in all exploited agricultural lands is barely enough to balance the NPP demand for food consumption, including the imported component. This represents a high level of

vulnerability and leads to the speculation that if population increases or climate conditions worsen, this balance may be altered in a way that makes the local population more food insecure, if no action is taken to mitigate or otherwise adapt to future conditions.

We also note that while the demand for wood products is continuously increasing over time, the supply in wood as reflected by the satellite record of total NPP in woodlands and forests remains insufficient to balance population demand. For the entire period, the ratio of the NPP demand to NPP supply exceeds 180% of the wooded ecosystems potential, suggesting that the population in Morocco appropriates in one year about twice as much wood products as the land can produce, indicating a high level of vulnerability. The absence of large stocks of wood product supplies in Morocco is compensated for by imports; a high cost to the economy and a remote ecological footprint.

Table 3. Evolution of NPP for food and wood products demand and supply for 2000, 2003, 2005 and 2007 in MTC.

	2000	**2003**	**2005**	**2007**
Food				
NPP demand	18.08	19.26	20.22	21.24
NPP supply	22.23	23.79	19.50	22.17
Demand/supply (%)	81.31	80.98	103.68	95.83
Wood				
NPP demand	4.88	5.16	6.74	5.65
NPP supply	2.67	2.51	2.27	2.95
Demand/supply (%)	182.44	205.72	297.07	191.54

This annual amount of NPP demand was compared to a map of annual NPP supply to produce a spatially distributed vulnerability index over the entire country (Figure 3). Results show large variations in VI across the country, reflecting the population distribution and land productivity. The largest indices are apparent over urban regions with large populations and where the productivity of the landscape, altered by urbanization, is low. The vulnerability index is from 100% to 200% in most urban areas and exceeds 200% in urban centers, suggesting an annual NPP demand much higher than what the local natural landscape can produce. Urban suburbs experience a VI from 45% to 80%, whereas in remote rural areas, the vulnerability index is less than 45%, partly due to higher land productivity and clement climate and partly to small and sparsely distributed rural populations. In the semi-arid regions south of the Atlas Mountain, where soils are poor and the climate is harsh, even a small appropriation led to large VI. In large cities, such as Es-Semara, Laayoune and Dakhla in the extreme south and Errachidia in the east with a high population count and low productivity, the vulnerability index is larger than 200%. In desert areas, where the gridded NPP supply is null and the population is small, VI is not defined.

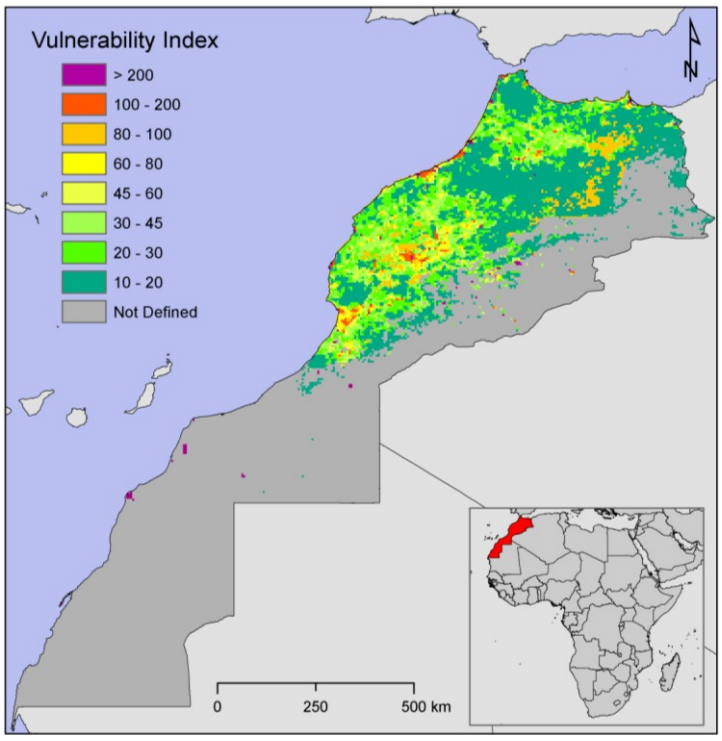
These results are in line with those from Imhoff *et al.* [10], which show at a global scale a ratio of NPP demand to supply varying from nearly 0% in sparsely populated areas to over 30,000% in large urban agglomerations with low productivity. As seen in Table 3, the vulnerability index is dominated by the appropriation for food and wood products and may increase, due to changes in forcing factors, such as over-exploitation of the landscape, increases in population or worsening of climate conditions, all of which are already happening in Morocco. Given this level of vulnerability, the country should

renew its emphasis on shoring up its domestic food supply to avoid dependence on costly food imports and develop a national food security policy to improve the access for all its people and at all times to adequate food for a healthy and productive life through increases in production, productivity, and trade [30].

Since the NPP demand depends on population size and distribution, technology and affluence, any change in these forcings will affect VI. Similarly, the VI will be affected by changes in the supply component through changes in climate signatures, such as temperature and precipitation, whether induced by interannual variations or long-term climate trends.

Increased pressure on agricultural production is likely to require an expansion in agricultural land use in an attempt to compensate for a decrease in production due to unfavorable climate change and to accommodate for a larger urban population. Some new land could be brought into cultivation, but the competition for land for other human activities makes this an increasingly unlikely and costly solution [31]. This could be especially true in Morocco, where arable lands are confined to a relatively narrow region north of the Atlas Mountain, water is scarce, technological development is average and population growth not yet stabilized, leading, thus, to an increasingly growing demand for agricultural products.

Figure 3. Vulnerability map (%) showing the ratio of NPP supply to demand at 5 km × 5 km resolution. Vulnerability index (VI) values of 100% indicate that the population appropriates in one year all the landscape production.



4.2. Plausible Future Evolution

Future food security depends on investment decisions made today for addressing climate change and adaptation issues, conserving water resources, bioengineering new seeds, renewing investments in agricultural water and diversifying food production away from traditional farming [32]. The consumption-based approach for estimating NPP demand allows for some basic socio-economic

factors to be introduced as modulators to the processes. Holdren and Ehrlich [33] introduced a simple relationship (I = PAT) describing the overall ecological impact (I) of human activities as a direct product of population size (P), affluence (A) and technology (T). We extend this model to include the impact of climate (C) through changes in temperature and precipitation and their impact on the NPP supply, such as I = PATC. We elect to perform a quantitative assessment of the aggregated impact of these factors on the NPP demand and supply under two of the IPCC Special Report on Emissions Scenarios (SRES), A2 and B2 [34], and compare it to the 2007 baseline.

4.2.1 Projection of the Demand

Following these scenarios, we have assumed that under B2 and for the horizon of 2025, Morocco will attain the same technological advance (T) as the industrialized nations have now [10]. Similarly, and because the technological advance in A2 is expected to be lower than that in B2, we have assumed that the technological advance in A2 will lag behind that of B2 by five years. The level of technology is related to efficiencies in harvest and crop residue left on the ground, efficiencies in wood processing and transport and an increase in the level of recycling, which, in our calculation, represent the aggregate technological development indicator (Te) of the country. Furthermore, and for consistency, we have considered for Morocco the average annual population growth rate used in the IPCC scenarios [34]. Finally, for affluence, we have assumed that under A2, by 2025, the per capita appropriation in Morocco will double with respect to that of 2007, whereas for B2, we have estimated the per capita appropriation from the actual rate of change computed over the period 1995–2007 and extended it to 2025.

Using these scenarios, we assessed the sensitivity of the total NPP demand to each of these factors (Table 4). We find the population size to have an important effect on NPP demand, and so does affluence, which, under the A2 assumptions, could increase by more than 100% compared to 2007. While technological advance modestly reduced the NPP required, it did more so in the B2 than the A2 scenario. Overall, from 2007 to 2025, the aggregate impact of P, A and T increased the total NPP demand from 29.73 MTC to 71.58 MTC (140.8%) under A2, while it increased it only to 39.53 MTC (33%) under B2, suggesting that for the next 15 years, the B2 scenario provides a better socioeconomic trajectory for Morocco.

This simple sensitivity analysis shows that the NPP demand can be reduced by simply changing nutritional habits and increasing technological efficiencies in production. It also helps to identify areas where adaptation strategies need to be emphasized. For example, improving food production efficiency can increase the food supply. It is known that in high-income countries, as much as 30% of all food grown may be lost or wasted before and after it reaches the consumer [35], while in low-income countries, much waste occurs on the farm and in the transportation of goods [15]. As such, investment in physical infrastructure to reduce losses during harvesting, transportation, processing and storage of goods is achievable, practical and of high priority.

Table 4. Total NPP demand as a function of changes in population, affluence and technology under the A2 and B2 scenarios and relative change with respect to year 2007.

	Population scenario (P)		**Affluence scenario (A)**		**Technology scenario (T)**		**PAT**	
	A2	B2	A2	B2	A2	B2	A2	B2
2015	32.80	31.22	39.67	32.90	29.37	29.20	64.77	33.88
2020	34.87	32.37	49.58	34.86	29.04	28.73	68.06	36.63
2025	37.06	33.57	59.50	36.83	28.73	28.30	71.58	39.53
Relative change (%)	24.70	12.95	100	23.92	−3.33	−4.78	140.84	33.02

4.2.2. Projection of Supply

The IPCC AR4 projects a warming and drying over the entire Mediterranean region, including Morocco [1]. Similar to the IPCC AR4 results, the down-scaled analysis used in this study shows a countrywide precipitation decrease associated with an increase in surface temperature. By 2025, the decrease in precipitation is expected to be about 10% under B2 and will reach 20% under A2, while the temperature may increase by 1 °C and 2 °C under B2 and A2, respectively [12]. High temperature and low soil moisture are known to inhibit photosynthesis [36] for most plants and reduce production [37].

To obtain the NPP supply projections for the horizon of 2025, we used MODIS NPP products. We aggregated the MODIS land use classes under three broad biomes: (1) woodlands, including forests and parts of the woody savannahs; (2) agricultural lands, including cereals and croplands; and (3) a biome named 'other classes', where all other classes were lumped (Table 5). Starting from 2007, the NPP of each of these three biomes was projected for 2015, 2020 and 2025 under both A2 and B2. For agricultural lands, under A2 and B2, we used NPP rates of decrease of 1.83%/y and 1.58%/y for cereals and 3.21%/y and 3.09%/y for croplands [38]. For woodlands and 'other classes', we have projected the NPP using average rates of change obtained using the past ten years of MODIS NPP observations, modulated by the relative difference of the C3 and C4 rates of change given by Bindi *et al.* [38] for A2 and B2. In all these projections of supply, we considered business as usual conditions and did not include any technological improvement.

Table 5. NPP supply projections from 2007 to 2015, 2020 and 2025 under the A2 and B2 scenarios in MTC.

NPP Observations			**NPP Projections**					
Biomes		2007	2015		2020		2025	
			A2	B2	A2	B2	A2	B2
Woodlands		2.9500	2.9528	2.9531	2.9553	2.9560	2.9579	2.9589
Agricultural lands	Cereals	2.6920	2.6427	2.6493	2.5944	2.6073	2.5469	2.5659
	Croplands	19.4740	18.849	18.872	18.243	18.289	17.658	17.724
Others classes		35.1220	34.659	34.745	34.204	34.373	33.756	34.007
Total		**60.2390**	**59.103**	**59.219**	**57.997**	**58.225**	**56.919**	**57.256**

Woodlands include: evergreen needleleaf trees, evergreen broadleaf trees, deciduous broadleaf trees, mixed trees classes and 50% of woody savannas; agricultural lands include: croplands and cropland/natural vegetation mosaic with cereal classes; others classes include: closed shrublands, open shrublands, savannas, permanent wetlands, urban and built-up, barren or sparsely vegetated and 50% of woody savannas.

We find that both under A2 and B2, the woodland NPP supply increases slightly. Our analysis indicates that under the more optimistic B2 scenario, the NPP supply for wood could increase by 0.0031 MTC for 2015 and 0.0089 MTC by 2025. This relatively small increase is mostly driven by an increase in productivity from woody savannas, as indicated in MODIS data. The food products (cereals and croplands) are projected to undergo an important decrease. Again, for B2, cereals are projected to lose 0.0427 MTC in 2015 and 0.1261 MTC in 2025. Similarly, cropland productivity loss is projected to reach 0.6020 MTC in 2015 and 1.750 MTC, or 9% of the 2007 baseline in 2025. Overall, under B2 and including all 'other classes', the NPP supply is projected to decrease 1.02 MTC in 2015 and 2.98 MTC in 2025. Furthermore, compared to 2007, and as expected, the NPP will decrease more in the A2 than the B2 scenarios.

4.2.3. Plausible Future Situation

Our analysis shows a projected increase in demand coupled with a decrease in supply for both the A2 and B2 scenarios. Therefore, in order to meet the challenge of reducing vulnerability and achieving food security in a changing climate, not only food production in Morocco must undergo a transformation, but a more responsible consumption and use of modern technology must be put in place, as well, to reduce the adverse effects of climate and population growth. To illustrate that, a sensitivity analysis showing changes in NPP demand and supply as a function of changes in population (P), affluence (A), technology (T) and climate (C) drivers is presented (Table 6). The sensitivity analysis assumes the variation of one variable at a time, keeping all other invariant, and projects the NPP demand from its 2007 baseline of 29.73 MTC and the NPP supply from its 2007 total amount of 60.23 MTC, assuming, at the first order, that all the NPP produced over the country may be converted to NPP for food and wood commodities. Compared to 2007, the increase in population alone to its 2025 level increased the NPP demand from 29.73 to 37.07 MTC under A2 (24.07%) and to 33.57 MTC under B2 (12.95%) (Table 6). Affluence also appears to play a significant role; the difference between A2 and B2, representing changes in nutritional habits, can save about 22.67 MTC of the NPP demand by 2025. The effect of improving technology resulted in a modest decrease in NPP demand of one and 1.43 MTC under A2 and B2, respectively. Finally, acting alone, climate change would decrease the NPP supply by 5.51% under A2 and 4.95% under B2. The overall impact of these forcings acting together (I = PATC) shows the NPP demand to reach 125.75% of the supply by 2025 under A2, indicating that it would take more than one and one quarter year for all the ecosystems in Morocco to produce the amount of NPP appropriated by local populations in one year. As expected, under the less constraining B2 scenario, the overall effect of the same forcings led to a ratio of NPP demand to supply of 69.05%. The projections indicate that under A2, the VI reaches 109.58% in 2015 and 117.36% in 2020, whereas under the B2 scenario, corresponding values will reach only 57.22 and 62.91%, respectively. If the NPP demand was constrained to be supplied exclusively from agricultural lands and woodlands, VI would reach 309.02% under A2 and 170.03% under B2 in 2025, a clearly non-sustainable situation.

Table 6. Sensitivity analysis showing total NPP demand and supply (MTC) projected for the year 2025 and starting from 2007 as a function of population (P), affluence (A), technology (T) and climate (C) under the A2 and B2 scenarios. D represents the NPP demand; S represents the NPP supply. The last row represents the ratio of total NPP demand to NPP supply in percent for 2025. The 2007 NPP demand is 29.73 MTC, and the NPP supply is 60.23 MTC.

Combination					Scenarios A2		Scenario B2	
	P	A	T	C	D	S	D	S
1	↑	-	-	-	37.06		33.57	
2	-	↑	-	-	59.50		36.83	
3	-	-	↑	-	28.73		28.30	
4	-	-	-	↑		56.92		57.26
5	↑	↑	↑	↑	71.58	56.92	39.53	57.26
Vulnerability Index for 2025 (%)					125.75		69.05	

5. Concluding Remarks

We present the first detailed analysis using a unique combination of satellite, socioeconomic and field data to explore the relationship between food and wood demand and supply in Morocco. We analyze both the present and projected near future situations at spatial scales fine enough to provide guidance on local policies on food security. Because the UNFAO data reflects the influence of population, affluence and product preferences, combined with our model, which includes the effect of technology on the demand and aspects of the effect of climate change on the supply, we were able to model food and wood appropriation for both current conditions, as well as potential future socioeconomic trajectories in Morocco. The methodology fully accounts for impacts in particular ecosystems and identifies the specific source areas for the NPP required for foods and wood.

We find the total annual amount of NPP required to support the Moroccan population to be 29.73 MTC in 2007, whereas the total NPP produced and available on the landscape for the same year is 60.24 MTC. Overall, we find that the NPP demand for food products has increased by 34.5% between 1995 and 2007, primarily reflecting an increase in population and an implicit improvement of living conditions in Morocco, and the NPP demand for wood consumption has decreased by 16.3% over the same period. This result indicates that the population appropriated about 50% of the country's natural NPP resources in 2007 with large regional variability.

Our analysis shows that the NPP demand for food is high and, as a fraction, represents more than 80% of the NPP supplied by agricultural lands for the entire study period. This indicates that, including the imports of food, as of 2007, the NPP supply in all agricultural exploitations is barely enough to balance the NPP demand for food consumption. This represents a high level of vulnerability if no action is taken to mitigate adverse conditions. Although not part of this land-based study, fish production represents an important part of the food security balance in Morocco.

For both IPCC SRES A2 and B2, we show a projected increase in demand coupled with a decrease in supply. As a first order, we considered that all the NPP produced over all of the landscape may be used for food and wood commodities. In that case, the overall impact of changes in population,

affluence, technology and climate acting together as expressed by VI showed that under the A2 scenario, it would take more than one and one quarter year for all the terrestrial ecosystems in Morocco to produce the amount of NPP demand appropriated by local populations in one year. This ratio was 69.05% under the B2 scenario. When the NPP demand was constrained to be supplied exclusively from agricultural lands and woodlands, VI would reach 309.02% under A2 and 170.03% under B2 in 2025. While these two cases represent the extremes, they do bracket the potential future socioeconomic evolution in Morocco.

Acknowledgments

The authors would like to thank the African Climate Change Fellowship Program (ACCFP) and the System for Analysis Research and Training (START) secretariat for their financial support. Thanks are also extended to the staff of the Biospheric Sciences Laboratory of NASA's Goddard Space Flight Center.

Author Contributions

Dr. Rochdane performed all calculations presented in this work including the vulnerability index parameters. She developed and calculated the various socioeconomic projections scenarios and realized the regional vulnerability mapping and conducted the field survey. She also worked on the discussion of the results. Dr. Bounoua developed the scientific idea of this research paper, supervised and guided this work. He formulated and developed the vulnerability index model presented in this paper and provided the database used in this work. He established the methodology, participated in the results presentations and discussion and developed the concluding scientific remarks of this paper. Dr. Zhang developed the computation of the NPP part of the paper; she provided and calculated the NPP supply data for the ten years studied in this paper. Dr. Zhang also contributed to mapping the results and participated in the analysis. Dr. Imhoff developed the original methodology used in this paper. He also provided guidance and values for the different processing efficiency coefficients from his previous work. Dr. Messouli supervised and guided Dr. Rochdane performing this work. He also provided and developed the data pertaining to Morocco and necessary for this research. Messouli also worked in the results presentation and discussion. Dr. Yacoubi Khebiza has coordinated, analyzed and managed the fieldwork data. He has also participated in the analysis.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. International Panel on Climate Change (IPCC). Summary for Policymakers. In *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2007; p.976.
2. Tagesson, T.; Mastepanov, M.; Tamstorf, M.P.; Eklundh, L.; Schubert, P.; Ekberg, A.; Sigsgaard, C.; Christensen, T.R.; Ström, L. High-resolution satellite data reveal an increase in peak growing

season gross primary production in a high-Arctic wet tundra ecosystem 1992–2008. *Int. J. Appl. Earth Obs. Geoinf*. **2012**, *18*, 407–416.

3. Bounoua, L.; DeFries, R.S.; Imhoff, M.L.; Steininger, M.K. Land use and local climate: A case study near Santa Cruz, Bolivia. *Meteorol. Atmos. Phys*. **2004**, *86*, 73–85.
4. Easterling, W.E.; Aggarwal, P.K.; Batima, P.; Brander, K.M.; Erda, L.; Howden, S.M.; Kirilenko, A.; Morton, J.; Soussana, J.F.; Schmidhuber, J.; *et al.* Food, fibre and forest products. In *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*; Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E., Eds.; Cambridge University Press: Cambridge, UK, 2007; pp.273–313.
5. Droogers, P. Adaptation to climate change to enhance food security and preserve environmental quality: example for southern Sri Lanka. *Agr. Water. Manage*. **2004**, *66*, 15–33.
6. Droogers, P.; Aerts, J. Adaptation strategies to climate change and climate variability: A comparative study between seven contrasting river basins. *Phys. Chem. Earth*. **2005**, *30*, 339–346.
7. Rosenzweig, C.; Parry, M.L. Potential impact of climate change on world food supply. *Nature* **1994**, *367*,133–138.
8. Food and Agriculture Organization (FAO). *The State of World Fisheries and Aquaculture 2008*; FAO: Rome, Italy, 2009; p. 176. Available online: ftp://ftp.fao.org/docrep/fao/011/i0250e/i0250e.pdf (accessed on 20 March 2014).
9. FAO. Global hunger declining, but still unacceptably high. Available online: http://www.fao.org/docrep/012/al390e/al390e00.pdf (accessed on 20 March 2014).
10. Imhoff, M.; Bounoua, L. Exploring global patterns of net primary production carbon supply and demand using satellite observations and statistical data. *J. Geophys. Res.* **2006**, *111*, D22S12.
11. FAO. *"Climate-Smart" Agriculture Policies, Practices and Financing for Food Security, Adaptation and Mitigation*; FAO: Rome, Italy, 2010; Available online: http://www.fao.org/fileadmin/user_upload/newsroom/docs/the-hague-conference-fao-paper.pdf (accessed on 20 March 2013).
12. Babqiqi, A.; Messouli, L. Simulation of climate and its implication on agriculture in Morocco using Statistical Downscaling. *Int. J. Latest Res. Sci. Tech.* **2013**, *2*, 83–96.
13. Arnell, N.W.; Livermore, M.J.L.; Kovats, S.; Levy, P.E.; Nicholls, R.; Parry, M.L.; Gaffin, S.R. Climate and socio-economic scenarios for global-scale climate change impacts assessments: Characterising the SRES storylines. *Glob. Environ. Change.* **2004**, *14*, 3–20.
14. Gommes, R.; Kanamaru, H.; El Hairech, T.; Rosillon, D.; Babqiqi, A.; Balaghi, R.; Doukkali, R.; Driouech, F.; El Ouali, A.; Jlibene, M.; *et al.* World Bank—Morocco study on the impact of Climate change on the agricultural sector. Available online: http://www.fao.org/nr/climpag/pub/FAO_WorldBank_Study_CC_Morocco_2008.pdf (accessed on 20 March 2014).
15. Imhoff, M.; Bounoua, L.; Ricketts, T.; Loucks, C.; Harriss, R.; Lawrence, W.T. Global patterns in human consumption of net primary production. *Nature* **2004**, *429*, 870–873.
16. Recensement général de la population et de l'habitat (RGPH). Royaume Du Maroc, Haut Commissariat au Plan. Available online: http://www.hcp.ma/downloads/Demographie-Caracteristiques-demographiques-et-socio-economiques-RGPH-2004_t13063.html (accessed 20 March 2014). (In French)

17. Zhao, M.; Running, S.W. Response to Comments on "Drought-Induced Reduction in Global Terrestrial Net Primary Production from 2000 through 2009". *Science* **2011**, *26*, 1093.
18. PMV Plan Maroc Vert. L'Agriculture Marocaine en Chiffres 2010. Royaume de Maroc, Ministere de l'Agricultutre et de la Pêche Maritime. Available online: http://www.agriculture.gov.ma/sites/default/files/MA-AGRI%20EN%20CHIFFRES-VF.pdf (accessed 20 March 2014). (In French)
19. Royaume Du Maroc Haut Commissariat Au Plan, Division Des EnquetesAupres Des Menages. Enquete Nationale Sur La Consommation Et Les Depenses Des Menages 2000/2001. Available online: http://www.hcp.ma/file/103035/ (accessed on 28 March 2014). (In French)
20. Tamsamani, Y. La tarification des produits pétroliers au Maroc revisitée. Observatoire français des conjonctures économiques. Available online: http://www.ofce.sciences-po.fr/blog/?p=2418 (accessed on 20 March 2014). (In French)
21. Agence Nationale de Réglementation des Télécommunications. Evaluation de la qualité de service (QoS) des réseaux publics de télécommunications au Maroc. Available online: http://www.anrt.ma/sites/default/files/2013-QoS-2G-3G-fr.pdf (accessed on 20 March 2014). (In French)
22. Programme Nationa De Gestion Des Dechets Menagers Et Assimiles. Royaume Du Maroc Conseil National De L'environement, 2007. Available online: http://www.benimellal.cci.ma/docs/112282011123932AM.pdf (accessed on 20 March 2014). (In French)
23. Le soir. Papier-Carton: un secteur à remodeler. Available online: www.lesoir-echof.com/papier-carton-un-secteur-a-remodeler/economie/22446 (accessed on 5 March 2013). (In French)
24. Council for Agricultural Science and Technology. Animal agriculture and global food supply, Task Force Rep. R135, Ames, Iowa. Available online: http://www.cast-science.org/cast/pub/anag_nr.htm (accessed on 15 January 2013).
25. Sere, C.; Steinfeld, H. *World Livestock Production Systems*; Food and Agriculture Organization of the United Nations; 1995. Available online: http://www.fao.org/ag/againfo/programmes/en/lead/toolbox/Paper127/cover1.htm (accessed on 20 March 2014).
26. Friedl, M.A.; McIver, D.K.; Hodges, J.C.F.; Zhang, X.Y.; Muchoney, D.; Strahler, A.H.; Woodcock, C.E.; Gopal, S.; Schneider, A.; Cooper, A.; *et al.* Global land cover mapping from MODIS: algorithms and early results. *Remote Sens. Environ.* **2002**, *83*, 287–302.
27. Giri, C.; Zhu, Z.; Reed, B. A comparative analysis of the Global Land Cover 2000 and MODIS land cover data sets. *Remote Sens. Environ.* **2005**, *94*, 123–132.
28. Myneni, R.B.; Hoffmana, S.; Knyazikhina, Y.; Privette, J.L.; Glassyc, J.; Tiana, Y.; Wanga, Y.; Songa, X.; Zhanga, Y.; Smitha, G.R.; *et al.* Global products of vegetation leaf area and fraction absorbed PAR from year one of MODIS data. *Remote Sens. Environ.* **2002**, *83*, 214–231.
29. Balaghi, R.; Jlibene, M.; Tychon, B.; Eerens, H. La prédiction agrométéorologique des rendements céréaliers au Maroc. Available online: http://www.inra.org.ma/publications/ouvrages/prediction1212.pdf (accessed on 20 March 2014). (In French)
30. FAO. Food Insecurity: When People must Live with Hunger and Fear Starvation. Available online: ftp://ftp.fao.org/docrep/fao/005/y7352e/y7352e00.pdf (accessed on 20 March 2014).
31. Godfray, H.C.J.; Pretty, J.; Thomas, S.M.; Warham, E.J.; Beddington, J.R. Linking Policy on Climate and Food. *Science* **2011**, *331*, 1013–1014.

32. Hanjra, M.A.; Qureshi, M.E. Global water crisis and future food security in an era of climate change. *Food Policy* **2010**, *35*, 365–377.
33. Holdren, J.P.; Ehrlich, P.R. Human population and the global environment. *Am. Sci.* **1974**, *62*, 282–292.
34. Nakicenovic, N.; Alcamo, J.; Davis, G.; de Vries, B.; Fenhann, J.; Gaffin, S.; Gregory, K.; Grubler, A.; Jung, T.Y.; Kram, T.; *et al. IPCC Special Report on Emissions Scenarios (SRES)*; Cambridge University Press: Cambridge, UK, 2000.
35. Business for Social Responsibility. Waste Not, Want Not: An Overview of the Food Waste Issue. Available online: http://www.bsr.org/reports/BSR_Waste_Not_Want_Not_An_Overview_Food_Waste.pdf (accessed on 20 March 2014).
36. Bounoua, L.; Collatz, G.J.; Sellers, P.J.; Randall, D.A.; Dazlich, D.; Los, S.; Berry, J.; Fung, I.; Tucker, C.J.; Field, C.; *et al.* Interactions between vegetation and climate: Radiative and physiological effects of doubled atmospheric CO_2. *J. Clim.* **1999**, *12*, 309–323
37. Anjum, S.A.; Xie, X.; Wang, L.; Saleem, M.F.; Man, C.; Wang, L.W. Morphological, physiological and biochemical responses of plants to drought stress. *Review. Afr. J. Agric. Res.* **2011**, *6*, 2026–2032.
38. Bindi, M.; Moriondo, M. Impact of a 2 °C global temperature rise on the Mediterranean region: Agriculture analysis assessment. In *Climate Change Impacts In The Mediterranean Resulting From A 2 °C Global Temperature Rise*; Giannakopoulos, C., Bindi, M., Moriondo, M., Tin, T., Eds.; World Wide Fund For Nature: Morges, Switzerland, 2005; pp. 54–66.