CO-OPTIMIZING SOLUTIONS: WATER AND ENERGY FOR FOOD, FEED AND FIBER

DESCRIPTION OF NEXUS MODEL METHODOLOGY

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1 Rationale

Businesses have recognized a clear need to develop new solutions to deal with the interconnectedness of water, energy and food, feed and fiber. The challenge is to provide more food, fiber and fuel in a growing and more affluent world and at the same time to be more efficient in the use of water and energy – both vital resources already under strain. Moreover, it is not only necessary to save water and energy but also other resources, such as land and scarce minerals, while mitigating and adapting to climate change.

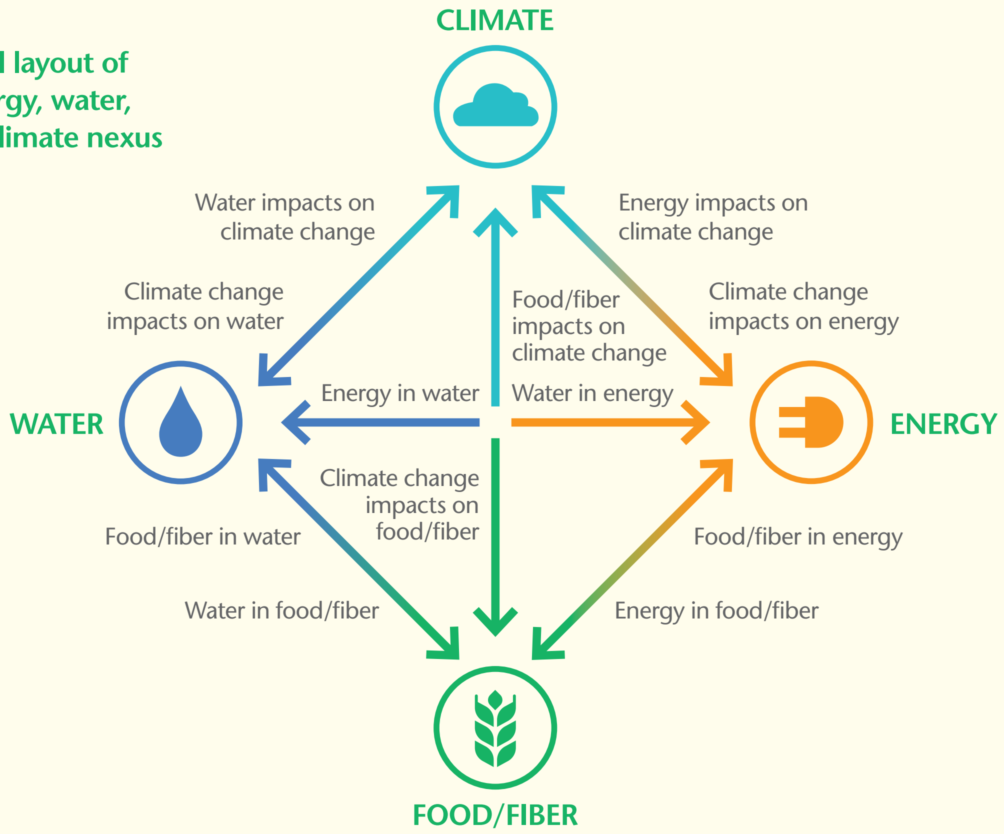
The WBCSD's climate, water, energy and food nexus pathway reflects business actions in the search for co-optimized solutions.

Analytical work has been done to understand the nexus linkages at the national as well as at the regional levels. A systematic approach was required to address such vast and complex topics. The approach adopted here builds upon existing knowledge and science.

This document briefly describes the methodology of the WBCSD's nexus modeling. It also offers some promising directions in terms of a solutions feed, having identified, understood and quantified the interconnectedness of the nexus.

The framework aims to inform national, regional and global policies and regulations while offering businesses an effective tool to assess risks and opportunities. It is important to note that its wider application and usefulness is currently restricted due to the technical and complex data structure of the output. Hence a simpler, intuitive user interface is recommended to amplify the impact of the model.

Figure 1
Conceptual layout of water, energy, water, food and climate nexus



2 Objectives and framework

- Develop long-term insights for short-term responses to the water, energy, food/feed/fiber/fuel and climate change nexus.
- Understand and document the linkages between water, energy, food/feed/fiber/fuel and climate change and develop policy and technology options to address the challenges identified.

The WBCSD kick-started the work on water and energy in October 2007 which led to the publication of *Water, Energy and Climate: A contribution from the business community* in March 2009. In 2012, the WBCSD carried out analytical work to guide businesses in making strategic decisions. The objective of this analysis was to answer the following questions:

- What are the constraints on the availability of water and energy resources as a result of future demand for food/feed/fiber/fuel/biomaterials?
- Which crops and geographies of interest can be considered hotspots today and in 2030, 2050? Why?
- If yield intensification is associated with high water and energy use in crops, then how does this translate into additional water and energy required if the intensities are scaled up to meet demand?

This publication describes the conceptual framework, scope of work and modeling methodology of the WBCSD's nexus pathway. It focuses specifically on targets for:

1 Water demand for energy (i.e. power and fuel types)

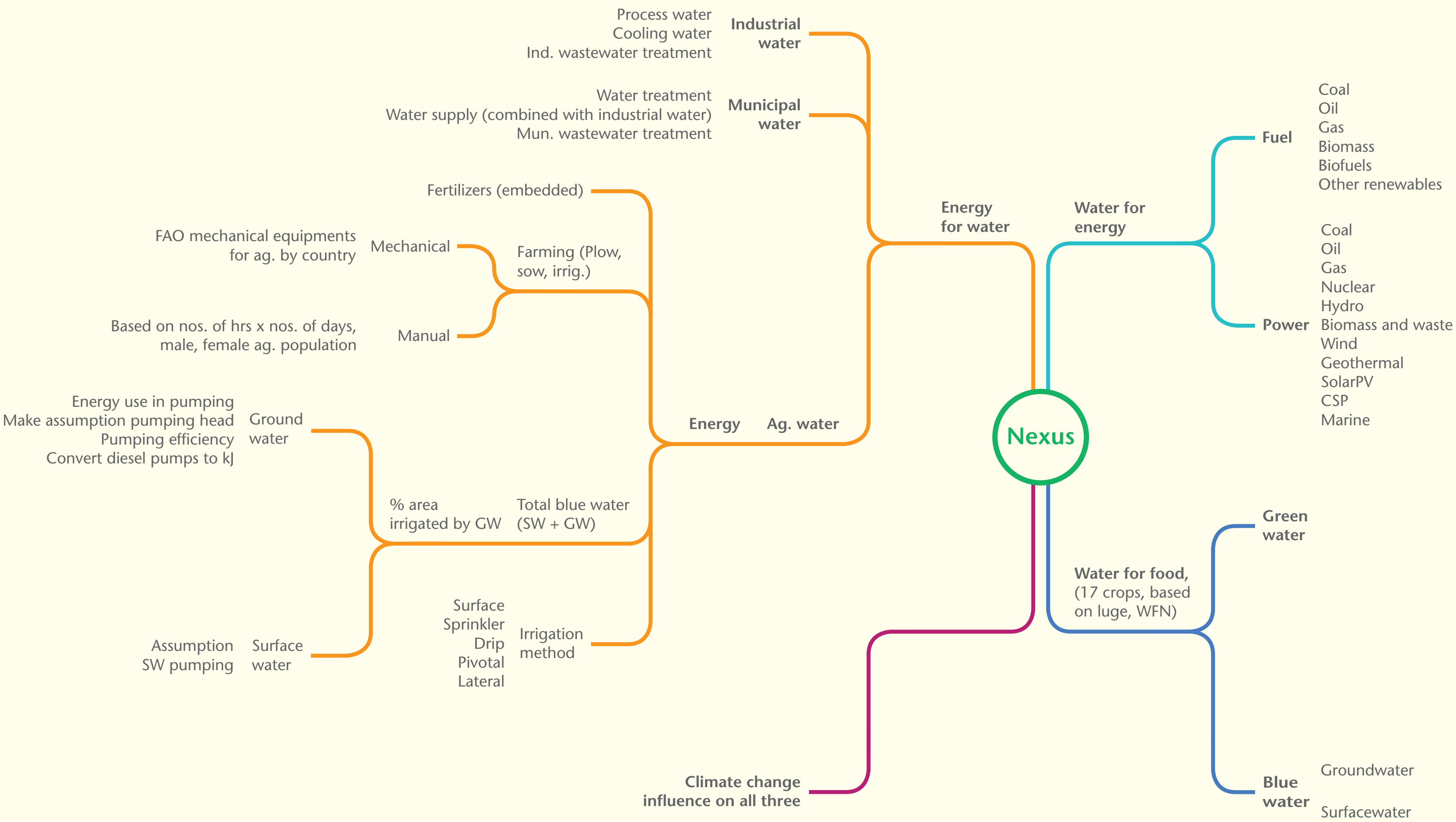
2 Water demand for food, feed, fuel and fiber (i.e., crops)

3 Energy demand for water supply and treatment (only the agriculture sector will be a focus in this phase; municipal and industrial sectors are left for the next phase)

4 Energy demand for food production (i.e., within farms for crop production)

A conceptual plan for the modeling work is illustrated in figure 1. So far, quantitative analysis of water demand for energy (number 1 above) and water demand for food (number 2 above) have been completed. This is illustrated on the right-hand side of figure 1. Current and future work will focus on the left-hand side of the flow diagram. At present, only energy demand for agriculture will be considered; energy demand for industrial water and municipal water has been identified as future work.

Figure 2
Conceptual framework for nexus modeling



3 Scope of work

1 Water demand for energy (i.e. power and fuel types)

a Water demand for energy has been broadly categorized into i) fuel and ii) power.

b Fuel has been further subdivided into coal, oil, gas, biomass, biofuels and other renewables.

c Power has been subdivided into coal, oil, gas, nuclear, hydro, biomass and waste, wind, geo-thermal, solar photovoltaic (PV), concentrated solar power (CSP) and marine.

2 Water demand for food, feed, fuel and fiber (i.e., crops)

a Seventeen crop categories have been identified for the analysis of water (and energy) demand for food crops. These crops are listed in appendix 1.

b The 17 crops identified account for around two-thirds of total agriculture water and roughly the same amount of area harvested globally.

3 Energy demand for water supply to agriculture

a This includes energy demand for only blue water for supply at farm gates, e.g., groundwater pumping and surface water supply.

b Energy demand for green water (i.e., rainwater, soil moisture) is out of the scope of this work.

4 Energy demand for farming (i.e., within farms for crop production)

a Energy demand within farm gates is considered in this analysis. Energy demand for farming includes:

i Farming, e.g., plowing, sowing, harvesting; this is subcategorized into manual and mechanical energy

ii Irrigation methods, e.g., surface/flood, sprinkler, drip, pivotal, lateral

iii As an exception, embedded energy in fertilizers is considered here; this is attributed to the selected crops and locations.

iv Energy for seeds, insecticides and pesticides has been left out due to lack of data and with the assumption that energy demand from these categories will be insignificant; this hypothesis could be checked in the future through a review of literature.

5 Solutions feed

a The solutions feed is the important component of the modeling. Once the problem is quantified, with reference to the water, energy and food nexus, various solution pathways are applied by adjusting and fine-tuning water, energy and food indicators.

b This model focuses on smart varieties of seeds, pressurized irrigation, effective fertilizer application, alternative farming practices and pumping efficiency. A detailed list of various solution pathways is given in appendix 3.

c The economic costs of each solution pathway have been identified as a future scope of work.

6 Climate change

a This is carried out in the final phase of the modeling. Various climate change scenarios are applied to project future energy, water and food supplies. However, climate change impacts that are already known through a review of the literature are applied during projections of water, energy and food supplies.

4 Methodology

1 Water demand for energy (i.e., power and fuel types)

a Detailed methodology and data can be found in Schornagel, J. et al. 2012.

2 Water demand for food, feed, fuel and fiber (i.e., crops)

a Blue water and green water

i Detailed methodology for green and blue water for crop production can be found in "The green, blue and grey water footprint of crops and derived crop products".[1]

ii Spatial resolution of the Water Footprint Network (WFN) output is available in 5-by-5 minutes latitude and longitude (i.e., approximately 9X9 km at the equator).

b Global crop area and yield

i Crop yield and crop area harvested is based on Monfreda et.al. 2008.

ii Spatial resolution of Land Use and the Global Environment (LUGE) output is available in 5-by-5 minutes latitude and longitude (i.e., approximately 9X9 km at the equator).

c Irrigation efficiency

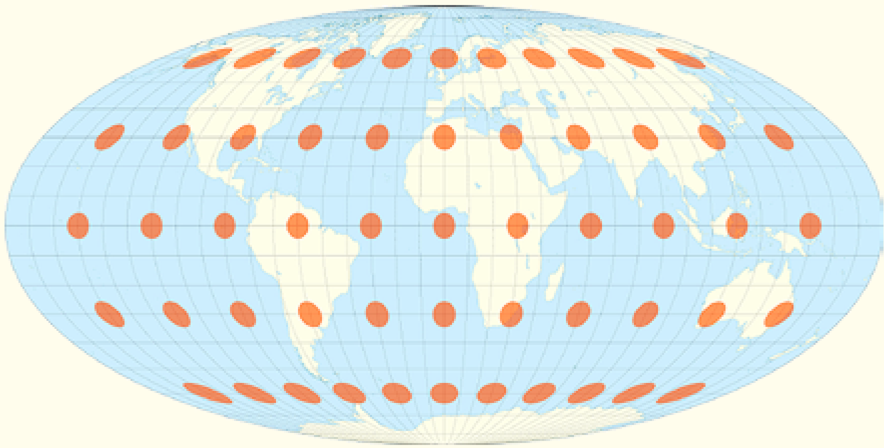
i Data for irrigation efficiency was taken from International Water Management Institute (IWMI). The study is based on Seckler et al. 1998.

d Groundwater use

i Data on global groundwater use was taken from two different sources. Groundwater use for irrigation was taken based on Siebert et al 2010.

ii Spatial allocation of groundwater and area and size of aquifers was based on Gleeson et al. 2012.

Figure 3
Geographic projections



e Socioeconomic data on agriculture

i Data such as population (male and female) engaged in agriculture, share of agriculture in national gross domestic product (GDP) and mechanization in agriculture was based on FAOStat.

f Fertilizer use data

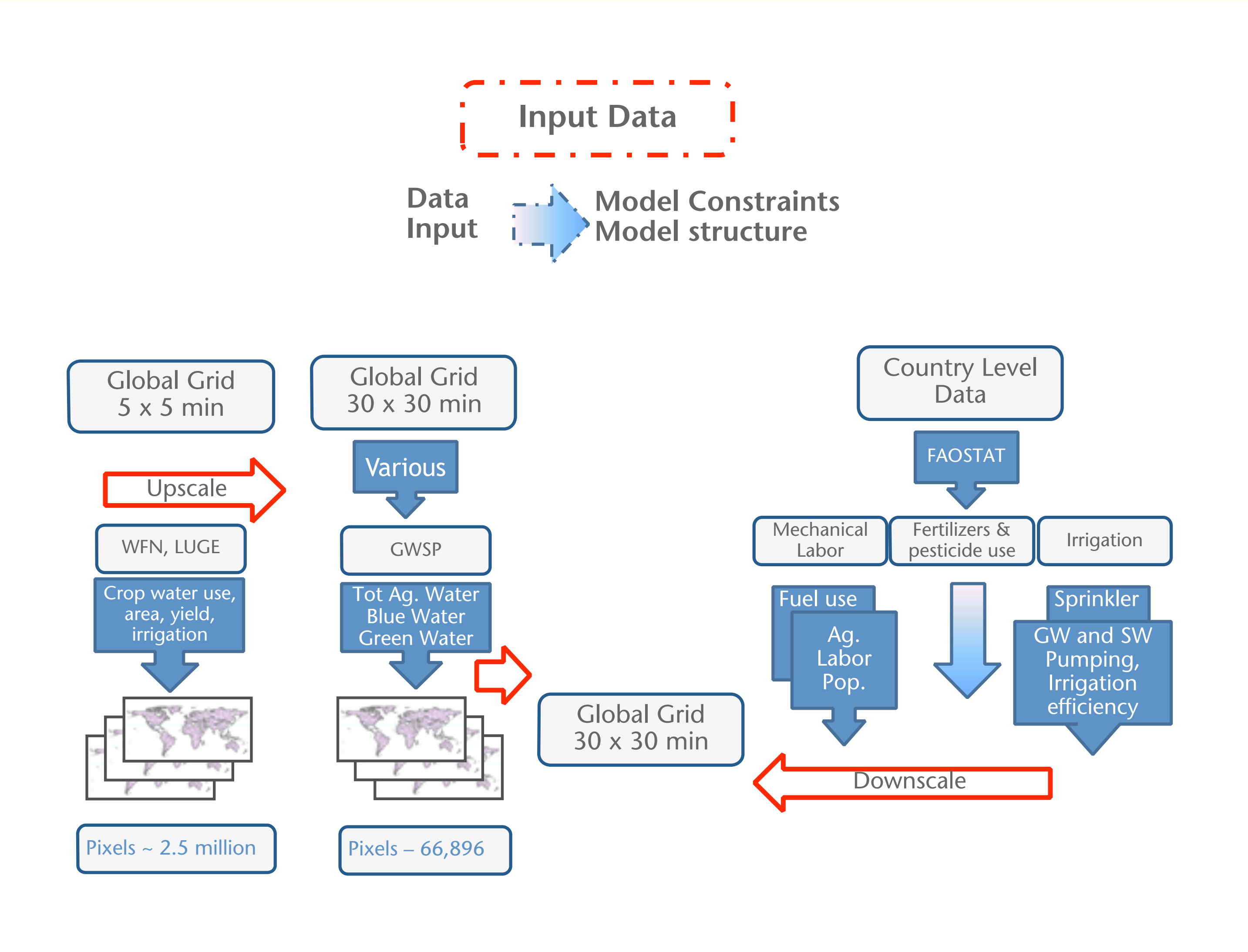
i Spatial allocation of fertilizer use data was taken from Potter et al. 2010.

ii Fertilizer use by crop in each individual country was based on FAO 2006.

[1] Mekonnen and Hoekstra, 2011

Figure 4

Conceptual layout of model



g Spatial resolution, upscaling and downscaling

i The resolution of the WBCSD model was kept at 30-by-30 minutes (i.e., 0.5 X 0.5 degrees; approximately 55 X 55 km at the equator).

ii Data available in finer resolution were upscaled and the coarser resolution data were downscaled. However, it is possible to convert all datasets into 5 X 5 min. resolution, which will require additional computational calculations.

iii Water demand for energy pathways is analyzed at country level. This is considered as a sufficient unit.

iv Data such as total water consumption (blue and green) from the WFN and LUGE were upscaled to 30 X 30 minutes. This was done by taking average or sum as appropriate of each of the 36 5-by-5 arc minute grid cells contained in the 30-by-30 arc.

v For attributes such as water consumption (both green and blue) and total area harvest for a given crop, the sum of all 36 5-by-5 arc minutes grid cells was taken. In the case of crop yields, the average of each 5-by-5 arc minutes falling within 30-by-30 arc minutes cell was taken.

Figure 5
Methodology for upscaling

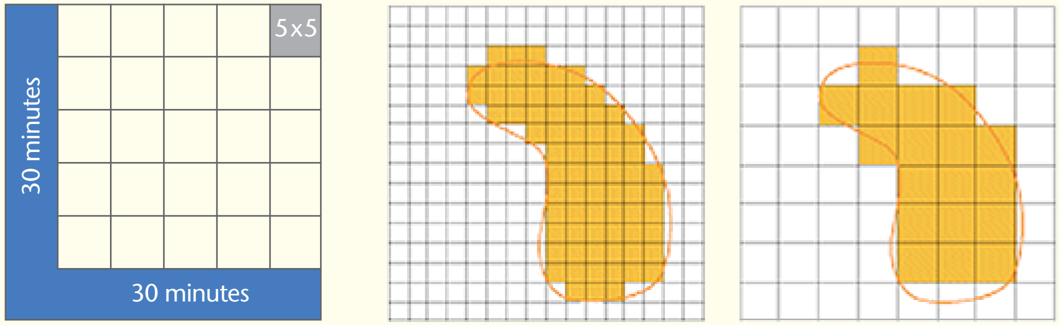
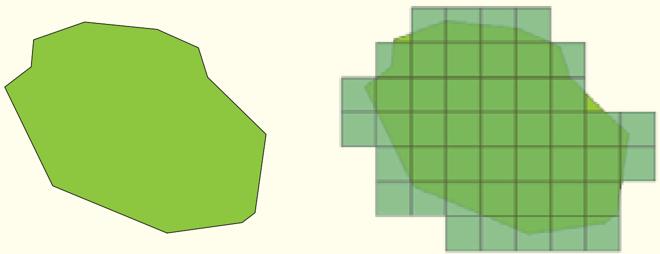


Figure 6
Methodology for downscaling



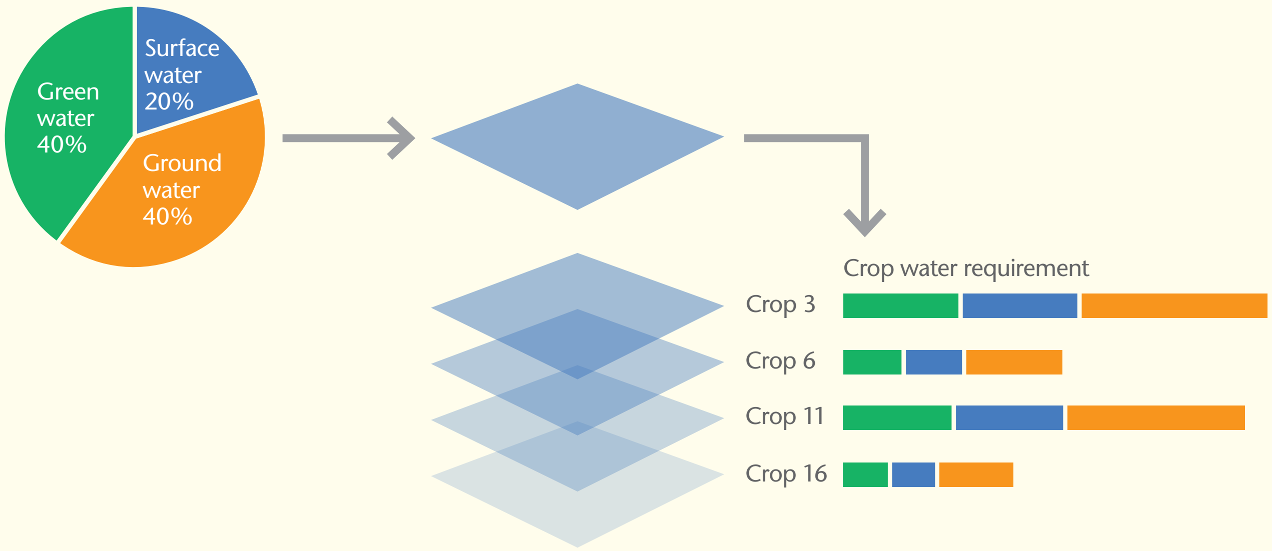
vi The model uses IWMI's irrigation efficiency (2c above). The irrigation efficiency is available at country level; the same irrigation efficiency has been applied to all pixels falling in the respective country polygon. Further, all crops grown in a given pixel were assumed to have the same irrigation efficiency.

vii The assumption has been made that the same proportion of groundwater (or surface water and rainwater) is applied to all crops falling within a given pixel. Figure 7 illustrates a logical method of water accounting for an individual crop. For instance, a given pixel receives groundwater (40%), surface water (20%) and rainwater/green water (40%). This proportion was applied to all crops grown in this pixel.

viii These are significant generalizations, but it is expected that the model will offer flexibility to users to adjust these numbers (refer to model's user interface).

Figure 7

Conceptual diagram – water accounting for blue and green water for individual crop in a pixel



3 Energy demand for water supply to agriculture

a Total groundwater use for a given crop is estimated based on 2d (groundwater use) and 2e (socioeconomic data on agriculture).

b Area and size of groundwater aquifers is based on Gleeson et al. 2012.

c Groundwater is estimated based on levels indicated in a literature review; expert opinion is crucial for this exercise.

d Energy use for pumping groundwater is estimated based on Shah et al. 2009, Rothausen and Conway 2011, and Wang et al. 2007.

e The energy requirement for groundwater pumping is calculated based on,

$$\text{Energy (kWh)} = \frac{9.8\ (\text{m s}^{-2}) \times \text{lift (m)} \times \text{mass (kg)}}{3.6 \times 10^{6} \times \text{efficiency (\%)}}$$

f All energy use is converted into kilojoule (kJ).

g If there is demand among businesses for energy use for pumping groundwater in India, China and the U.S. (as they are the largest abstractors) at sub-national level, it can be calculated in detail.

h To estimate energy use for irrigation water application, two matrixes were developed: i) irrigation efficiency by technology (table 1) and ii) area covered under various irrigation methods by country.

i The energy use for irrigation method was taken based on a literature review. Table 2 gives values adopted in the model.

j Each country is allocated a proportion of drip, sprinkler, pivot, surface and other irrigation methods based on a literature review. Appendix 4 gives the values for each country.

k Total energy use for irrigation application is estimated based on the area under various irrigation methods, water efficiency under each method and water used under irrigation methods.

Table 1
Percentage of irrigation efficiency

Irrigation method	Lower	Mean	Upper
Automated irrigation	75%	90%	95%
Sub-surface drip	75%	90%	95%
Drip (micro irrigation)	70%	85%	95%
Lateral (linear)	80%	85%	87%
Pivotal (standard)	75%	80%	90%
Sprinkler	60%	75%	85%
Lateral (movable)	60%	70%	80%
Surface	25%	40%	55%

Source: Howell, 2003

Table 2
Energy use for irrigation application, kWh per cubic meter

Sprinkler irrigation	0.20
Drip irrigation	0.38
Pivot irrigation	1.01

4 Energy use for fertilizer production

a Energy use for fertilizer use is based on Gellings and Parmenter 2004. (Table 3)

b As mentioned in section 2f, spatial allocation of fertilizer use has been adopted from Potter et al. 2010.

c Global average energy use in kJ per kg was applied to LUGE fertilizer use data.

d Energy use for fertilizer is available for production (Prdt_kgpkg), packaging (Pckg_kgpkg), transport (Trnp_kjpkg), application (Apli_kjpkg) and total (Enr_kjpkg).

e The units for all are kJ per hectare.

Table 3
Global average of energy use for fertilizer, kJ/kg

	Nitrogen	Phosphate	Potash
Produce	69,530	7,700	6,400
Transport	4,500	5,700	4,600
Package	2,600	2,600	1,800
Apply	1,600	1,500	1,000
Total	78,230	17,500	13,800

Source: Gellings and Parmenter 2004

5 Energy demand for farming (i.e., within farms for crop production)

a Energy use for mechanical farming is estimated based on FAOStat. The dataset gives mechanical farming equipment used at country level. Expert opinion and literature review are carried out to assess total inputs required for individual crop. Again, normalization and generalization are made across country.

b Energy use for manual farming with the help of human inputs and animal inputs are estimated based on demographic data. The estimate is made based on:

Total male and female population engaged in agriculture X total hours spent for various farming activities, e.g., plowing, sowing, harvesting and other items, X total energy (calories) burned per hour of each activity

c Energy use for various irrigation methods is based on a literature review, commercial equipment brochures and interviews with irrigation equipment suppliers (e.g., Jain Irrigation Systems, International Development Enterprises (iDE), netafim). Distribution of irrigation methods across geographies and crops is based on expert opinion and equipment suppliers' interviews.

d Use of fertilizers across geographies is estimated based on FAOStat (resources) and IFA n.d. Fertilizer use across crop and across country is estimated based on FAO 2006. Energy use for fertilizer production is estimated based on a literature review, e.g., Gellings and Parmenter 2004 and IPCC n.d.

e Minor adjustments and alterations are made as per the requirement and with availability of new data.

6 Solutions feed

a For the time being, only smart variety seeds, pressurized irrigation, effective fertilizer application, alternative farming practices and pumping efficiency are considered for the modeling work.

b The solution feed also reviews literature on future crop production and crop yield projections by geographical area, including the influence of climate change.

c Some of the qualitative data is converted into quantitative data by assigning appropriate values and numbers. This is carried out on case-by-case basis.

d It is understood that since solutions are based on a literature review and case studies, generalization at large scale is not strictly appropriate. However, the aim of the model is to guide business decisions by answering generic "what-if" type questions with reference to comprehensive nexus perspectives.

e Again, the user interface offers flexibility to users to adjust some of the parameters and to make the model more relevant to ground realities.

5 Status of work

1 Water demand for energy

a Water demand for energy is complete and output can be found in Schornagel et al. 2012.

2 Water demand for food crops

a Water demand for 17 food crops (both green and blue) is complete and output is available in GIS format at 30-by-30 arc minutes resolution.

3 Energy demand for agricultural water

a Energy demand for agriculture water supply, mainly groundwater pumping, is available in GIS format at 30-by-30 arc minutes resolution.

b Energy demand for irrigation application for drip, sprinkler and pivot is available at country level in Excel format as well as in GIS format at 30-by-30 arc minutes resolution. However, it should be noted that country level numbers are equally distributed at pixel level. Therefore, it may not be accurate to compare sub-national level variation.

4 Energy demand for fertilizer application

a Energy demand for fertilizer application is available in GIS format at 30-by-30 arc minutes resolution for nitrogen and phosphorus.

5 Energy demand for farming

a Energy demand for farming due to mechanization and manual labor is currently being analyzed.

6 Visualization of solutions feed

a Various means of visualizing the solutions feed are under development.

6 User interface – geographic visualization

a The current output (as well as future energy demand for food and agricultural water) needs two additional features to make better informed decisions:

   i A comprehensive picture of water, energy and food: Currently, various maps and spreadsheets of indicators remain independent and do not interact with each other; and

   ii Solution feeds: This will be at least as important as identifying and narrating a problem. Eventually businesses would like to ask "what-if" type questions and see results to make decisions.

b The next phase of the nexus modeling aims to combine the above two – linking all water, energy and food pieces together and providing solution feeds to users. The objective of the user interface is to offer companies a linkages tool to make strategic business decisions.

c The tool will answer "what if" scenarios backed by the spreadsheet numbers in various cross sections with past, current and future trends; it allows users to run queries and get answers.

7 Appendices

Appendix 1
Crop selection**

Crop number	Crop	Category
1	Barley	Food/bioenergy/biofuel
2	Cassava	Food/bioenergy/biofuel
3	Coconut	Food/bioenergy/biofuel
4	Coffee	Food/bioenergy/biofuel
5	Cotton	Fiber
6	Groundnut	Food/bioenergy/biofuel
7	Maize	Food/feed/bioenergy/biofuel
8	Millet	Food/feed/bioenergy/biofuel
9	Palm oil	Food/bioenergy/biofuel
10	Potatoes	Food/bioenergy/biofuel
11	Rapeseed	Food/bioenergy/biofuel
12	Rice	Food/bioenergy/biofuel
13	Sorghum	Food/feed/bioenergy/biofuel
14	Soybean	Food/feed
15	Sugarcane	Food/bioenergy/biofuel
16	Sunflower	Food/bioenergy/biofuel
17	Wheat	Food/bioenergy/biofuel
18	Rest of all	Food/feed/fiber/bioenergy/biofuel

** Note: Commercial plantation crops such as eucalyptus, pine, etc. will be added to this list as the data becomes available.

Appendix 2
Additional data sources and information

Sr.no	Sources and type of data	Output
1	**Collection and analysis of secondary data**	**Global, national**
	1 Data collection and analysis a FAO AQUASTAT b FAOStat (crop production, land resources, consumption, trade, price and food balance data) c Population (UNStat) d GDP (IMF) e Energy data (IEA/US EIA) f Published literature	Analysis and insight used for presentations/papers and to build the model
2	**National administrative boundaries overlay to Global Water System Project (GWSP) point maps**	**National + sub-national**
	2 GWSP data (0.5X0.5 degree) maps, (GWSP_ Withdrawal) a Total agriculture water = Irrigation water (waterwithdrirrigation) + Livestock water (waterwithdrlivestock), km^3 b Blue water (bluewater1_0), km^3 c Green water (Green water consumption on cropland), km^3	Per country water withdrawal, a Agri b Blue c Green
3	**Land use analysis**	**National + sub-national**
	3 GIAM/University of Kassel a Land use map (Kassel) (global land use, LADA Land Use System) b Area and volume of irrigation water, by crops (GIAM)	a Area under irrigation (preferably GW/SW b Arable, pasture, forest land (various classifications) c irrigation water volume, km^3 (joint exercise with IWMI)

Appendix 2 (continued)
Additional data sources and information

Sr.no	Sources and type of data	Output
4	**Data validation/comparison with other sources**	**National data**
	4 Output 2(a) with 3(c) as well as FAO land data, FAO AQUASTAT (ResourceSTAT-Land1.xls) 5 Output 2(b), (c) with Water Footprint Network (WFN) country/point data	adjusted water withdrawal, a Agri b Blue c Green d Irrigation water (GW/SW)
5	**Country level primary and secondary data**	**National**
	6 Fertilizer use a FAO Fertistat +(ResourceSTAT-Fertilizers1) IFA, fertilizer.org 7 Mechanization energy use a FAO (Resources > ResourceSTAT-Machinery 1.xls) b John Deere c Pimental 8 Occupation type a Demographic data (UNStat) b Occupation categories (FAO – Resources > PopSTAT-Annual-Time-Series1.xls)/CIA Factbook) 9 Pesticide consumption a FAO (Resources > ResourceSTAT-Pesticides_ Consumption1) 10 Water management practices a Area under sprinkler/drip irrigation b SW/GW pumping	a Fertilizer use, interpolation energy use b Mechanization, interpolation energy use c Labor inputs, interpolation energy use d Pesticide inputs, interpolation energy use e Irrigation water (GW/SW), interpolation energy use

Appendix 2 (continued)
Additional data sources and information

Sr.no	Sources and type of data	Output
6	**Primary data collection**	**National + sub-national**
	11 Water productivity (m^3/tonne) for all 17 crops	
	12 Energy productivity (GJ/tonne) for all 17 crops (as many as possible)	
7	**Groundwater data analysis**	**Global, national**
	13 GRACE data	
8	**Overlay of Global maps to 0.5X0.5 grid map**	**Global, national + sub-national**
	14 Koppan climate class map	Global, national + sub-national
	15 Geological map http://portal.onegeology.org	
	16 Global NDVI CoV	
	17 Potential rainfed ag. Production (food_l_e00)	
9	**Analysis of 0.5X0.5 grid map**	**National + sub-national**
	18 Mean annual ET 1950-2000	
	19 Mean annual precipitation 1950-2000	
	20 Mean annual runoff 1950-2000	
10	**Advancement of the model**	**National + sub-national**
	21 Incorporate external models/outputs, ex. IMPACT, GIAM, IEA	

Acronyms:
GW: groundwater; SW: surface water; GIAM: Global Irrigated Area Mapping, IWMI's research; NDVI: Normalized Difference Vegetation Index; CoV: Coefficient of Variation; ET: Evapotranspiration; GRACE: Gravity Recovery and Climate Experiment

Appendix 3
Area under irrigation, by method, in hectares

Country	Total irrigation area	Drip irrigation	Sprinkler	Pivot	Other	Surface
Afghanistan	3,759,391.90	75.19	187.97	375.94	1,879.70	3,756,873.11
Albania	341,918.10	34.19	170.96	34.19	170.96	341,507.80
Algeria	811,777.20	8.12	162.36	81.18	405.89	811,119.66
American Samoa	1.00	0.01	0.00	0.00	0.00	0.99
Angola	151,213.10	3.02	7.56	15.12	75.61	151,111.79
Antigua and Barbuda	126.60	0.63	6.33	0.01	0.06	119.56
Argentina	2,264,278.60	679.28	1,132.14	226.43	1,132.14	2,261,108.61
Armenia	314,436.70	125.77	157.22	31.44	157.22	313,965.05
Australia	2,579,697.50	2,063.76	206,375.80	25,796.98	1,289.85	2,344,171.12
Austria	118,238.50	59.12	59.12	11.82	59.12	118,049.32
Azerbaijan	1,527,285.80	305.46	763.64	152.73	763.64	1,525,300.33
Bahamas	1.00	0.00	0.00	0.00	0.00	1.00
Bahrain	5,636.50	28.18	112.73	0.56	2.82	5,492.21
Bangladesh	3,831,726.10	191.59	191.59	191.59	1,915.86	3,829,235.48
Barbados	1,536.60	7.68	76.83	0.15	0.77	1,451.17
Belarus	131,412.90	65.71	65.71	13.14	65.71	131,202.64
Belgium	65,895.70	0.66	32.95	6.59	32.95	65,822.56
Belize	25,329.40	0.25	2.53	2.53	12.66	25,311.42
Benin	32,292.60	161.46	9.69	3.23	16.15	32,102.07
Bermuda	1.00	0.01	0.05	0.00	0.00	0.94
Bhutan	45,184.30	2.26	2.26	4.52	22.59	45,152.67
Bolivia	219,486.50	658.46	109.74	21.95	109.74	218,586.61
Bosnia and Herzegovina	9,446.90	47.23	0.94	0.94	4.72	9,393.05
Botswana	6,824.20	34.12	0.34	0.68	3.41	6,785.64

Source: Based on authors' estimation.

Appendix 3 (continued)
Area under irrigation, by method, in hectares

Country	Total irrigation area	Drip irrigation	Sprinkler	Pivot	Other	Surface
Brazil	3,452,562.50	172,628.13	1,035,768.75	345,256.25	1,726.28	1,897,183.09
Brunei	1,569.00	47.07	47.07	0.16	0.78	1,473.92
Bulgaria	814,614.60	40.73	162.92	81.46	407.31	813,922.18
Burkina Faso	39,477.20	0.39	11.84	3.95	19.74	39,441.28
Burundi	34,114.20	3.41	1.71	3.41	17.06	34,088.61
Cambodia	421,149.40	84.23	21,057.47	42.11	210.57	399,755.01
Cameroon	51,168.90	0.51	2.56	5.12	25.58	51,135.13
Canada	921,246.20	184.25	184.25	92.12	460.62	920,324.95
Cape Verde	3,186.20	95.62	0.32	0.32	1.59	3,088.35
Cayman Islands	1.00	0.00	0.00	0.00	0.00	1.00
Central African Republic	523.80	0.01	0.05	0.05	0.26	523.43
Chad	58,648.50	0.59	2.35	5.86	29.32	58,610.38
Chile	2,181,787.80	21.82	218.18	218.18	1,090.89	2,180,238.73
China	61,731,358.00	740,776.30	1,358,089.88	370,388.15	30,865.68	59,231,238.00
Clipperton Island	1.00	0.00	0.00	0.00	0.00	1.00
Côte d'Ivoire	143,878.30	7.19	71.94	14.39	71.94	143,712.84
Colombia	1,186,669.00	1,186.67	593.33	118.67	593.33	1,184,177.00
Comoros	232.10	0.00	0.02	0.02	0.12	231.94
Congo, Democratic Republic	21,826.20	0.22	2.18	2.18	10.91	21,810.70
Congo, Republic	3,324.40	0.03	0.33	0.33	1.66	3,322.04
Costa Rica	147,694.40	443.08	7.38	14.77	73.85	147,155.32
Croatia	12,971.40	220.51	6.49	1.30	6.49	12,736.62
Cuba	1,116,315.70	11.16	111.63	111.63	558.16	1,115,523.12
Cyprus	51,717.80	517.18	517.18	25.86	25.86	50,631.73

Appendix 3 (continued)
Area under irrigation, by method, in hectares

Country	Total irrigation area	Drip irrigation	Sprinkler	Pivot	Other	Surface
Czech Republic	64,936.00	974.04	32.47	6.49	32.47	63,890.53
Denmark	481,443.00	240.72	24.07	48.14	240.72	480,889.34
Djibouti	2,687.10	0.03	0.27	0.27	1.34	2,685.19
Dominica	1.00	0.00	0.00	0.00	0.00	1.00
Dominican Republic	352,196.30	3.52	35.22	35.22	176.10	351,946.24
Ecuador	1,123,467.90	112.35	561.73	112.35	561.73	1,122,119.74
Egypt	3,731,214.20	373.12	1,865.61	746.24	1,865.61	3,726,363.62
El Salvador	74,137.30	0.74	37.07	7.41	37.07	74,055.01
Equatorial Guinea	1.00	0.00	0.00	0.00	0.00	1.00
Eritrea	39,192.30	0.39	3.92	3.92	19.60	39,164.47
Estonia	1,485.10	44.55	0.74	0.15	0.74	1,438.91
Ethiopia	483,199.50	4.83	43.49	48.32	241.60	482,861.26
Faroe Islands	1.00	0.00	0.00	0.00	0.00	1.00
Fiji	6,196.70	0.06	0.62	0.62	3.10	6,192.30
Finland	115,945.60	57.97	8.12	11.59	57.97	115,809.94
France	2,881,898.60	1,285,326.78	634,017.69	288,189.86	1,440.95	672,923.32
French Guiana	4,862.90	0.05	0.49	0.49	2.43	4,859.45
French Southern Territories	1.00	0.00	0.00	0.00	0.00	1.00
Gabon	9,716.70	0.10	0.97	0.97	4.86	9,709.80
Gambia	5,681.20	0.06	0.57	0.57	2.84	5,677.17
Georgia	416,253.20	124.88	208.13	41.63	208.13	415,670.45
Germany	639,283.90	319.64	639.28	63.93	319.64	637,941.40
Ghana	45,932.50	0.46	9.19	4.59	22.97	45,895.29
Greece	1,555,225.10	15.55	155.52	155.52	777.61	1,554,120.89

Appendix 3 (continued)
Area under irrigation, by method, in hectares

Country	Total irrigation area	Drip irrigation	Sprinkler	Pivot	Other	Surface
Greenland	1.00	0.00	0.00	0.00	0.00	1.00
Grenada	138.90	1.39	17.92	0.01	0.07	119.51
Guadeloupe	2,371.30	0.02	0.24	0.24	1.19	2,369.62
Guam	212.60	0.00	0.02	0.02	0.11	212.45
Guatemala	171,637.20	85.82	34.33	17.16	85.82	171,414.07
Guinea	127,612.50	893.29	63.81	12.76	63.81	126,578.84
Guinea-Bissau	25,451.20	0.25	2.55	2.55	12.73	25,433.13
Guyana	155,548.30	1.56	15.55	15.55	77.77	155,437.86
Haiti	138,489.50	1.38	13.85	13.85	69.24	138,391.17
Honduras	114,916.00	1.15	11.49	11.49	57.46	114,834.41
Hong Kong	4,491.30	0.04	0.45	0.45	2.25	4,488.11
Hungary	364,721.50	182.36	182.36	36.47	182.36	364,137.95
Iceland	1.00	0.00	0.00	0.00	0.00	1.00
India	59,883,315.20	898,249.73	1,497,082.88	299,416.58	29,941.66	57,158,624.36
Indonesia	5,596,812.80	55.97	559.68	559.68	2,798.41	5,592,839.06
Iran	9,223,736.70	156,803.52	922,373.67	92,329.60	4,611.87	8,047,618.03
Iraq	3,849,188.80	769.84	384.92	384.92	1,924.59	3,845,724.53
Ireland	1,185.90	0.01	0.12	0.12	0.59	1,185.06
Israel	181,164.20	54,349.26	45,834.54	9,058.21	90.58	71,831.61
Italy	3,884,478.10	349,603.03	388,447.81	174,801.51	1,942.24	2,969,683.51
Jamaica	38,537.60	3.85	19.27	3.85	19.27	38,491.35
Japan	3,838,295.80	767.66	345.45	383.83	1,919.15	3,834,879.72
Jordan	125,398.90	37.62	62.70	12.54	62.70	125,223.34
Kazakhstan	2,496,172.10	124.81	1,248.09	249.62	1,248.09	2,493,301.50
Kenya	141,178.60	1.41	7,058.93	14.12	70.59	134,033.55

Appendix 3 (continued)
Area under irrigation, by method, in hectares

Country	Total irrigation area	Drip irrigation	Sprinkler	Pivot	Other	Surface
Korea, Democratic People's Republic	1,467,643.60	14.68	146.76	146.76	733.82	1,466,601.57
Korea, Republic of	1,137,796.80	227,559.36	113.78	102.40	568.90	909,452.36
Kosovo	73,192.80	0.73	7.32	7.32	36.60	73,140.83
Kuwait	9,273.70	185.47	1,103.57	0.93	4.64	7,979.09
Kyrgyzstan	1,468,877.40	73.44	73,443.87	146.89	734.44	1,394,478.76
Laos	414,824.80	4.15	41.48	41.48	207.41	414,530.27
Latvia	1,164.40	0.01	0.12	0.12	0.58	1,163.57
Lebanon	162,158.20	32.43	48.65	16.22	81.08	161,979.83
Lesotho	6,199.60	0.06	0.62	0.62	3.10	6,195.20
Liberia	2,984.20	0.03	0.30	0.30	1.49	2,982.08
Libya	666,126.80	6.66	66.61	66.61	333.06	665,653.85
Lithuania	4,649.00	23.25	232.45	0.46	2.32	4,390.52
Luxembourg	624.80	0.01	0.06	0.06	0.31	624.36
Macedonia	172,875.90	1.73	17.29	17.29	86.44	172,753.16
Madagascar	1,335,331.40	13.35	26.71	133.53	667.67	1,334,490.14
Malawi	66,681.20	3.33	3.33	6.67	33.34	66,634.52
Malaysia	499,727.60	249.86	249.86	49.97	249.86	498,928.04
Mali	363,832.60	3.64	36.38	36.38	181.92	363,574.28
Martinique	4,279.80	0.04	0.43	0.43	2.14	4,276.76
Mauritania	61,617.80	0.62	6.16	6.16	30.81	61,574.05
Mauritius	31,285.30	312.85	312.85	15.64	15.64	30,628.31
Mexico	8,229,417.60	123,441.26	2,468,825.28	82,376.47	4,114.71	5,550,659.88
Micronesia	1.00	0.00	0.00	0.00	0.00	1.00
Moldova	347,193.60	173.60	173.60	34.72	173.60	346,638.09

Appendix 3 (continued)
Area under irrigation, by method, in hectares

Country	Total irrigation area	Drip irrigation	Sprinkler	Pivot	Other	Surface
Mongolia	139,314.10	6.97	13.93	13.93	69.66	139,209.61
Montenegro	1,945.70	38.93	0.58	0.19	0.97	1,905.02
Morocco	1,999,691.40	999.85	999.85	199.97	999.85	1,996,491.89
Mozambique	229,613.80	2.30	22.96	22.96	114.81	229,450.77
Myanmar	2,137,711.20	21.38	213.77	213.77	1,068.86	2,136,193.43
Namibia	25,994.40	129.97	129.97	2.60	13.00	25,718.86
Nauru	1.00	0.00	0.00	0.00	0.00	1.00
Nepal	1,111,357.60	11.11	11.11	111.14	555.68	1,110,668.56
Netherlands	431,987.00	215.99	43.20	43.20	215.99	431,468.62
Netherlands Antilles	1.00	0.00	0.00	0.00	0.00	1.00
New Caledonia	1.00	0.00	0.00	0.00	0.00	1.00
New Zealand	591,311.60	118.26	295.66	59.13	295.66	590,542.89
Nicaragua	71,513.20	71.51	7.15	7.15	35.76	71,391.63
Niger	117,195.70	1.17	11.72	11.72	58.60	117,112.49
Nigeria	523,554.80	5.24	52.36	52.36	261.78	523,183.08
Niue	1.00	0.00	0.00	0.00	0.00	1.00
Northern Mariana Islands	43.20	0.00	0.00	0.00	0.02	43.17
Norway	173,833.50	1.74	17.38	17.38	86.92	173,710.08
Oman	131,458.20	65.73	1,314.58	13.15	65.73	129,999.01
Pakistan	14,648,136.30	1,464.81	732.41	1,025.37	7,324.07	14,637,589.64
Palau	1.00	0.00	0.00	0.00	0.00	1.00
Palestine	41,522.40	0.42	4.15	4.15	20.76	41,492.92
Panama	49,335.50	789.37	2.47	4.93	24.67	48,514.06
Papua New Guinea	1.00	0.00	0.00	0.00	0.00	1.00
Paraguay	81,629.30	0.82	8.16	8.16	40.81	81,571.34

Appendix 3 (continued)
Area under irrigation, by method, in hectares

Country	Total irrigation area	Drip irrigation	Sprinkler	Pivot	Other	Surface
Peru	2,113,159.20	2,113.16	1,056.58	211.32	1,056.58	2,108,721.57
Philippines	1,914,811.80	957.41	957.41	191.48	957.41	1,911,748.10
Poland	179,336.60	89.67	1,793.37	17.93	89.67	177,345.96
Portugal	792,127.80	396.06	396.06	79.21	396.06	790,860.40
Puerto Rico	33,669.10	16.83	16.83	16.83	16.83	33,601.76
Qatar	13,663.60	136.64	546.54	6.83	6.83	12,966.76
Reunion	22,372.10	0.22	2.24	2.24	11.19	22,356.22
Romania	2,226,162.00	222.62	1,113.08	222.62	1,113.08	2,223,490.61
Russia	5,686,698.80	2,843.35	1,137,339.76	682,403.86	2,843.35	3,861,268.49
Rwanda	9,937.70	0.10	0.99	0.99	4.97	9,930.64
Saint Helena	1.00	0.00	0.00	0.00	0.00	1.00
Saint Kitts and Nevis	13.10	0.13	0.00	0.00	0.01	12.96
Saint Lucia	327.50	0.00	0.03	0.03	0.16	327.27
Saint Pierre and Miquelon	1.00	0.00	0.00	0.00	0.00	1.00
Saint Vincent and the Grenadines	1.00	0.00	0.00	0.00	0.00	1.00
Samoa	1.00	0.00	0.00	0.00	0.00	1.00
Sao Tome and Principe	8,179.60	0.08	0.82	0.82	4.09	8,173.79
Saudi Arabia	2,153,691.10	1,076.85	258,442.93	215,369.11	1,076.85	1,677,725.37
Senegal	181,313.20	36.26	18.13	18.13	90.66	181,150.02
Serbia	91,223.70	0.91	9.12	9.12	45.61	91,158.93
Sierra Leone	45,869.10	0.46	4.59	4.59	22.93	45,836.53
Slovakia	251,642.70	2.52	25.16	25.16	125.82	251,464.03
Slovenia	21,786.20	10.89	10.89	2.18	10.89	21,751.34

Appendix 3 (continued)
Area under irrigation, by method, in hectares

Country	Total irrigation area	Drip irrigation	Sprinkler	Pivot	Other	Surface
Solomon Islands	1.00	0.00	0.00	0.00	0.00	1.00
Somalia	243,699.20	2.44	24.37	24.37	121.85	243,526.17
South Africa	2,119,881.20	211,988.12	317,982.18	211,988.12	1,059.94	1,376,862.84
Spain	3,713,119.50	816,886.29	297,049.56	148,524.78	1,856.56	2,448,802.31
Sri Lanka	612,935.20	12.26	612.94	61.29	306.47	611,942.25
Sudan	2,182,188.80	21.82	218.22	218.22	1,091.09	2,180,639.45
Suriname	68,211.20	0.68	2.73	6.82	34.11	68,166.86
Svalbard and Jan Mayen	1.00	0.00	0.00	0.00	0.00	1.00
Swaziland	69,611.60	3.48	6.96	6.96	34.81	69,559.39
Sweden	198,496.10	1.98	19.85	19.85	99.25	198,355.17
Switzerland	71,611.80	0.72	7.16	7.16	35.81	71,560.96
Syria	1,525,532.40	152.55	762.77	152.55	762.77	1,523,701.76
Taiwan	594,131.60	5.94	59.41	59.41	297.07	593,709.77
Tajikistan	758,114.70	7.58	75.81	75.81	379.06	757,576.44
Tanzania	319,596.60	3.20	31.96	31.96	159.80	319,369.69
Thailand	5,644,933.20	56.45	564.49	564.49	2,822.47	5,640,925.30
Timor-Leste, East	36,964.20	0.37	3.70	3.70	18.48	36,937.96
Togo	11,738.10	35.21	3.52	1.17	5.87	11,692.32
Tokelau	1.00	0.00	0.00	0.00	0.00	1.00
Tonga	1.00	0.00	0.00	0.00	0.00	1.00
Trinidad and Tobago	5,271.90	1.05	1.05	0.53	2.64	5,266.63
Tunisia	577,411.10	115.48	288.71	57.74	288.71	576,660.47
Turkey	5,813,198.40	2,906.60	4,069.24	2,325.28	2,906.60	5,800,990.68
Turkmenistan	1,945,361.70	972.68	194.54	194.54	972.68	1,943,027.27
Tuvalu	1.00	0.00	0.00	0.00	0.00	1.00

Appendix 3 (continued)
Area under irrigation, by method, in hectares

Country	Total irrigation area	Drip irrigation	Sprinkler	Pivot	Other	Surface
Uganda	21,927.40	0.22	855.17	2.19	10.96	21,058.86
Ukraine	3,336,881.80	333.69	1,334.75	333.69	1,668.44	3,333,211.23
United Arab Emirates	356,153.50	178.08	213.69	178.08	178.08	355,405.58
United Kingdom	234,773.70	164.34	117.39	23.48	117.39	234,351.11
United States	28,927,775.90	867,833.28	4,339,166.39	1,446,388.80	14,463.89	22,259,923.56
United States Minor Outlying Islands	1.00	0.00	0.00	0.00	0.00	1.00
Uruguay	279,511.90	2.80	27.95	27.95	139.76	279,313.45
Uzbekistan	4,161,997.40	416.20	1,248.60	416.20	2,081.00	4,157,835.40
Vanuatu	1.00	0.00	0.00	0.00	0.00	1.00
Venezuela	839,962.80	419.98	671.97	419.98	419.98	838,030.89
Vietnam	3,199,236.80	31.99	1,599.62	1,279.69	1,599.62	3,194,725.88
Virgin Islands, U.S.	1.00	0.00	0.00	0.00	0.00	1.00
Wallis and Futuna	1.00	0.00	0.00	0.00	0.00	1.00
Western Sahara	1.00	0.00	0.00	0.00	0.00	1.00
Yemen	527,744.30	527.74	527.74	52.77	263.87	526,372.16
Zambia	255,319.40	2.55	127.66	25.53	127.66	255,036.00
Zimbabwe	279,553.20	2.80	55.91	27.96	139.78	279,326.76
Total		**5,937,395**	**15,046,334**	**4,407,264**	**157,377**	**289,205,442**

8 References

BRGM (Bureau de Recherches Géologiques et Minières) 2005. *Safe and High Quality Food Production using Low Quality Waters and Improved Irrigation Systems and Management (SAFIR). A Specific Targeted Research Project under the Thematic Priority "Food Quality and Safety"*. Work Package 6, Economic impact analysis and technologies assessment. Available at http://www.safir4eu.org/Lib/SAFIR/Deliverable/SAFIR_D6_3.pdf

FAO (Food and Agriculture Organization of the United Nations) 2006. *Fertilizer use by crop*. Food and Agriculture Organization of the United Nations: Rome.

FAOStat (Food and Agriculture Organization of the United Nations, Statistics Division). Available at http://faostat3.fao.org/faostat-gateway/go/to/home/E.

Filipovic et al. 2004. *Influence of different soil tillage systems on fuel consumption, labour requirement and yield in maize and winter wheat production*. Original scientific paper. ISSN 1330-7142.

Gellings, C. W. and K.E. Parmenter 2004. "Energy efficiency in fertilizer production and use". In Gellings, C.W. and K. Blok (Eds), *Efficient Use and Conservation of Energy, Encyclopedia of Life Support Systems*. Eolss Publishers, Oxford, UK.

Gleeson, T. et al. 2012. "Water balance of global aquifers revealed by groundwater footprint". Nature 488, 197-200.

Howell, T.A. 2003. "Irrigation efficiency". *Encyclopedia of Water Science*. United States Department of Agriculture.

IFA (International Fertilizer Industry Association), n.d. Available at www.fertilizer.org.

IPCC (Intergovernmental Panel on Climate Change), no date. 7.4.3.2 "Fertilizer manufacture". Available at http://www.ipcc.ch/publications_and_data/ar4/wg3/en/ch7s7-4-3-2.html.

Jackson, T. 2009. "An appraisal of the on-farm water and energy nexus in irrigated agriculture". DPhil thesis. School of Environmental Sciences, Faculty of Science, Charles Sturt University, US.

Mekonnen, M. and A.Y. Hoekstra 2011. "The green, blue and grey water footprint of crops and derived crop products". *Hydrology and Earth System Sciences* 15, 1577-1600. Available at http://www.waterfootprint.org/Reports/Mekonnen-Hoekstra-2011-WaterFootprintCrops.pdf

Malik, D.P. and M.S Luhach 2002. "Economic dimensions of drip irrigation in context of fruit crops". Department of Agricultural Economics, CCS Haryana Agricultural University, Hisar.

Miodragovic et al. 2011. "Energy and distribution parameters of the mobile wheel line sprinkler system". UDC, 631.347:631.67. Pregledni rad, Review paper.

Monfreda, C. et al. 2008. "Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000". *Global Biochemical Cycles*. Vol. 22, issue 1.

Narayanamoorthy, A. 2007. *Micro-Irrigation and Electricity Consumption Linkages in Indian Agriculture: A Field Based Study.* Available online at http://www.iwmi.cgiar.org/EWMA/files/papers/Drip-energy-AN-paper%20(2).pdf.

Payero, J. et al. 2005. "Advantages and disadvantages of subsurface drip irrigation". *Agriculture and Natural Resources*. Extension. University of Nebraska-Lincoln and United States Department of Agriculture.

Pervanchon, F. et al. 2002. "Assessment of energy use in arable farming systems by means of an agro-ecological indicator: the energy indicator". *Agricultural Systems*, vol. 72, 149–172.

Potter, P. et al. 2010. "Characterizing the Spatial Patterns of Global Fertilizer Application and Manure Production". *Earth Interactions* 14, 1-22. American Meteorological Society Journals online.

Rothausen, S. and D. Conway 2011. "Greenhouse-gas emissions from energy use in the water sector". *Nature Climate Change* 1, 210-219.

Schornagel, J. et al 2012. "Water accounting for (agro) industrial operations and its application to energy pathways". Resources, Conservation and Recycling, vol. 61, April 2012, pp. 1-15. Available at http://www.sciencedirect.com/science/article/pii/S0921344911002783.

Seckler, D., U. Amarasinghe, D. Molden, R. de Silva, R. Barker1998. *World water demand and supply, 1990 to 2025: Scenarios and issues*. Research Report 19. Colombo, Sri Lanka: International Water Management Institute.

Shah, T. 2009. « Climate change and groundwater: India's opportunities for mitigation and adaptation". *Environ. Res. Lett.* 4 035005. Available at http://iopscience.iop.org/1748-9326/4/3/035005

Siebert, S., J. Burke, J. M. Faures, K. Frenken, J. Hoogeveen, P. Doll, F. T. Portmann 2010. "Groundwater use for irrigation – a global inventory". *Hydrology and Earth System Sciences*, 14, 1863-1880.

Styles, S.W., and C.M. Burt1996. *Evaluation of Subsurface Drip Irrigation on Peppers*. Cal Poly Irrigation Training & Research Center, submitted to the California Energy Commission.

Wang, J. et al. 2007. "Agriculture and groundwater development in northern China: trends, institutional responses, and policy options". *Water Policy* (Impact Factor: 1.6). 01/2007.

WBCSD (World Business Council for Sustainable Development) 2009. *Water, Energy and Climate – A Contribution from the Business Community*. Available at http://www.wbcsd.org/pages/edocument/edocumentdetails.aspx?id=40&nosearchcontextkey=true