The Future of Agriculture in a Resource-Constrained World: A Scenario Analysis

by

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I dedicate this work to my grandfather – Paul Springer – who devoted much of his personal and professional life to the betterment of the natural world. I hope I can someday inspire in my grandchildren the same appreciation for the environment that he helped instill in me.

ABSTRACT

This study evaluates the potential to feed future world populations with available endowments of land and water. It then evaluates two ways for mitigating the pressures caused by future increases in demand. One way is to tolerate unsustainable resource use by expanding agricultural production onto forestland and withdrawing quantities of water for irrigation beyond the amount necessary for social and environmental needs. A more sustainable alternative is considered in which food demand is reduced in rich regions while technologies are adopted in Africa and Latin America that improve crop yields and allow alternative land use options. Four hypotheses are proposed about the feasibility of meeting future food demand under these conditions and the resulting differences in agricultural production, food prices, and resource use. These hypotheses are tested in a scenario analysis using a global, inter-regional input-output model that determines production and resource use endogenously based upon regional comparative advantages based on production costs and physical availability of factor inputs.

The study concludes that future demand for food cannot be met without either unsustainably expanding land and water use or adopting dietary and technological solutions. Feeding future populations is possible if land and water are allowed to expand unsustainably, but land use increases by 50%, water withdrawals for irrigation by 75%, and water uptake from rainfall by 110% (compared to the baseline). A significant portion of this land expansion takes place on forestland in Latin America, Africa and North America. Feeding future populations is also possible by adopting the dietary and technological solution, with increases in land use of only 14% (also compared to baseline). This solution requires a higher dependence on irrigated crop production and hence further global increases water withdrawals (by 79%). However, the regional situation is nonetheless improved, as withdrawals are reduced in water-scarce China while net increases come from water rich regions such as Latin America. In both cases, world production is dependent upon large increases in agricultural production in developing countries, particularly Africa. Also in both cases, food commodity prices rise, but only 11 - 18% if technological and dietary solutions are adopted compared to 37 - 63% with unsustainable resource expansion.

1. Introduction

A decade into the 21st century, an old yet pressing challenge persists: how to maintain worldwide agricultural production at a level that can sustain the human population. Increasing population and affluence around the world will require further dramatic production increases to satisfy demand. These growing demands are juxtaposed against the limited availability of resource inputs, particularly land and water. The availability of these inputs differs regionally, both physically and economically, complicating efforts to supply sufficient and equitable amounts of food around the world. The three main purposes of this study are indented to address this challenge. The first purpose is to address the prospect of future agricultural production given changes in population, diets, and resource availability. The second purpose is to explore how additional changes to diets, resource use, and agricultural production technologies can potentially reduce these pressures. The third purpose is to determine the potential for feeding future populations with sustainable levels of land and water use.

1.1 Research motivation

The first purpose is addressed by considering potential obstacles to achieving sufficient future food production. How much will production need to increase to meet future demand given current technologies? Will there be enough resources to achieve policy goals of increased food availability in developing regions? Even if so, what regions benefit from increased production or suffer from resource scarcity? How dramatically will food prices increase?

Secondly, and perhaps more importantly, this study aims to test potential solutions to these increased pressures on the global food system. To what degree can different solutions alleviate the problems associated with these increases in global consumption? What are the tradeoffs between these different solutions? What solutions improve development prospects or help achieve sustainable resource use?

This study considers three ways to alleviate the increased pressure on resource use in 2050: expansion of agricultural production using additional land and water resources, intensification of agricultural production using higher-yield technologies, and contraction of domestic demand for food (particularly animal products). Each solution can reduce food prices to different degrees by taking pressure off resource use. Yet agricultural expansion is strategically different since it could potentially result in the unsustainable use of land and water resources. Both reducing domestic food demand and increasing yields through improved land and water use can lower food prices while simultaneously lowering resource use.

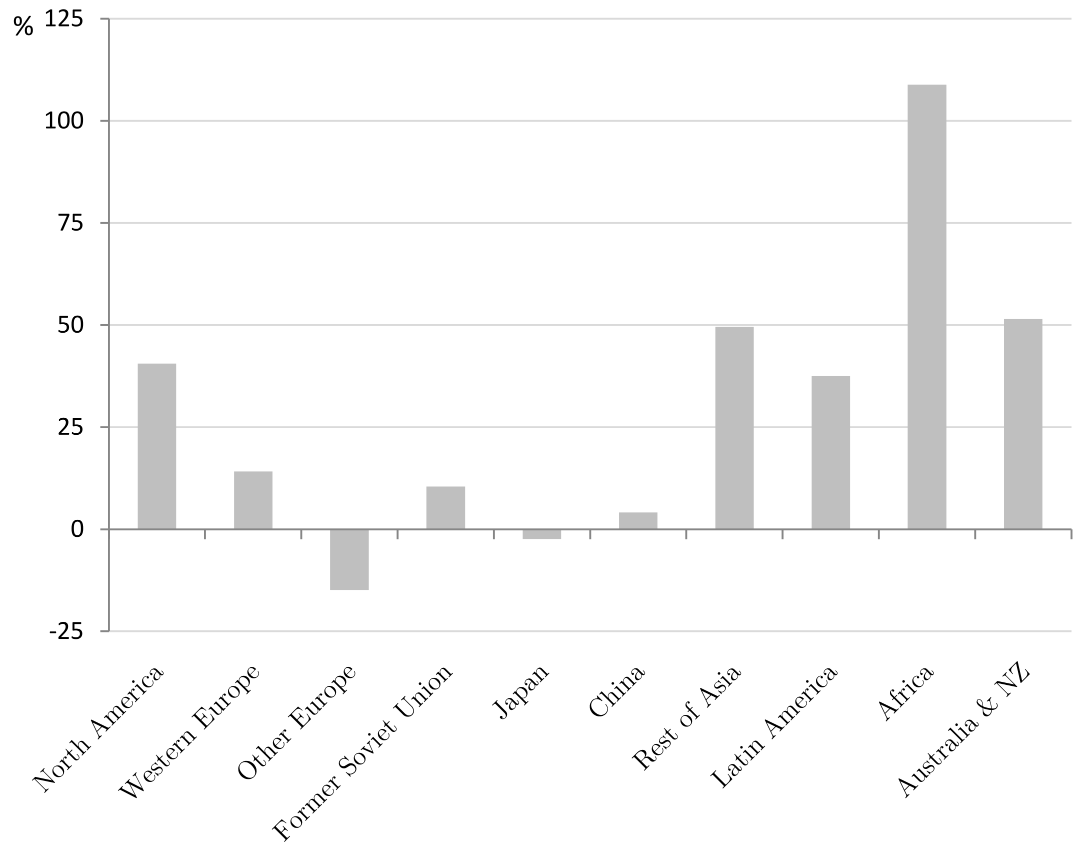
The obstacles are starker for world regions where population growth and diet changes could be particularly dramatic. The solutions have more potential for world regions with a greater possibility to use untapped resource endowments, improve yields, or reduce per capita food availability. Africa and Latin America stand apart as regions that simultaneously have potentially great obstacles and solutions. Hence, these two regions are particularly important for the global future of food and they ultimately become a focus in the formal scenario analysis at the crux of this dissertation.

1.2 Changes in global population and world diets

Projected world population growth will result in large increases in demand for food. Global population has increased from 5.4 billion people in 1990 to the current population 7 billion, and in their medium growth scenario the UN (2010) estimates that by 2050 this total will reach 9.7 billion. Both Asia and Africa see the largest absolute increases in population over this 60 year time span – about 2 billion and 1.5 billion respectively – and Figure 1.1 shows that Africa has the greatest regional growth rates over this period.

Additional increases to final demand of agricultural products will come from changes in diets. Total average food availability per region (Alexandratos *et al.* 2006), which is defined as the average supply of food available for the regional population as a whole (FAO 2011a), has increased in the past 40 years for most regions (Table 1.1). The largest increases have happened in developing regions such as East Asia; others (such as sub-Saharan Africa) have seen little change and transition countries have actually seen declines. This range shows that large decreases in food availability are just as possible as large increases over decade time scales. Although average food availability in all regions is projected to continue increasing to 2050, the largest increases are projected to come from Africa where current per capita availability is the lowest. Except Africa and South Asia, food availability is expected to rise above 3000 kcal/capita/day by 2050.

Figure 1.1 – Percentage increase in population by region from 1990 to 2050



Source: Medium-growth scenario from UN (2010).

The structure of global diets varies widely, particularly the percentage of overall caloric intake that originates from animal products. Increased consumption of animal products is of particular interest to this study because in addition to direct inputs, animal products require large indirect amounts of land, water, and other factors to produce their feed. Therefore, increases in demand for animal products put greater pressure on land and water resources compared to plant products. Table 1.2 presents the regional differences in availability of animal products using results from a formal k-means cluster analysis of 175 countries. The cluster analysis was performed for this study using data on 15 different food types (FAO 2010) in order to create clusters of countries with similar diets.

This cluster analysis resulted in 18 regional clusters, which are presented as seven groups in the table by geographical location and total caloric availability. The content of total diets that consists of animal products varies widely between clusters. In the Developed and Transition group, which is composed of clusters 11 – 15, animal products make up over 20% of total caloric availability, some regions as high as 31%; yet in the Africa group, which are composed of clusters 1 - 3, animal products make up less than 10% of total caloric availability.

Table 1.1 – Past and future per capita food availability (kcal $person^{-1}$ day^{-1})

	1969/71	1979/81	1989/91	1999/01	2015	2030	2050
World	2411	2549	2704	2789	2950	3040	3130
Developing countries	2111	2308	2520	2654	2860	2960	3070
sub-Saharan Africa	2100	2078	2106	2194	2420	2600	2830
- excluding Nigeria	*2073*	*2084*	*2032*	*2072*	*2285*	*2490*	*2740*
Near East / North Africa	2382	2834	3011	2974	3080	3130	3190
Latin America and Caribbean	2465	2698	2689	2836	2990	3120	3200
South Asia	2066	2084	2329	2392	2660	2790	2980
East Asia	2012	2317	2625	2872	3110	3190	3230
Industrial countries	3046	3133	3292	3446	3480	3520	3540
Transition countries	3323	3389	3280	2900	3030	3150	3270

Source: Table 2.1 in Alexandratos (2006).

Current trends suggest that the consumption of animal products is increasing worldwide, particularly in developing regions where population increases are expected to be the highest and where urbanization and demographic changes affect social eating habits (Steinfeld, Wassenaar, and Jutzi 2006). This trend has been particularly associated with Asia, where diets have become increasingly similar to those of North America and Europe (Pingali 2007), and yet Figure 1.2 shows that availability of animal products has continued to increase in some developed countries while in other developing countries it has hardly increased at all. Future projections of meat consumption are usually made based on a correlation with GDP growth, often using parameters from China's change in GDP and meat consumption (Keyzer *et al.* 2005).

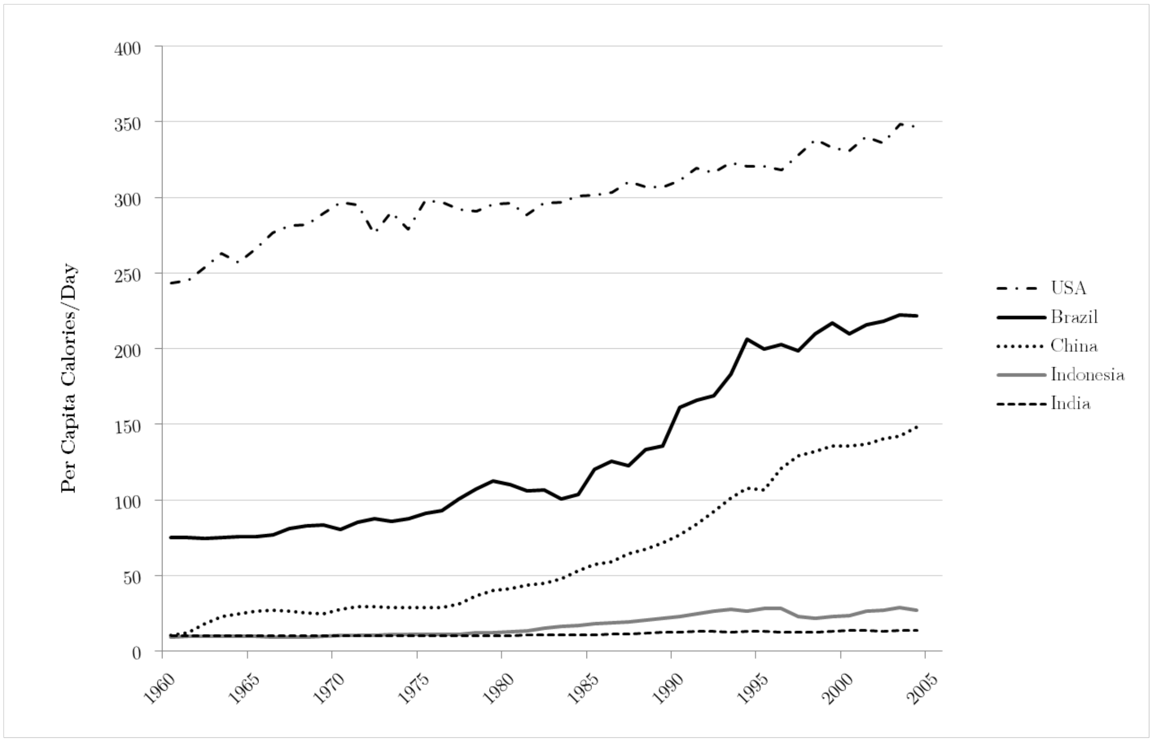
Table 1.2 – Regional total food availability and percentage from animal products for 18 worldwide clusters in the year 2000 (kcal capita^{-1} day^{-1})

Group	Cluster	Representative Countries	Total	% Animal Products
Africa	1	Burundi, Uganda, Rwanda	2,238	7
	2	Nigeria, Ghana, Angola	2,297	4
	3	Ethiopia, Malawi, Botswana	2,043	6
Latin America	4	Bahamas, Barbados, Bermuda	2,764	27
	5	Mexico, Brazil, Costa Rica	2,974	16
	6	Bolivia, Honduras, Venezuela	2,563	14
Asia	7	Armenia, Georgia, Uzbekistan	2,669	17
	8	Japan, China, South Korea	2,597	11
	9	Bangladesh, Vietnam, Nepal	2,481	6
	10	Sri Lanka, Fiji, Phillipines	2,724	12
Developed and Transition	11	France, USA, Australia	3,520	31
	12	UK, Portugal, Hungary	3,554	27
	13	Russia, Romania, Latvia	2,916	20
	14	Sweden, Iceland, Estonia	3,313	31
	15	Spain, Greece, Italy	3,495	24
Middle East	16	Turkey, Lebanon, Tunisia	3,188	11
Southern Temprate	17	Chile, Argentina, South Africa	2,815	22
Develeloping Mix	18	India, Guatemala, Zimbabwe	2,237	10

Source: Own computations based on data from FAO (2010).

Note: Representative countries are not inclusive, but simply provide an example of countries included in the cluster.

Figure 1.2 – Increase in consumption of meat for selected countries



Source: FAO (2010).

From the perspective of land and water scarcity, these increases in dietary demand are troubling. Yet, from the perspective of developing regions where present food availability is not sufficient, such dietary changes are positive and desirable. A number of studies have used 3000 kcal/capita/day - with 20% of calories coming from animal products - as a benchmark for the level of food availability necessary to eliminate undernourishment in a given region (Seckler and Amarasinghe 2003; Rockström *et al.* 2005; Rockström *et al.* 2009; Paillard, Treyer, and Dorin 2011). Similarly, for regions with current food availability above 3000 kcal/capita/day and more than 20% from animal products, this excess represents the potential for reductions in food consumption without approaching undernourishment. These studies do not claim that a diet based upon 3000 kcal/captain/day and 20% animal product availability is a necessary condition to maintain a healthy diet, but simply a regional average of food availability consistent with regions that have low rates of malnutrition.

Another important metric in analyzing regional hunger and food security is the price of food, both in terms of the factor income going to farmers and the cost of food for consumers. The food riots that accompanied the dramatic increases in global food prices in 2008 showed the vulnerability of regions such as Africa, Latin America, and Asia to increasing costs, highlighting the importance of keeping food affordable for the poorest part of the global population. Concurrently, increases in food prices have the potential to increase agricultural income. Which regions receive this increased income depends on the cost of production and how much each region can produce for domestic and foreign demand.

This study utilizes these two concepts – increased food availability and non-increasing food prices – to represent a reduction in global hunger and malnutrition. Still, these are not the only metrics that are needed to indicate a reduction of hunger and malnutrition. Currently, there is enough food produced globally to satisfy demand (Pinstrup-Andersen 2002) and global food prices had been declining consistently, yet hunger, famine, and lack of food security are widespread, not only in regions with low food availability but in even in regions that have food availability above 3000 kcal/capita/day.

A substantial literature is devoted to addressing the absence of food security in a world that has enough food available to satisfy global demand. Sen (1990) discusses the concept of entitlements, suggesting institutional barriers keep hunger present even when food availability per capita is sufficient. Buttel (2000) notes the limitations a supply-side "productionist" perspective that assumes hunger is caused by inadequate agricultural technologies or lack of economic growth in other sectors of the economy. Simultaneously, Buttel notes the limitation of a "neo-Malthusian" perspective that assumes hunger is as result of overpopulation and overexploitation of resources, not the structural barriers preventing a more equal distribution of food.

This study does not claim that achieving an "adequate" level of food availability and maintaining low food prices is sufficient to reduce hunger and malnutrition globally. Instead, it assumes that these two conditions are necessary for maintaining a secure and sustainable food future. The limitations of these metrics is important to keep in mind when considering the results of the scenario analysis, given that the main thrust of this research does not deal with the structural causality that underlies the persistence of hunger in many regions. Complimentarily research analyzing the persistent structural causes of hunger and famines is necessary to define the institutional changes that will help overcome hunger and malnutrition.

1.3 Land and water endowments: potential for expansion

In addition to the challenges posed by potential population and diets requirements to 2050 is the challenge of producing enough food without straining the regional endowments of natural resources. Land and water are of particular interest as they are both non-substitutable and limited resource inputs necessary for agricultural production that are also necessary for other uses, particularly environmental purposes. This section presents the conceptual distinctions between different types and quantities of land and water as well as estimates from the literature on past, current, and future use.

1.3.1 Current and future use of rainfed, irrigated, and pastureland

Agricultural land is multi-faceted natural resource with many different conceptual distinctions. It can be tabulated simply as one category of agricultural land; arable land can be separated into irrigated land and rainfed land or distinguished from pastureland; it can be categorized by is productivity potential (Fischer *et al.* 2002) or by the length of the growing season (Darwin *et al.* 1996; Juliá and Duchin 2007); it can be tabulated as land available for use, land equipped for irrigation, land actually used (% of land available), or land harvested (greater or less than land used depending on crop losses and intensity of multiple cropping); and other land classes (such as forests) can be included as potential arable land (FAO 2000).

As a result of these different definitions – and due to the somewhat unreliable nature of data from different sources and methods at this level of aggregation (Gibbs *et al.* 2010) - the estimation of land resources can vary from study to study. This study distinguishes between three different types of land - rainfed land, irrigated land, and pastureland.

Table 1.3 shows different estimates of global rainfed land used, harvested, and available from various studies. Available land is the area ready to be used in a given year. Harvested land differs from used land as it takes into account both crop losses and cropping intensity (such as double or triple cropping). Rainfed land used is higher than rainfed land harvested because the area subtracted due to crop losses is greater than area added due to cropping intensities (since multiple cropping is not as common with rainfed land). Between 1990 and 2006, total global estimates of availability and use vary between about 1,100 and 1,400 million hectares while harvested area varies between about 850 and 1,000 million hectares. Note that developing regions have a larger percentage of harvested land than used land since they have land with higher cropping intensities.

Table 1.4 shows different estimates of equipped, used, and harvested irrigated land from various studies. Since double and triple cropping is more common with irrigated land, harvested area is actually larger than used area. Area equipped for irrigation is greater than area actually irrigated, and Bruinsma (2009) estimates that irrigated land actually in use is often about 80 and 90 percent of the area equipped. Some of the largest discrepancies between estimates from different sources can be seen by comparing those estimates of harvested land between Table 1.4 and Table 1.5. In North America, for instance, Siebert and Döll (2010) estimate harvested rainfed land to be 60% higher than Calzadilla *et al.* (2010) while irrigated land is 50% lower.

Table 1.5 shows global estimates of current pastureland use by region. Pastureland differs from arable land in that it is used solely for grazing, and is often less productive and marginal land compared to arable land. Estimates of global use are 3100 – 3400 million hectares, except for Ramankutty (2008) who use land cover data from satellites to estimate that global pastureland is significantly less (at ~2,700 million hectares). In each estimate, over two-thirds of pasture use is in developing countries, with the largest endowments in Africa and Latin America.

A handful of studies, all of which will be discussed in more detail in the literature review, estimate future rain and irrigated land used and harvested (Table 1.6 and Table 1.7). Global rainfed land use changes vary between 0 and 10%. Global irrigated land use increases in all scenarios, but with a large range of 5 – 32%. Both rainfed and irrigated land use in developing regions are strictly increasing for all studies, but the direction of the change in developed countries is indeterminate.

Table 1.3 – Estimates of globally available, used and harvested rainfed land (10^6 ha)

Source	FAO (2011c)	Bruinsma (2008)	Fischer *et. al.* (2007)	EXIOPOL (2011)	Bruinsma (2008)	de Fraiture *et al.* (2007)	Calzadilila *et al.* (2010)	Siebert and Döll (2010)	Bruinsma (2008)
Year measured	1990	1990	2000	2000	2006	2000	2000	2000	2006
(I) Available (II) Used (III) Harvested	(I)	(I)	(II)	(II)	(II)	(III)	(III)	(III)	(III)
Rich and Transition	577	609	583	475	584	299	268	425	422
Developing	560	661	683	787	777	529	583	568	649
Asia									
East Asia	78	176	88			156	64	84	
South Asia	200	106	192			95	207	220	
Latin America	117	133	152			101	92	112	
North Africa and Middle East		96	55			18	45		
Africa	165							153	
Sub-saharan		161	196			158	171		
ROW		7	3			32	4		
Total	1137	1271	1269	1262	1361	860	852	993	1070

Source: Compiled from sources listed above each column.

Note: Rich and Transition region includes North America, Europe, Former Soviet Union, Japan, and Australia. Aggregations of some regions were roughly estimated in some cases, as the authors of each estimate use different regional aggregations.

Table 1.4 – Estimates of globally equipped, used and harvested irrigated land (10^6 ha)

Source	FAO (2011c)		Bruinsma (2008)	Alcamo *et al.* (2007)	Rosegrant *et al.* (2002)	Siebert and Döll (2010)	Fischer *et. al.* (2007)	EXIOPOL (2011)	Bruinsma (2008)		de Fraiture *et al.* (2007)	Siebert and Döll (2010)	Calzadilila *et al.* (2010)
Year measured	Potential	1990	1990	1995	1995	2000	2000	2000	2006	2006	2000	2000	2000
(I) Equipped (II) Irrigated (III) Harvested	(I)	(I)	(I)	(I)	(I)	(I)	(I)	(I)	(II)	(III)	(III)	(III)	(III)
Rich and Transition	106	69	66	51	82	71	74	53	51	51	78	57	109
Developing	350	175	178	192	293	203	197	209	189	270	264	256	319
Asia				162									
East Asia	65	49	64		91	60	58				117	87	123
South Asia	185	98	67		112	94	78				104	138	163
Latin America	62	17	17	18	17	18	20				17	16	19
North Africa and Middle East			25		26	25	20				21		7
Africa	38	11		12								15	
Sub-saharan			5		25	6	8				6		6
ROW					23		13						1
Total	456	243	244	243	375	273	271	262	240	321	342	312	428

Source: Compiled from sources listed above each column.

Note: Rich and Transition region includes North America, Europe, Former Soviet Union, Japan, and Australia. Aggregations of some regions were roughly estimated in some cases, as the authors of each estimate use different regional aggregations.

Table 1.5 – Estimates of global pastureland (10^6 ha)

Source	Juliá and Duchin (2007)	FAOSTAT (2010)	Bouwman *et al.* (2006)	Ramankutty *et al*. (2008)	EXIOPOL (2011)
Year measured	1990	1990	1995	2000	2000
Rich and Transition	1011	888	1075	881	1029
Developing	2122	2251	2209	1800	2396
Asia					
East Asia	400	532		354	
South Asia	235	310		55	
Latin America	587	550		518	
North Africa and Middle East				145	
Africa	900	859			
Sub-saharan				728	
ROW					
Total	3133	3139	3284	2681	3426

Source: Compiled from sources listed above each column.

Note: Rich and Transition region includes North America, Europe, Former Soviet Union, Japan, and Australia. Aggregations of some regions were roughly estimated in some cases, as the authors of each estimate use different regional aggregations.

Table 1.6 – Estimates of future rainfed land used and harvested (10^6 ha)

Source	Bruinsma (2008)				de Fraiture *et al.* (2007)		Calzadilila *et al.* (2010)	
Year estimated	2050	% Δ	2050	% Δ	2050	% Δ	2050	% Δ
(II) Used (III) Harvested	(II)		(III)		(III)		(III)	
Rich and Transition	536	-8	426	1	300	0	224	-17
Developing	864	11	753	16	604	14	627	7
Asia								
East Asia					182	17	58	-10
South Asia					84	-12	205	-1
Latin America					148	46	113	23
North Africa and Middle East					16	-11	17	-63
Africa								
Sub-saharan					174	10	229	34
ROW					16	-50	4	16
Total	1400	3	1179	10	920	7	851	0

Source: Compiled from sources listed above each column.

Note: Rich and Transition region includes North America, Europe, Former Soviet Union, Japan, and Australia. Aggregations of some regions were roughly estimated in some cases, as the authors of each estimate use different regional aggregations.

Table 1.7 – Estimates of future irrigated land available, used, and harvested (10^6 ha)

	Rosegrant *et al.* (2002)		Fischer *et. al.* (2007)		Bruinsma (2008)						de Fraiture *et al.* (2007)				Calzadilila *et al.* (2010)	
Year estimated	2025	% Δ	2050	% Δ	2050	% Δ	2050	% Δ	2050	% Δ	2050	% Δ	2050	% Δ	2050	% Δ
(I) Equipped (II) Irrigated (III) Harvested	(I)		(II)		(I)		(II)		(III)		(III)		(III)		(III)	
Rich and Transition	87	6	82	11	68	3	51	0	51	0	47	-39	87	12	106	-2
Developing	355	21	254	29	251	41	222	17	325	20	311	17	364	38	358	12
Asia																
East Asia	108	18	68	17	97	52					136	16	170	46	118	-4
South Asia	140	25	101	29	86	28					123	18	135	30	172	5
Latin America	22	31	38	90	24	41					20	18	23	42	24	28
North Africa and Middle East	31	22	26	30	36	44					22	4	23	10	33	342
Africa																
Sub-saharan	32	26	21	163	8	76					11	77	13	100	11	77
ROW	22	-2	20	54											1	27
Total	441	18	356	31	319	31	273	14	377	17	358	5	451	32	464	8

Source: Compiled from sources listed above each column.

Note: Rich and Transition region includes North America, Europe, Former Soviet Union, Japan, and Australia. Aggregations of some regions were roughly estimated in some cases, as the authors of each estimate use different regional aggregations. Estimates by come from two different scenarios, see Chapter 2 for a more detailed discussion of this study.

1.3.2 Current and future use of blue water withdrawals and green water consumption

As rainfed is distinguished from irrigated land, the types of water applied to these two different land categories must be distinguished as well. It is common for water experts to distinguish water runoff from soil moisture, and this distinction has been popularized more recently using the terms blue water and green water, respectively. Green water exists as moisture in the non-saturated layer of soil, and although it is used by both rainfed and irrigated land, it is the sole source of water for the former. Blue water is water runoff in streams and rivers as well as water stocks in lakes and aquifers, and the majority of blue water use worldwide is for irrigation.

Another important concept is the difference between water consumption and water withdrawals, the former being the amount of water (blue or green) actually evapotranspired by a plant and the latter being the amount of blue water anthropogenically removed for various uses. The difference between withdrawals and consumption include the various types of efficiency losses (Shiklomanov 2000). This study considers both green water consumption and blue water withdrawals to represent rainfed and irrigated production. Both types of water will be necessary for considering improved crop-water technologies as discussed in Section 1.4.1. Yet Duchin and Lopez (2011) note that although it is important to consider both blue and green water as distinct factors of production, the availability of blue water requires additional attention due to its multiple uses (such as industrial and domestic uses) and sources (such as groundwater or aquifers).

Table 1.8 shows both agricultural and other water withdrawals as estimated from various sources. Estimates of total global withdrawals vary between about 3,500 and 3,900 cubic kilometers, with more than two-thirds coming from developing countries and nearly half from Asia. Also note that rich and transition countries use less than half of total regional withdrawals for irrigation, with the majority being used for industrial and domestic purposes. These same sources estimate that future global withdrawals will increase by 37 – 43 % (Table 1.9). Future increases in regional withdrawals vary by source: 0 – 28% for developed regions, 69 – 124 % for Latin America, and 71 – 230 % for Africa.

Table 1.8 – Estimates of global water withdrawals (km^3)

	Shiklomanov (2003)			Alcamo *et al.* (2007)			de Fraiture & Wichelns (2010)			FAO (2010c)		
Year measured	1990			1995			2000			2000		
	Irrigation	Other	Total	Irrigation	Other	Total	Irrigation	Other	Total	Irrigation	Other	Total
Rich and Transition	505	661	1,166	493	619	1,112	477	675	1,152	477	640	1,192
Developing	1,888	530	2,418	2,005	477	2,482	2,153	219	2,372	2,153	351	2,382
Asia	1,672	395	2,067	1,749	352	2,101	1,613	133	1,746	1,613	368	1,905
East Asia							518	99	617	518	213	656
South Asia							1,095	34	1,129	1,095	154	1,249
Latin America	92	60	152	122	98	220	175	52	227	175	78	265
Africa	124	75	199	134	27	161				0	30	212
Africa and Middle East							241	34	275	241		
Sub-saharan							68	10	78	68		
North Africa and Middle East							173	24	197	173		
ROW							124	0	124	124		
Total	2,393	1,190	3,584	2,498	1,096	3,594	2,630	894	3,524	2,630	991	3,574

Source: Compiled from sources listed above each column.

Note: Rich and Transition region includes North America, Europe, Former Soviet Union, Japan, and Australia. Aggregations of some regions were roughly estimated in some cases, as each study uses different regional aggregations.

Table 1.9 – Estimates of future global water withdrawals (km^3)

	Shiklomanov (2003)			Alcamo *et al.* (2007)			de Fraiture & Wichelns (2010)		
Year simulated	2025			2055			2050		
	Irrigation	Other	Total	Irrigation	Other	Total	Irrigation	Other	Total
Rich and Transition	590	855	1,445	460	650	1,110	509	967	1,476
Developing	2,532	1,160	3,692	1,795	2,027	3,822	2,466	996	3,462
Asia	2,244	860	3,104	1,565	1,233	2,798	1,796	594	2,390
East Asia							601	419	1,020
South Asia							1,195	175	1,370
Latin America	112	145	257	114	379	493	196	254	450
Africa	175	156	331	116	415	531			
Africa and Middle East							328	142	470
Sub-saharan							100	60	160
North Africa and Middle East							228	82	310
ROW							146	6	152
Total	3,122	2,015	5,137	2,255	2,677	4,932	2,975	1,963	4,938

Source: Compiled from sources listed above each column.

Note: Rich and Transition region includes North America, Europe, Former Soviet Union, Japan, and Australia. Aggregations of some regions were roughly estimated in some cases, as each study uses different regional aggregations.

1.3.3 Potential land use and water withdrawals: defining endowments

The estimates of land and water use in the previous section are estimates of past or future use, but they do not describe the regional endowments of resources, or the total *potential* for expansion of land and water use. In the short term, this amount is restricted by infrastructure constraints and prevents the use of all potential resources. López-Morales and Duchin (2011) term this the *effective supply*. The effective supply is comparable USGS concept of *reserves*, which denotes the amount of a resource available at current economic prices and infrastructure (or the *reserve base* if sub-economic resources that can potentially be used are included) (USGS 2010). In the long term, the regional endowment of land and water becomes the renewable supply, or the amount that is physically available to be used for production. This long term endowment of land and water is akin to the USGS concept of *resources*, which denotes the absolute amount of a resource available, regardless of its quality, location, or price of extraction.

A common approach to circumvent the need to define *potential* quantities of regional land and water endowments is to use the price of economic reserves as the limiting constraint on production. If resources become scarce, prices will increase and act as a constraint until 1) additional capacity is added increase supply, utilizing the resource base 2) the price of a substitute becomes relatively cheaper or 3) demand decreases. Pindyck (1978) offers the standard explanation that there is therefore no such thing as a fixed reserve base since the reserves increase and decrease based on the price of the resource, the extraction technology available to make the resource available, and the quality of the absolute quantities of the remaining resource. From this perspective, price elasticities of substitution act as boundaries for substitution of factors and technologies. With this framework in place, there is no need for a conceptual measure of physical constraints to factor availability.

As a result of this approach, physical limits to resource stocks are therefore not included in most economic models or databases as pointed out by Duchin (2007). Yet defining physical constraints on resource availability, not only of land and water but of traditional factors of production such as capital and labor, is an important component for determining regional comparative advantages. Within this theoretical framework, the lowest cost producer continues to produce until it runs out of its endowment of any factor or production, including land or water. This constraint induces the next lowest cost producer to produce until it also runs out of a factor of production or demand is met. The quantity of physical regional endowments is therefore necessary to determine not only which producers produce, but which regions and factors gain rents and at what price the produced commodity is ultimately sold.

Potentially cultivable arable land is percentage of regional land that has qualities sufficient to grow crops. Two sources are available that calculate potentially cultivable arable land. The FAO (2000) defines the *potential* rainfed land for each country based on the physical capacity to produce crops, not on its current land use. Therefore, these estimates include current cropland, forests, land with human settlement, and protected land among other types. IIASA (Fischer *et al.* 2002) provides a more detailed estimate of potential arable land based on the production capacity of individual parcels of land (and like the FAO does not discriminate based on the current use of land).

Irrigated land is defined by the existence of infrastructure for delivering blue water resources. Potential irrigated land is therefore an estimate of the future amount of irrigated land that could be equipped with irrigation technology. Aquastat (FAO 2011b) estimates suggest that the largest potential is in Southeast Asia, with large potential in also Latin America, Africa, and the Former Soviet Union.

The potential for additional pastureland is small as land experts suggest that extensive pastureland has reached its limits (Steinfeld *et al.* 2006; Gibbs *et al.* 2010). Therefore, the renewable supply and effective supply of pastureland are the same. There is potential for livestock production to expand onto arable land, either land currently used for crops or potential arable land such as forests.

The potential supply of blue water is the renewable supply (or the total runoff of water in a given year) while the potential supply of green water for agriculture is the percentage of rainfall that can potentially be maintained in the soil of arable land. The former is much simpler to measure and commonly defined in databases. Potential green water supplies are more difficult to determine since they not only depend on the amount of potential arable land, but on the moisture-retaining capacity of the soil.

1.3.4 Environmental restrictions to potential land and water endowments

The expansion of land and water use to their potential endowments or *resources* may be physically possible, but not necessarily sustainable. Since the research questions posed by this study concern meeting future food demand sustainably, it becomes important to define the quantities of land and water that are necessary for environmental reasons. In addition to the definition of the *effective supply* of blue water, López-Morales and Duchin (2011) define the *environmentally sustainable supply* of blue, which considers the *environmental water requirements* (EWR, or the amount of water necessary to maintain vital environmental functions) in addition to the infrastructure constraints preventing the use of all potential resources. Duchin *et al.* (2010) extend this framework by attempting to define the environmentally sustainable supply for all types of factor inputs, including land. The approach of this study is to define the levels at which land and water use becomes unsustainable and to subtract the amount of the land and water endowment that is undesirable for expansion.

Unsustainable land use: Forestland and protected land

Two types of land expansion are considered by this study as unsustainable: expansion onto forestland and expansion onto protected land. This study argues that the *environmental land requirements* (ELR) should include more than simply protected land. Land area necessary to maintain vital ecosystem functions should be included as well, such as land that contains high levels biodiversity, carbon sequestration capacity, or hydrological services. This is particularly true for the world's forestland.

IIASA provides regional estimates of the percentage of forestland that is potentially arable Fischer *et al.* (2002) and uses this logic to deduct the portion of potentially arable land that is forested for environmental reasons (Fischer and Heilig 1997). This study uses the IIASA estimates and multiplies them by FAO data on total regional forestland (FAO 2011c). Estimates of protected land are taken from UNEP (2011). Table 1.10 shows potentially arable forestland and protected land as components of the entire endowment of potentially arable land.

Africa and Latin America have the largest potential arable land stocks with over 50% of global potential arable land and over 65% of net potential arable land (land not currently in use for agriculture). Yet forestland and protected land are large components of the global endowment, and after subtracting these two categories 86% of the remaining rainfed land is in Latin America and Africa (labeled other potential land in Table 1.10). It is entirely possible that the endowment of potential arable forestland could be unsustainably deforested by 2050, as annual deforestation in Latin America and Brazil are currently 4 million and 3.5 million hectares per year, respectively (FAO 2011c). The estimate of both potential land and effective supply of land are key concepts for the scenario analysis, as described in Chapter 5.

Table 1.10 – Potential arable land by region and type (10^6 ha)

	Forest	Protected	Rainfed Land Use	Irrigated Land Use	Other Potential Land	Total
North America	121	109	202	28	90	551
Western Europe	7	25	81	12	30	155
Other Europe	25	20	91	8	21	164
Former Soviet Union	76	88	183	20	33	399
Japan	3	3	3	3	4	16
China	9	46	101	67	49	273
Rest of Asia	22	55	265	107	98	548
Latin America	262	251	135	13	336	995
Africa	126	220	184	12	609	1,150
Australia & NZ	44	42	30	4	18	137
World	696	859	1,274	272	1,286	4,388

Sources: Own computations based on potential arable land estimates from FAO (2000). Data on rainfed and irrigated land use is from Siebert and Döll (2010) for the year 2000. See text for sources forest and protected land.

Note: About 10% of total protected land is also forestland Hayes and Ostrom (2005), and this was used to prevent double-counting.

Arguably the most influential country Latin America – in terms of both its land and water resources and its economic production - is Brazil, and it is here that the intersection between crop and livestock production on cropland, pastureland, and forestland is particularly prominent. As the global leader in cattle exports, Gibbs (2010) shows that it is also the only region in the world where expansion of pastureland is still taking place, either by expanding onto current cropland or onto forestland. In addition, Brazil has recently begun reconsidering its Forest Code, which currently specifies that 80% of a landholding in the Amazon remain forest, 35% in the Cerrado , and 20% in other areas (Barrionuevo 2011). This reconsideration is driven in part by pressure from farmers and ranchers who are benefiting from increased prices for soybeans and beef that make such land increasingly valuable for agriculture (Tollefson 2011). This trade-off land for use of crops, livestock, or ecosystems services makes this region of particular relevant to the research questions of this study.

The intersection of agricultural production and land expansion is also prominent in Africa, where foreign direct investments in large land holdings have increased in recent years, popularized as foreign "land grabbing" (Cotula *et al.* 2009). This reflects the central role of Africa's endowment of potential arable land and pastureland, which will affect Africa not only for its own food production, but the food production of other regions around the world that are increasingly land scarce.

Unsustainable water use: measuring water stress

Multiple approaches exist for estimating when water withdrawals are creating water scarcity and potentially taking water from vital environmental services. A common approach within the water literature is to create an index by dividing total water withdrawals by total runoff (total runoff is equivalent to the renewable supply). This index or ratio has many different names, including the Water Resources Vulnerability Index (Raskin *et al.* 1997), the Criticality Ratio (Alcamo, Henrichs, and Rosch 2000), and the Water Exploitation Index (Lallana and Marcuello 2004; López-Morales 2010).

This study will utilize the Water Exploitation Index (WEI) to limit withdrawals and prevent regions from using water unsustainably and reaching critical water scarcity. If the WEI is between 0.2 and 0.4, a region is considered water scarce, and if a region goes above 0.4 it is considered critically water scarce. Although other measures of environmental water stress are more detailed (such as the environmentally sustainable supply defined by López-Morales and Duchin 2011), the WEI is commonly used in studies analyzing water stress at the global scale, the same scale considered in this dissertation.

Defining the stock of green water requires unique and detailed knowledge of the soil characteristics of a specific parcel of land, and therefore its availability is a much harder concept to define. This study has not seen any studies that attempt to define the potential availability, and any measure the environmentally sustainable supply of green water would be a strictly local concept, and hence difficult to apply the broad regions used in this study.

1.4 Potential of improved agricultural technologies

In Sections 1.2 and 1.3, two solutions have been outlined that could help overcome increases in population and food consumption: potential reductions of domestic demand for food (in particular animal products) in regions where excess food availability is currently high and expansion of agriculture using additional regional endowments of land and water. A third possibility is to increase the efficiency of land and water inputs per unit output through technological improvements. The general conclusion coming from major international agricultural institutions, such as IFPRI and the FAO, is that potential improvements in yields can increase output enough to overcome future global increases in food demand (Keyzer *et al.* 2005). This study tests this conclusion by considering two types of technological changes: improvements in crop-water management and possibility of growth of industrial livestock technologies.

1.4.1 Potential for improved crop-water management on rainfed and irrigated land

The same production ecology models that estimate the extent of potentially arable land (Fischer *et al.* 2002; van de Ven *et al.* 2003) also define the yield potential of these endowments based upon climate, soil types, elevation, and the “optimal” inputs such as water, fertilizer, etc. Establishing an upper bound for physically attainable yields allows the calculation of the yield gap – the difference between current yields and potential yields. A common approach is to estimate what percentage of this potential is likely to be achieved globally. A more precise approach also suggests specific technological options – either individually or as a group – that when implemented can actually attain these improved yields.

This study follows this logic by considering the potential yield improvements that can be attained by improvement management of both blue and green water for agricultural production. Improved land yields (tonne ha^{-1}) also improve water productivity (m^3 $tonne^{-1}$). These improvements are centered on Latin America and Africa as these two regions have a large potential to close this yield gaps.

Improved management of water resources on rainfed land

Improved irrigation management has been the key focus for decades (Gleick 2003a), although Molden (2007) points out that most of the growth in food production in recent decades have come from rainfed agriculture. As this fact has become increasingly recognized, a numbers studies have considered rainfed water management strategies in addition to improvements in irrigation infrastructure (Falkenmark and Rockström 2006; de Fraiture *et al.* 2007).

Table 1.11 shows estimates from de Fraiture *et al.* (2007) of potential cereal yield improvements on rainfed land that are possible in both these regions. Potential increases are more than 150% for all cereal types in both regions, and as high as 320% for rice production in Africa.

Table 1.11 – Cereal crop yields (tonnes ha^{-1}) in the year 2000 and 2050

	Sub-saharan Africa			Latin America		
	Baseline	Projected	% Δ	Baseline	Projected	% Δ
Wheat	1.3	3.2	246	2.2	3.7	168
Rice	1.0	3.2	320	1.4	3.8	271
Maize	1.4	4.1	293	2.7	4.9	181
Total	1.2	3.5	284	2.1	4.1	197

Source: High-yield scenario from de Fraiture *et al.* (2007). Projected yields are optimistic and close 80% of the yield gap.

These improved yields in rainfed agriculture can be achieved by increasing the portion of green water consumption that is used productivity *without* increasing green water consumption. Green water management strategies include land leveling, terracing, soil fertility management, and tillage (Falkenmark and Rockström 2006; de Fraiture *et al.* 2007). These strategies do not increase the amount of soil moisture evapotranspired by the plant, but instead increase the portion of green consumptive water transpired. Since green water consumption –which consists of the combination of evaporation and transpiration – doesn't decrease, this additional transpiration results from reducing evaporation. This concept is known as a *vapor shift,* since it simply shifts evaporation to transpiration. Reducing the portion of soil moisture lost as non-productive evaporation improves yields (tonnes ha^{-1}) and hence green water productivity (m^3 $tonne^{-1}$). Falkenmark and Rockström (2006) suggest that such strategies can achieve vapor shifts that double yields in regions where current yields are between 1 and 3 tonnes ha^{-1}.

Improved irrigation efficiency and blue water consumption

Crop-water management on irrigated land has the potential to increase the amount of blue water consumed per unit withdrawn. This ratio is known as the irrigation efficiency: a higher ratio means less water needs to be withdrawn for a given yield. Such improvements can be achieved by the adoption of different irrigation technologies, such as micro-irrigation systems or improvements in on-farm water management. Particularly, technologies such as sprinkler or drip irrigation achieve this by more precise timing or placement of water, thereby improving irrigation efficiency by reducing the amount of water needed to be withdrawn to provide for the same water consumption. This precise timing and placement of irrigation water also creates a *vapor shift* in blue water consumption that reduces the amount of consumptive water lost as evaporation, improving yields and the blue water productivity even further.

Again, the Africa and Latin America are regions where the most irrigation efficiency improvements can be made. Both de Fraiture *et al.* (2007) and Calzadilla *et al.* (2010) estimate this ratio can be raised in these regions from relatively inefficient ratio of 0.4 to more efficient ratio of 0.7, a level consistent with irrigation efficiency in developed regions.

1.4.2 Potential for alternative livestock technologies

Over 70% of global agricultural land is used for grazing of ruminants (Stehfest *et al.* 2009) – often on extensive pastureland that cannot be used for other agricultural purposes – and hence pastoral livestock production will continue to be a key aspect to meeting increased global demand for meat. Yet in recent years, meeting increased demand for beef has been done by using livestock production systems dependent on feed crops (Naylor, 2005). A small literature explores the relationships among diets, pastureland use, and alternative livestock technologies. These studies distinguish two types of livestock systems: pastoral livestock systems that primarily forage on extensive pastureland and mixed/industrial systems that supplement grazing with feed and fodder from crops grown on arable land (Delgado *et al.* 1999; Steinfeld *et al.* 2006; Stehfest *et al.* 2009).

Given the lack of additional pastureland for expansion of pastoral systems (Foley *et al.* 2005), the use of mixed/industrial systems may provide a way to meet future demand. Figure 1.3 compares the pastureland required for production of livestock for different regions. Output per hectare of pastureland using mixed/industrial systems is much lower than similar systems in industrialized countries, highlighting the potential of more efficient mixed/industrial livestock systems in regions such as Latin America and Africa that simultaneously have a large remaining portion of potential pastureland. However, as mixed/industrial systems rely on additional inputs of feed crops, they also indirectly require the additional inputs required to grow the crops they are fed.

Figure 1.3 – Meat and milk production per hectare of pastureland (kg ha^{-1}) for different livestock production systems

Region	Pastoral	Mixed/ Industrial	Average
Developing	1.0	4.5	1.4
Industrial	0.5	10.0	3.2
Transition	0.7	9.0	2.0
World	0.9	7.2	1.8

Source: Own computations using data from Bouwman *et al.* (2006).

1.5 Hypotheses and scenarios

This study suggests three hypotheses in response to these research questions, listed in Table 1.12. The set of hypotheses test the implications of succeeding in the broad policy goals of increasing food availability and agricultural development in developing countries while maintaining sustainable use of land and water.

Hypotheses

Hypothesis 1 proposes that it is not possible to meet future global agricultural demand with current technologies and the environmentally sustainable supplies of land and water. If this hypothesis is rejected, then the future of agricultural production is not as dire as feared, and the potential tradeoffs between sustainability, development, and food prices will not be quite as sharp. However, if this Hypothesis 1 is not rejected then offsetting reductions in consumption, technological improvements, or further resource expansion will be necessary to produce a feasible solution.

Hypothesis 2 proposes that the technology and diet solutions – low-resource diets in developing countries, crop-water management, and livestock technologies – will save enough land to lower use below 1990 levels. Projections of future land use are mixed, with some studies suggesting future increases in rainfed and pastureland, while other suggest decreases. An switch from less efficient rainfed land to more efficient irrigated land, coupled with diet and livestock technologies, may be enough to reduce land back to baseline levels (at the expense of increases in blue water use). Even if Hypothesis 2 is rejected, a large reduction in resource use would be a good argument for contraction and intensification instead of expansion.

Hypothesis 3 proposes that although the technology and diet solutions will accomplish sustainable levels of land and water use – that is preventing expansion onto forestland and keeping the WEI of blue water below 40% – they will also result in higher food prices than the resource expansion scenario. The reason for this hypothesis is that the majority of potential forested land for agriculture is in Latin America and Africa where land prices and agricultural production is cheap. Although the technological changes introduced into Latin America and Africa will also take advantage of these cheap prices, they still will not have access to the large amount of forestland.

Therefore, it is hypothesized that land will run short in these scenarios sooner, and once the cheap land in these regions is used up, production will go to more expensive regions, raising world prices. From a sustainability perspective, the difference between these two prices levels is just as important, for even if this hypothesis is not rejected, slightly lower prices may not be an acceptable tradeoff if dramatic amounts of forestland must be cleared to make this possible.

Table 1.12 – Three hypotheses tested in this study

Hypothesis	Description
1	Meeting the global demand in 2050 is possible, but only with either unsustainable resource expansion or adoption of low-resource diets and technological changes.
2	Low-resource diets and technological changes can reduce global land use to Baseline levels
3	Low-resource diets and technological changes can meet future global demand sustainably but with higher food prices compared to unsustainable resource expansion

Notes: Increased global demand in 2050 is based on population and diet assumptions in S2050. Resource expansion refers to potential arable forestland and renewable supplies of water. Low-resource diets refer to rich regions. Technological changes refer to improved crop-water management and industrial livestock technologies in Africa and Latin America.

Scenarios

This study employs multiple scenarios to pursue these purposes. They test the implications of succeeding in the broad policy goals of increasing food availability and agricultural development in developing countries while maintaining sustainable use of land and water.

Six scenarios are used to test the hypotheses and discuss the implications of the results (see Table 1.13). The first scenario – S2050 – is distinct from the other categories as its intention is to show "how bad things can get." This scenario is constructed to quantify the potential stress that population and diet change will have on the global production system and the world's natural resources. Although land and water availability are increased in this scenario, land and water use are restricted to their sustainable supplies, further exacerbating the situation by limiting the available factors that can be used for production.

The remaining scenarios are solution scenarios, intended to reduce the increased pressure on global production from S2050. The second scenario – Scenario Resource Expansion (SRE) – is distinct as it reduces pressure on global production by increasing resource use. This scenario is identical to S2050 expect regional endowments are expanded to include potentially arable forestland and the renewable supply of blue water.

The third, fourth, fifth scenarios are constructed to represent the three ways for reducing food prices while also reducing resource use. The third scenario – Scenario Diet (SD) – introduces less resource intensive diets in rich countries. The fourth scenario – Scenario Water (SW) – introduces crop-water management strategies in Latin America and Africa, increasing their efficiency of land and water use. The fifth scenario – Scenario Livestock (SL) – separates mixed/industrial livestock technologies from pastoral technologies in Latin America and Africa, allowing each region to utilize either or both technologies based on factor availability and the cost structure of each technology. The sixth scenario – Scenario Diets, Water, and Livestock (SDWL) – combines scenarios SD, SW, and SL to show the cumulative effect of all three scenarios at once.

The scenarios are analyzed using the World Trade Model (WTM), an inter-regional input-output model based on comparative advantage that consistently reflects both the economic and physical variables and parameters analyzed in the scenarios. The basis for the WTM baseline and the six scenarios is the WTM database, a global input-output database that has been used in multiple previous studies (Juliá and Duchin 2007; Strømman and Duchin 2006; Strømman et al. 2009). All three hypotheses are tested using scenarios constructed from this database and the majority of the scenario analysis results and discussion presented in this study are primarily from this database.

Only two of the six scenarios were constructed using the WTM/EXIOPOL database, a much more detailed database (21 regions and 79 sectors) constructed as part of a multi-institution project through the European Union (EXIOPOL 2011). Originally, this database was intended to be the main database used to run the scenario analysis and test the hypotheses; however, over the course of this project, a number of problems with the database were identified, partly though efforts of this scenario analysis (Duchin, Springer, and Levine 2011). The results from the WTM/EXIOPOL scenarios will be used to highlight the potential of a more detailed database to provide a more in-depth analysis while showing the practical difficulties of implementing more detailed scenarios and the implications for future studies.

Table 1.13 – Six scenarios used to test the three hypotheses

Scenarios		Name	Description
1	S2050	Scenario 2050	Increased global population, improved diets in developing regions, increased land and water endowments (sustainably), and livestock can use cropland
2	SRE	Scenario Resource Expansion	S2050 + Land endowments increased to include arable forestland and blue water endowments increased to renewable supplies
3	SDWL	Scenario Diets, Water, and Livestock	S2050 + SD + SW + SL
	-- SD	Scenario Diets	S2050 + Adoption of low-resource diets in regions above 3000 kcal $capita^{-1}$ day^{-1} and 20% animal products
	-- SW	Improved water management	S2050 + Adoption of for improved rainfed and irrigated cereal production in Latin America and Africa
	-- SL	Technological choice for livestock industry	S2050 + Distinction between industrial and pastoral livestock systems in Latin America and Africa

Note: Rich regions are North America, Europe, Former Soviet Union, Japan, and Australia/New Zealand. Developing regions are China, Rest of Asia, Latin America, and Africa.

1.6 Summary of findings and organization of study

Table 1.14 shows the results of the hypotheses tests along with the scenarios used to test them and a summary of the results. Scenarios S2050, SRE, and SDWL are used to test the first hypotheses: meeting future food demand in 2050 is possible, but not without land expansion onto forestland, diet changes in developed countries, or technological changes in Africa and Latin America. **Hypothesis 1 is not rejected** as S2050 is infeasible yet both SDWL and SRE are feasible. SRE is feasible due to the large amount of additional forestland that is used for agricultural production, particularly due to increased rainfed agricultural production and expansion of livestock production onto current or potential croplands. SDWL is feasible as well, showing that the proposed diet and technological changes are also sufficient to meet future food demand without land expansion of onto forestland and protected areas.

Table 1.14 – Results of hypothesis tests from the scenario analysis

Hypothesis	Description
1	Meeting the global demand in 2050 is possible, but only with either unsustainable resource expansion or adoption of low-resource diets and technological changes.
	Not rejected. Even with increased land and water endowments S2050 is infeasible
2	Low-resource diets and technological changes can reduce global land use to Baseline levels
	Rejected. However, land use only 14% higher than baseline
3	Low-resource diets and technological changes can meet future global demand sustainably but with higher food prices compared to unsustainable resource expansion
	Rejected. Prices are much lower for SDWL

Hypothesis 2 is rejected as only pastureland use is below 1990 levels. Rainfed land use is still almost double Baseline rainfed land use, although *both* rainfed and irrigated land use are lower than SRE. Only blue water use is higher in SDWL compared to SRE, since the large amounts of rainfed land available in SRE reduce the amount of more expensive irrigated production. This is confirmed by the high use of green water in SRE, which is twice as much as SDWL.

Food prices in SRE increase 42 – 63% above 1990 levels, compared to only 11 – 18% in SDWL. Therefore **Hypothesis 3 is rejected**. Not only is SDWL successful as limiting land expansion onto forests and protected land but it also meets final demand with a much lower increase in food prices.

The literature review in Chapter 2 compares the research questions and scenarios of this dissertation with other studies that ask similar research questions and that consider similar scenarios. This chapter also discusses the methodologies used in these various studies in the context of the theoretical approach of this study, which utilizes the World Trade Model (WTM), an inter-regional input-output model that determines production, trade, commodity prices, physical resource use, and factor income based upon the theory of comparative advantage. Chapter 3 presents the details of the WTM methodology and the unique model extensions utilized for this scenario analysis. Chapter 4 presents the data used to construct the Baseline Scenario for 1990, including the WTM database among other sources. Chapter 5 explains the data and construction of S2050, along with a brief explanation of the results. Chapter 6 explains the data and construction of the remaining scenarios, along with a detailed exposition of the results from SRE and SDWL. Chapter 7 concludes with a discussion of the main findings and the continuing research avenues that extend from this work.

2. Review of studies: scenarios about future global agriculture

This chapter presents a literature review of studies that model scenarios of future agriculture production and estimate subsequent changes in production, trade, resource use, or food prices. These studies come from many different disciplines and use a number of different methodological approaches. The studies most relevant to this dissertation can be grouped into three categories. First are studies from applied physical scientists that address the future availability and sustainability of natural resource use (land, water, soil, climate, etc.) along with the different mechanisms for improving physical food production in light of population and diet changes. Some of these studies were presented in Chapter 1 when discussing the current availability of land and water.

Second are studies that utilize economic partial or general equilibrium models to consider policy scenarios. This group includes studies from well-established international agricultural institutions - such as the Food and Agricultural Organization (FAO), the International Food and Policy Research Institute (IFPRI), or the International Water Management Institute (IWMI) - with research goals rooted in sustainable development and food security, as well as studies with the more strict economic research motivations, such as analyzing trade policies and the role of land and water prices. These studies utilize well known models like GTAP and IMPACT. A handful of studies reflect an interdisciplinary approach that either use output data from or endogenously link with physical models. For instance, MagPIE is a good example, which utilizes a land use model (LPJmL) and a partial equilibrium model (Lotze-Campen and Popp 2009).

Finally is a group of studies based in input-output framework and associated with the recent resurgence in the development of global multi-sectoral input-output databases. In particular is a group of studies that utilize the World Trade Model (WTM), an input-output based alternative to partial and general equilibrium approaches. This group is unique as it analyzes future production and resource use in the context of regional resource endowments and cost structures. The WTM has never been used to address the research questions considered in the first two literature groups.

This chapter focuses on the scenarios analyzed in these various studies. Some are more specialized and focus only one scenario (such as diets or crop-water technologies) while others (more rarely) consider multiple scenarios. Those that present one type of scenario are often more detailed, while studies that present multiple scenarios mirror this study in their ability to paint a more comprehensive picture. This dissertation combines this state-of-the-art detail from the more specialized studies with the breadth and comprehensiveness of studies that combine multiple scenarios.

A summary of the most important studies and their characteristics can be found in Table 2.1 and Table 2.2.

2.1 Applied studies using physical models

A number of studies use methods and models that are based solely upon physical aspects of agricultural production, food consumption, and resource use. Some use global trends to highlight the link between increased consumption and the consequential expansion of resource use or intensification in production methods. Often these studies are focused on the future use of a particular resource, such as land or water. For instance, Smil (2002) calculates that if the global population increased meat consumption to 80 kg per capita per year agricultural land use would increase by two-thirds (Africa, for instance, had an average consumption of about 40 kg per capita in 2000). Gibbs *et al.* (2010) suggests that yield increases suggested by experts are optimistic and that a large expansion of land use for agricultural production may be necessary to meet increased demand for food commodities. Gleick (2003b) compiles over a dozen studies that have estimated future water withdrawals and notes that past attempts have often overestimated future use. Gleick suggests that such attempts lacked "critically important real-world dynamics." More recent studies have based scenarios upon estimates using global land use and hydrology models.

Increasingly land and water use are considered at the same time, reflecting the link between these two resources when distinguishing rainfed land from irrigated land. Three groups of such studies are highlighted here. Alcamo *et al.* (2000; 2007) use the WaterGAP hydrology model to analyze future water stress. They consider multiple scenarios that include changes in population and diets and improvements to rainfed land yields, land use expansion, improvements to irrigation efficiency, and changes in regional production and trade. They find that domestic water withdrawals due to projected income growth put the most stress on future water resources.

Lotze-Campen *et al.* (2008; 2009) use the LPJml land use model - along with economic data from the GTAP database - to determine the degree to which yields will need to increase to fulfill future global demand in 2055 given restrictions on land and water availability. Increases in demand are represented by translating population and income growth (GDP) into changes in physical dietary patterns using high demand elasticities for meat consumption, i.e. the authors assume a certain level of GDP growth, which is correlated with increased meat consumption. The authors also model technological change by increasing crop and livestock yields, finding that crop yield efficiency must increase 0.8% per year to meet increased demand from population growth and diet changes.

Two additional scenarios consider different land and water use changes, one introducing endogenous cropland expansion with land price constraints and the second introducing crop-water improvements by increasing water application which then increases crop yields. When land use is allowed to expand the annual yield efficiency requirements decrease by 60% worldwide. With less optimistic water improvements required yields increase in the Middle East, Africa, and Former Soviet Union, although only marginally.

A group of studies (Falkenmark and Rockström 2006; Rockström, Lannerstad, and Falkenmark 2007; Falkenmark, Rockström, and Karlberg 2009; Rockström *et al.* 2009) analyze the potential of crop-water management strategies to overcome increased water scarcity and land use due to increased population and food demand. They also use the LPJmL model with very detailed analysis of the green water and blue water consumption on rainfed and irrigated land.

Rockström *et al.* (2007) considers the impact of increasing population and consumption of animal products and find that most of the additional water necessary for future global production will come from rainfed production. Furthermore, they consider scenarios of yield growth and the use of fodder from pastureland for feeding livestock, finding that these technologies can reduce the rainfed water use by 40%.

Rockström *et al.* (2009) suggest that over half the world's population will have blue water shortages and over a third will have green water shortages as well. They also suggest that continued cropland expansion is inevitable even with efficiency improvements in land and water use and estimate that an additional 1,000 million ha of cropland will be needed by 2050. In the end, however, they recommend that future analyses should include scenarios further analyzing both land expansion and alternative farming systems.

2.2 Applied studies using equilibrium models

The studies presented here utilize an economic equilibrium models to run their scenario analysis. Two different types of equilibrium models are used: partial equilibrium (PE) and general equilibrium (GE). Many researchers choose partial equilibrium models because they are focused upon a single sector, which means that often the databases associated with these models have very detailed sub-sector divisions. Yet comprehensive multiple-sector models using input-output databases go beyond PE models that ignore cross-sector connections outside the chosen sector modeled in the PE framework.

Studies using partial equilibrium models

Tukker *et al.* (2008) use a partial equilibrium (PE) model CAPRI to address the effect of alternative diets on an index of environmental impacts in the EU. The authors utilize an environmentally extended input-output database with multiple agricultural sectors as input to CAPRI, which models the pressure that high meat and dairy diets puts on environmental impacts, such as land use and soil degradation.

Although this study is not global in scope, its major contribution is the detailed representation of dietary scenarios. A common approach is to use GDP growth, either exogenously or endogenously, to project what diets may look like in the future, with higher growth in GDP corresponding to higher overall food intake and a higher percentage of the diet coming from animal products. Instead, Tukker *et al.* construct scenarios of alternative diets for the EU, as compared to actual diets (which are measured using data from the FAO), to show their potential for reducing the environmental impact of diets. Tukker *et al.* also show that mapping between different physical representations of diet requires care. In order to make recommendations from nutritionists consistent with the FAO data, they use an average conversion factor of 1.8 to convert metabolizable energy into energy availability for final demand. They convert calories into kilograms by assuming a constant ratio between kg and calories for each food type. Different ratios exist for different food types since some foods have more calories per kilogram than others, depending on the fat, protein, carbohydrate, and fiber content.

A comprehensive approach considers the entire world economy. The global PE model IMPACT is a prime example, developed by the International Food Research and Policy Institute (IFRPI) and used in a number of studies (Delgado *et al.* 1999; Rosegrant *et al.* 2001; Rosegrant, Cai, and Cline 2002; Bruinsma 2003; Alexandratos *et al.* 2006). FAO studies by Bruinsma (2003) and Alexandratos *et al.* (2006) do not consider multiple scenarios but only a single baseline projection. The study by Delgado et al. (1999) is focused particularly on livestock. Rosegrant et al. (2001; 2002) consider multiple scenarios and the physical limitations of both land and water, but only to 2020 and 2025.

Bruinsma (2009) is the best example of a study from this group as the author makes future projections of both rainfed and irrigated expansion, yield increases, and water withdrawals necessary to meet future global food demand. The author, along with the institutional goals of the FAO, is motivated primarily by the desire to explore solutions to worldwide poverty and hunger in developing countries, including increases in crop yield efficiency and livestock feed efficiency.

A particular drawback of this study (a drawback that can also be applied to a number of other studies more generally) regards the shifting of simultaneous parameters in the scenario analyses. For instance, the change between the optimistic and pessimistic scenarios results from changing seven parameters simultaneously: malnutrition indicators, GDP growth rates, increased land yields, land area growth, irrigation area growth, population growth, and trade liberalization. Some of these assumptions are considered separately, yet others are not. The ability to handle numerous variables is an advantage of scenario analysis, but it can also be an impediment to understanding the causality behind specific changes.

The final example of global partial equilibrium approach comes from de Fraiture and Wilchens (2007; 2010), which is a particularly strong study due to its representation of rainfed and irrigated water technologies alongside land expansion. The authors are concerned with increasing food demand and the future availability of land and water, and the potential for crop-water management technologies to overcome them. They utilize the WaterSIM model, comprised of a partial equilibrium model and a detailed biophysical water supply and demand model.

They construct four scenarios: irrigation expansion, irrigation yield improvement, optimistic rainfed, and trade. Their scenarios are constructed particularly to evaluate not only the potential for both rainfed and irrigated agricultural improvements, but also the trade-off between land expansion with current technologies and yield improvements due to new technologies. They particularly focus on whether future production will take place on predominately rainfed or irrigated land, citing the mixed results of previous studies: Rosegrant (2002) estimates as much as 50% of additional grain production will take place on rainfed land, Seckler (2000) claims only 5%, and Bruinsma (2003) projects an estimated a 17% decrease. Their trade scenario exogenously forces water-abundant countries to increase production and export to water-scarce countries. The rainfed and irrigated scenarios consider two sub-scenarios with differing assumptions about technological improvements – an optimistic reduction in regional yield gaps of 80% and a pessimistic 20% reduction – and find that on-farm water management can reduce water withdrawals by as much as 46% in sub-Saharan Africa. Future food demand is endogenous based on a combination of population estimates, income projections, and food demand elasticities.

Studies using general equilibrium approaches

Changes in levels of food demand or in production technologies not only affect the agricultural and food sectors but also the manufacturing, energy, or service sectors as well, and PE models cannot capture this essential fact. The most common multi-sector modeling approach is computable general equilibrium (CGE) modeling.

The GTAP model is currently the standard-bearer of global CGE models. Alternative global CGE models exist, such as the Basic Linked System (BLS), which has been integrated with the biophysical agro-ecological zone (AEZ) model to simulate crop potentials according to the production ecology approach (Fischer *et al.* 2002). Yet GTAP dominates because of high sector and regional detail as well as a large community that uses the model and that develops a large number of model extensions. The GTAP database – upon which the GTAP model is based – is also currently the most widely used database for global economic analysis. Until the recent availability of more transparent and widely available alternatives, this database was even used for input-output studies that only use the regional IO tables and not the detailed elasticities necessary for a CGE scenario analysis

Some studies have built GTAP extensions to focus specifically on agricultural analysis. Darwin *et al.* (1995) for instance, integrate a global GIS land use model with the GTAP model to analyze how changing land endowments with different crop productivity characteristics affect future production and trade flows of agricultural goods. Darwin *et al.* is also the first example of a global CGE that includes water use alongside land use. Lee (2005) link spatially explicit land use models with GTAP using land use supply curves that endogenously shift production intensity and land use depending on the size of the land rents using elasticities of substitution between land types and other factors.

Berrittella *et al.* (2005) use a global CGE approach to consider future scenarios about agricultural water use. This study, and the subsequent group of studies, use a model extension called GTAP-W and maintain the same modeling structure and assumptions of the standard CGE model, such as the use of various price elasticities and the Armington assumption to distinguish a good depending on where it is produced. The main departure from the standard GTAP model is the inclusion of four additional factors of production: pastureland, rainfed land, irrigated land, and irrigation water. The study also uses the concept of embodied water in trade as a way to analyze how changes in trade patterns can reduce regional and global water use. Berrittella et al. (2007) develops scenarios restricting global water supply, Calzadilla *et al.* (2008) develop scenarios improving irrigation efficiency while Berrittella *et al.* (2008) analyzing water pricing policies. Calzadilla *et al.* (2010) is the only global CGE study to integrate an analysis of both blue and green water. They use GTAP-W to consider a water crisis scenario and a sustainable water scenario.

Bouwman *et al.* (2006) differs from all other CGE studies as a study from a small literature considering alternative livestock production systems. The authors link the biophysical IMAGE model with the GTAP data and model. To the knowledge of the author, this is the only study that constructs a scenario analyzing the tradeoffs between two ruminant technological systems – as they relate to indirect arable land use, direct pastureland use, and increasing global demand for livestock products – using a global economic model. They project that arable land increases by about 100 million hectares between 1995 and 2030, yet with larger increases in both arable land and mixed/industrial livestock systems coming from developing regions and declines in both grassland and pastureland use in developed countries.

The physical approaches described in Section 2.1 and the equilibrium approaches described in this section use either static trade parameters or trade elasticities calibrated to the base year. In the case of PE and CGE, the theory of trade is based upon the Armington assumption, which determines imports and exports of the same product (say wheat, for instance) by their place of origin, not by their comparative cost structures and factor endowments. This difference alone is grounds for distinguishing the input-output approach used in this dissertation from both the more common CGE approaches.

2.3 Applied studies using input-output models

This final section of the literature review discusses the input-output literature and the role of global input-output databases in shaping a renewed interest global economic issues, particularly in regards to natural resources use and environmental issues. Input-output databases are based upon the national accounting framework and a majority of input-output studies even to this day are at the regional or national level. The first Input-Output models at the global level was built during the 1970s when there was great interest in using such world models to look at the availability and price of fossil fuels, with Leontief (1977) being an early example of a global input-output model intended to address policy questions about the future state of the global economy.

Input-output studies at the national level have traditionally been more common. A number of relevant input-output studies have similar research interests to this dissertation in regards to physical land and water use and scarcity (Duarte, Sánchez-Chóliz, and Bielsa 2002; Hubacek and Giljum 2003; Hubacek, Guan, and Barua 2007; Fukuishi 2010) yet they are not global in scope or consider multiple resources or scenarios simultaneously. Wiedmann (2009) performed a meta-analysis of studies that use both single-region and multiple-region IO models – including an increasing number of studies using global multiple-region IO databases as input to their models – and yet none of these studies consider the future state of agriculture and food production.

A group of studies that use the World Trade Model (WTM) form distinct subset of the broader input-output literature. The WTM is the only inter-regional input-output model that determines production and trade endogenously, making it an ideal tool for constructing scenarios about the future (Duchin 2005).

Juliá and Duchin (2007) are the first to use the WTM to analyze scenarios about the future of global agriculture. The authors are concerned about the security of the future global food and agricultural system after climate change will shift land productivity. The authors develop an extension to the WTM called the WTM with climate sensitive land (WTMCL) by disaggregating land requirements and endowments of land into six types of arable land and six types of pastureland. The WTMCL is the first WTM study to include a choice-of-technology extension in the model that allows each region to produce agriculture on different types of agricultural land within each region. It is also the only study to allow for endogenous choice of different pastureland technologies in an economic scenario analysis. The regional availability of these different land types changes with climate and affects regional comparative advantages, and hence regional trade flows, production, and prices.

Juliá and Duchin hypothesize that global supply will meet global demand even after climate change shifts agricultural production and that regional price changes will not affect food availability. To test their hypotheses, the authors develop three climate change scenarios (based on three climate projections) that assume the doubling of the atmospheric CO_2 concentration. The main driver of the scenarios are the biophysical changes to land characteristics, particularly the length of the growing season, due to the influence of climate change on regional precipitation and temperatures.

The results of the scenarios show that worldwide final demand can be met with new agricultural land use patterns. However, contrary to the conclusion commonly found using CGE and PE models, using the WTMCL the authors anticipate that world prices for agricultural goods will increase due to climate change. Like Juliá and Duchin (2007), this dissertation considers whether future agriculture production can meet demand and at what cost. Instead of focusing on climate change and land, however, this dissertation will focus on population, diets, and farming technologies, especially the link between rainfed, irrigated, and pastureland and the addition and distinction of blue and green water as factors of production.

López-Morales and Duchin (2011) present the only study to date that integrates water use into the WTM to run scenarios about crop-water technologies. They use a model specification that allows for choice-of-technology between irrigated and rainfed agriculture and construct multiple scenarios about investing in water-conserving irrigation technologies, water pricing, and restricting the water supply to the sustainable supply. They allow a choice between gravity irrigation and sprinkler/drip irrigation, assuming that sprinkler/drip irrigation is more labor and capital intensive and hence not chosen unless land or water is scarce in other regions. They find that Mexico can achieve sustainable use of water by adopting more efficient irrigation technology and increasing food prices by 5%. This dissertation will also consider the potential for sustainable use of water and adoption of more efficient technologies in a similar way; however, it will also add the concept of sustainable land use, consider population and diet increases, introduce additional rainfed water management and livestock technological options, and expand the scope to the global level.

The treatment of irrigation by López-Morales and Duchin does not consider a scenario in which improved irrigation water technologies increase both irrigation efficiency and yields, but instead allow that model to choose more water efficient technologies if supply is constrained or water is priced. This approach assumes that these technologies are available to the farmer all along but have a higher annual capital and labor costs (plus water prices) that dissuades farmer from using improved irrigation technologies.

The approach used in this dissertation differs in that is assumes that upfront economic and social barriers prevent adoption of these improved technologies, and yields are improved exogenously for irrigated and rainfed land in these regions (not allowing a choice between flood and sprinkler, per se, but assuming the farmers in these regions adopt sprinkler because of its improved yields and water productivity). This is similar to the exogenous treatment of diet improvements in developing countries, which assumes a situation in which the diets in these regions are improved without suggesting the mechanisms needed to overcome the economic and social barriers currently preventing such changes.

Table 2.1 – Selected multi-regional studies: methodology, data, and scope

Study	Model or Methodology				Data Sources and Scale		
	Type	Model Name	Economic Model	Land or Water Model	Economic Database	Land and Water Data	Non-agricultural economic sectors
This study	IO		WTM		WTM, EXIOPOL	Multiple Sources	Yes
López-Morales (2010)	IO		WTM		Mexico IO Table	Multiple Sources	Yes
Juliá and Duchin (2007)	IO		WTM		WTM	FARM	Yes
Calzadilla et al. (2010)	CGE		GTAP-W		GTAP, IMPACT	GTAP-E, IMPACT-W	Yes
Fischer *et al.* (2007)	CGE	BLS-AEZ	BLS	AEZ	BLS	AEZ, Aquastat	Yes
Bouwman *et al.* (2006)	CGE	IMAGE	GTAP	AEZ	GTAP	Multiple Sources	Yes
de Fraiture and Wilchens (2010)	PE	WaterSIM			IMPACT	WaterGAP, Aquastat	No
Bruinsma *et al.* (2008)	PE	IMPACT	IMPACT	AEZ	IMPACT	FAO	No
Tukker *et al.* (2008)	PE	CAPRI	CAPRI	None	E3IOT	None	No
Rosegrant *et al.* (2001)	PE	IMPACT-W	IMPACT	WSM	IMPACT	WSM	No
Lotze-Campen *et. al* (2008)	Physical	MAgPIE	MAgPIE	LPJmL	GTAP, FAO	LPJmL	No
Rockstrom *et al.* (2007)	Physical	LPJmL	None	LPJmL	None	LPJmL	No
Alcamo *et al.* (2005)	Physical	WaterGAP	None	WaterGAP	None	WaterGAP	No

Table 2.2 – Selected multi-regional studies: Conceptual detail on land, water, and scenarios

	Land and Water Concepts			Scenarios						
Study	Land Distinction	Blue/Green Water	Consumption/ Withdrawals	Pop Growth	Diet shifts	Expansion onto Forestland	Rainfed Technology	Irrigation Improvments	Alternative Livestock Technologies	Climate Change
This study	Rainfed, Irrigated, Pasture	Both	Both	Yes	Yes	Yes	Yes	Yes	Yes	No
López-Morales (2010)	Rainfed and Irrigated	Blue	Withdrawals	No	No	No	No	Yes	No	No
Juliá and Duchin (2007)	Arable and Pasture	Neither	Neither	No	No	No	No	No	No	Yes
Calzadilla et al. (2010)	Rainfed, Irrigated, Pasture	Both	Both	Yes	No	No	No	Yes	No	Yes
Fischer *et al.* (2007)	Rainfed, Irriggated, Pasture	Blue	Withdrawals	Yes	No	No	No	Yes	No	Yes
Bouwman *et al.* (2006)	Rainfed, Irrigated, Pasture	Both	Both	Yes	Yes	No	No	No	Yes	Yes
de Fraiture and Wilchens (2010)	Rainfed and Irrigated	Both	Both	Yes	Yes	No	Yes	Yes	No	No
Bruinsma *et al.* (2008)	Irrigated and Rainfed	Blue	Withdrawals	Yes	Yes	Yes	No	Yes	No	Yes
Tukker *et al.* (2008)	Arable Land	Neither	Neither	Yes	Yes	No	No	No	No	No
Rosegrant *et al.* (2001)	Irrigated and Rainfed	Both	Both	Yes	Yes	No	No	Yes	No	No
Lotze-Campen *et. al* (2008)	Land and Water	Blue	Withdrawals	Yes	Yes	No	No	Yes	No	No
Rockstrom *et al.* (2009)	Rainfed and Irrigated	Both	Consumption	Yes	Yes	No	Yes	Yes	Yes	No
Alcamo *et al.* (2007)	Rainfed, Irrigated, Pasture	Both	Both	Yes	Yes	Yes	Yes	Yes	No	Yes

3. The World Trade Model with Rectangular Choice-of-Technology

The WTM is a linear program that minimizes factor input use for the world as a whole subject to regional constraints (Duchin 2005). As mentioned in the previous chapter, two studies in particular have used this model to analyze scenarios of global land and water use in the agricultural sector (Juliá and Duchin 2007; López-Morales and Duchin 2011). In addition to the advantages discussed in the literature review, using the WTM has two unique advantages for modeling scenarios of global agricultural futures.

First, not only does the WTM represent physical factors such as land and water alongside traditional economic factor such as capital and labor, but it consistently represents these factor inputs in terms of output (whether physical or monetary output). The approach is an alternative to the common approach of maximizing the efficiency of only one specific input. For instance, consider a study promoting the reduction of the yield gap: the input of other factors (labor, capital, water) and output (tonnes) is considered in terms of one specific factor (land), with the logic behind such a formulation often maximizing yields. The same can be said for a study promoting improved water productivity, in which all other factors are considered in terms of water (km^3 $tonne^{-1}$, km^3 ha^{-1}, etc.). Yet a reduction in land intensity or water productivity could just as well produce more output if the use of other factors is more cost efficient. The WTM defines all factors simultaneously in terms of total output. For instance, land productivity (ha $tonne^{-1}$ or ha $\$^{-1}$) is used instead of yields (tonne ha^{-1} or \$ ha^{-1}), along with water productivity (km^3 ton^{-1} or km^3 $\$^{-1}$), labor productivity (persons $tonne^{-1}$ or persons $\$^{-1}$), and so forth. This formulation is consistent with comparative advantage as it considers the entire cost of all factors, not simply maximizing the efficiency of one factor.

The second advantage is the application of the Rectangular Choice-of-Technology model, which will allow this study to consider alternative technologies simultaneously with the producing technologies determined endogenously by the model. This includes the ability to add multiple technologies for different sectors simultaneously and parsimoniously, with possibility that any number of these technologies can be producing in a given solution. The RCOT specification will be utilized to distinguish rainfed and irrigated agriculture as well as pastoral livestock production from mixed/industrial livestock production.

3.1 The World Trade Model

As the WTM model is a linear program, it contains a primal and a dual solution with the same final value for the objective function. The sets, exogenous parameters, control variables (exogenous), and endogenous variables are presented in Table 3.1. The objective function of the primal in the standard WTM is:

$$\min \quad z = \sum_i \pi_i ' F_i x_i \tag{1}$$

with the endogenous output vector x_i for all i regions. The objective assures that production will take place in the regions where factor costs are relatively lowest. The model has three constraints. The first constraint assures that worldwide production is large enough to cover intermediate and final demand:

$$\sum_i (I - A_i) x_i = \sum_i y_i \tag{2}$$

The second constraint assures that regional factor use is less than regional factor endowments.

$$\sum_i F_i x_i \le f_i \tag{3}$$

This constraint shows the importance of using data that explicitly quantifies the annual physical endowment of factors such as land and water, represented in vector f_i. Regional agricultural technologies are represented both by the A_i matrix, which defines the necessary input from other sectors for one unit of agricultural output, and the F_i matrix, which defines the necessary input from all factors for one unit of agricultural output. The final constraint assures that each region benefits from trade, or in other words, that each region on its own is no worse off when it trades with other regions.

$$\overline{p_i}'(I - A_i)x_i \le \overline{p_i}'y_i \tag{4}$$

The vector $\overline{p}$ contains the commodity prices for each region that would exist if it could not trade with other regions. This vector must be obtained for each region using a variant of the WTM called the no-trade model, which determines production by minimizing factor use for each region as if each region were in autarky. If total production is less than intermediate and final demand at no-trade prices, then production can't be more than its own final demand at no-trade prices; with world trade, however, production can be more than final demand (equation 2) but only by first reducing factor usage through shifts in production to other sectors and importing commodities in areas where production was reduced.

The dual solution to the WTM determines world prices, factor scarcity rents, and benefit-of-trade shadow prices. The dual objective function is:

$$\max \quad Z = p'\sum_i y_i - \sum_i r_i' f_i - \sum_i \alpha_i (\overline{p_i}' y_i) \tag{5}$$

As the primal minimizes factor input use, the dual maximizes the value of final demand net of scarcity rents. In other words, the dual model determines the prices at which final demand gets the most benefit with the least amount of factor use and trade costs. The single constraint on the dual objective assures that prices do not exceed factor use costs, or simply that sector prices reflect the costs of the individual factors that are used to produce them.

$$(I - A_i')p - F_i'r_i - (I - A_i')\overline{p_i}\alpha_i \le F_i'\pi_i \tag{6}$$

This constraint also shows the various components that make up the world price for each commodity. The production costs include the exogenous factor costs F'π and are the endogenous intermediate costs A'p. Regions fully utilize a factor input while producing a product gain additional factor rents F'π since they produce at a lower cost than the highest cost producer. Exporting regions also potentially gain a benefit-of-trade rent α if the world price of a commodity exceeds their no-trade price. This rent ensures that regions only trade when they can produce a commodity at a lower price than the world price, and quantifies the benefit they receive from trading at below the world commodity price. For all producing regions, the sum of these four components is strictly equal the world commodity price. For non-producing, the sum of production costs (A'p + F'π) is strictly greater than the world commodity price.

3.2 Rectangular Choice-of-Technology (RCOT) model

Input-output models have traditionally used square A matrices to represent a region's inter-industry flows, including all WTM empirical studies to date. However, Duchin and Levine (2011) develop a new version of the WTM in which there are more columns than rows. This allows for a good, represented by a row, to be produced using more than one technology, represented by any number of columns. A technology in input-output models is the ratio of different inputs required to produce a given level of output. In the WTM these inputs are the various sectors (A matrix) and factors (F matrix) required to produce a unit of output, represented by a column. The square matrix is a specific case in which each good is produced using one average technology. However, any number of columns can be included, allowing the objective function of the model to choose between the different technologies within a region, just as the model can choose between different technologies between regions. The resulting rectangular A matrix gives this WTM extension its name: the Rectangular Choice-of-Technology model (RCOT).

Other WTM studies have implemented a choice-of-technology option. Duchin and Lange (1995) lay the groundwork for this specification, followed by Juliá and Duchin (2007) and López-Morales and Duchin (2011). Yet these studies retain the square A-matrix and represent additional technologies by adding entire additional A-matrices with changes to the specific sectors in which there is a technological change. RCOT allows for the same choice-of-technology representation with fewer parameters by not repeating sectors in multiple A matrices. Second, RCOT allows regions to have different subsets of technologies. When adding (or subtracting) a technology to one region, it is not necessary to do so for other regions as well.

This is the first study to use the RCOT model for a global scenarios analysis with the WTM database. The model is the same except the dimension of some parameters is changes from n sectors to t technologies. In this formulation, the number of technologies is the same for all regions. The primal of the LP is:

$$\min \quad z = \sum_i \pi_i' F_i^* x_i^* \tag{1*}$$

s.t.

$$\sum_i \left(I^* - A_i^*\right) x_i^* = \sum_i y_i \tag{2*}$$

$$\sum_i F_i^* x_i^* \leq f_i \tag{3*}$$

$$\bar{p}_i'(I^* - A_i^*) x_i^* \leq \bar{p}_i' y_i \tag{4*}$$

$$x_i \geq 0$$

where A^* has the dimension (n x t), F^* has the dimension (k x t), and x^* has the dimension (t x 1).

3.3 Model extensions for this study

A few modifications have been added to the basic model to allow this study to better address the research questions in the scenario analysis. First, to utilize RCOT it was necessary to modify the no-trade model to be a linear program. The no-trade model is an essential component of the WTM since it determines no-trade prices in equation (4). For the standard model:

$$\vec{x}_i = \left(I - A_i\right)^{-1} y_i \qquad (7)$$

$$f_i = F_i \vec{x}_i \qquad (8)$$

$$\overline{p}_i = (I - A_i)^{-1} F_i' \pi_i \qquad (9)$$

$$x_i \geq 0$$

for all i regions. The RCOT model utilizes rectangular matrices that cannot be inverted, making this approach non-workable for RCOT. This study therefore employs a linear program for the no-trade model, similar to the LP for the WTM. Just like the standard no-trade model, this LP does not contain factor constraints. For the RCOT no-trade model:

$$\min \quad \overline{z} = \sum_i \pi_i' F_i^* \overline{x}_i^* \qquad (10)$$

s.t.

$$\left(I^* - A_i^*\right)\overline{x}_i^* = y_i \qquad (11)$$

where no-trade prices are determined in the dual:

$$\max \quad \overline{z} = \sum_i y_i' \, \overline{p} \qquad (12)$$

s.t.

$$\left(I^* - A_i^{*\prime}\right)\overline{p} = F_i^{*\prime} \pi_i \qquad (13)$$

Another new feature of this implementation of the WTM RCOT model distinguishes multiple factor prices (π) from the same factor endowment (f)**.** This was done in order to distinguish agricultural labor from the rest of the labor force so different wage rates could be applied.

Let j denote the size of π and k denote the size of f, where j > k. A single F is not longer sufficient since π is multiplied by F in equation (1*) and k is multiplied by F in equation (3*). Therefore, let F_j^* have the dimension (j x t) and F_k^* have the dimension (k x t). F_k^* is identical to the F^* while F_j^* now has additional rows to match the extra labor prices. Since F_j^* has two labor rows to match the two labor prices in π, the row in which the coefficients are placed designates the labor price for each technology. For instance, with one price for agricultural labor and one for other labor, coefficients for agricultural sectors in F_j^* are placed in the row corresponding to the price of agricultural labor.

The final WTM RCOT formulation used in this study is:

$$\min \quad Z = \sum_i \pi_i ' F_{j,i}{}^* x_i^* \tag{1'}$$

s.t.

$$\sum_i \left(I^* - A_i^*\right) x_i^* = \sum_i y_i \tag{2'}$$

$$\sum_i F_{k,i}{}^* x_i^* \leq f_i \tag{3'}$$

$$\overline{p}_i '(I^* - A_i^*) x_i^* \leq \overline{p}_i ' y_i \tag{4'}$$

$$x_i \geq 0$$

This extension is also useful for distinguishing factor use between two technologies that share the same endowment. In this study, it was used to calculate rainfed arable land use for crops and rainfed arable land use for livestock *ex post* the WTM solution. If q is the factor for rainfed land, and k = q, multiplying $F_{k,i}$ times x_i for all i provides a vector (k x 1) of total regional rainfed land use. Now suppose q is separated into two rows in $F_{j,i}$., one to designate rainfed land for livestock production and one to designate rainfed land for crop production. Row r only has entries for livestock technologies and row s only has entries for crop technologies. Now multiplying $F_{j,i}$ times x_i provides a vector (j x 1) with the amount of land used for livestock separated from the amount of land used for crops.

Table 3.1 – Parameters and variables for the RCOT Model

Variables and Parameters	Dimension	Description
Sets		
i		Set of regions
n		Set of sectors
t		Set of technologies
k		Set of factor endowments
j		Set of factor prices
Exogenous (for every region i)		
A^*	n x t	Matrix of intermediate input requirements
y	n x 1	Vector of final demand
F_j^*	j x t	Matrix of factor requirements
F_k^*	k x t	Matrix of factor requirements
π	j x 1	Vector of factor prices
f	k x 1	Vector of factor endowments
pbar	n x 1	Vector of prices with no trade
xbar	t x 1	Vector of output with no trade
I^*	n x t	"Identity" matrix
Endogenous		
x_i	t x 1	Vector of regional output for each region i
p	n x 1	Vector of world prices with trade
r_i	k x 1	Vector of regional scarcity rents for each region i
$\propto$	i x 1	Vector of 'benefit-of-trade' shadow price
z		Scalar of global factor costs

4. Data for the WTM Baseline Scenario

A clear distinction must be made between the WTM itself – which was presented in the previous chapter - with the data used to construct a Baseline Scenario. Once the Baseline Scenario is constructed, it can be run using the WTM, providing a basis against which the remaining scenarios can be compared. This dissertation utilizes two global input-output databases: the WTM database and the EXIOPOL database. Both databases are used separately to construct two distinct Baseline Scenarios. Each database has unique strengths and weaknesses, with varying levels of scope and detail in terms of regions, sectors, and factors. As a way to gather additional insight based upon these unique strengths, the intention of this study was to compare and contrast the results from the scenario analysis based upon these two distinct databases. Such a comparison would be used as a form of quality control to assure the sensibility and consistency of the results and conclusions.

The WTM database is used as a basis for constructing the primary Baseline Scenario (from this point referred to as "WTM Baseline" or simply "Baseline"). The WTM database is used primary database for a number of reasons. First, the WTM database has fewer regions and sectors compared to most other global IO databases, allowing for a tighter and more manageable dataset for constructing scenarios and analyzing the results. Second, the WTM database has been used in multiple WTM studies, particularly Juliá and Duchin (2007) and Strømman *et al.* (2009). Third, the process used to construct the scenarios with the WTM database was helpful constructing the scenarios with the much more detailed EXIOPOL database.

The final and main reason the WTM Baseline Scenario becomes the focus of this dissertation is that multiple problems arose with the new EXIOPOL database. Some of these problems were discovered while constructing of the scenarios using the EXIOPOL database, and still more once the EXIOPOL Baseline was run using the WTM. Interestingly, the most useful role EXIOPOL database may be as a control total in areas where its data is particularly strong, such as labor. This section will present the EXIOPOL Baseline Scenario in an effort to show the challenges associated with such a large and detailed database.

Additional data was required beyond that provided by the WTM database and the EXIOPOL database. This study expands these databases in three ways: it distinguishes rainfed and irrigated land, it adds two types of water as factor inputs, and it disaggregates technologies for both the cereal and livestock sectors. Integrating data from different sources requires assuring internal consistency. For the WTM, the challenge arises in maintaining value added equal to the sum of factor prices, or $V = F'\pi$. For instance, adding an additional input of land requires estimating both unit prices (ha $\$^{-1}$) for F (which much be consistent with physical factor availability of ha in f) and *ex ante* land in π, which together are a portion of the value added usually attributed to only labor and capital in input-output databases. This study compares data from multiple sources to improve the accuracy of the parameters and variables, and in the end estimates variables from such data where no direct comparison was available.

The WTM Baseline includes 10 regions, 10 sectors (3 agricultural, no separate food processing), 12 technologies, and 12 factors. The data in the EXIOPOL Baseline includes 21 regions, 78 sectors (10 agricultural and 10 food processing), 81 technologies, and 25 factors. The additional technologies come from the representation of irrigated and rainfed crops. The data for each Baseline Scenario covers the entire global economy and resource endowment. Table 4.1 outlines the data sources used for different parts of the Baseline Scenario and Appendix A shows classifications for the WTM and EXIOPOL databases.

4.1 Data taken from the WTM database

The main input-output data comes from the WTM database, which has been used in multiple published studies to date. Duchin (2005) constructed a 10 region, 8 sector, and 3 factor (capital, labor, and land) database to demonstrate the empirical significance of the WTM. Starting from this database, Strømman and Duchin (2006) added four transportation sectors, three fossil fuels as factors, and weight and distance matrices to model bilateral trade between regions. Juliá and Duchin (2007) disaggregated the agricultural sector into three agricultural sectors and disaggregated land into 12 different types, 6 types of arable and land and 6 types of pastureland. This study uses the WTM database from Juliá and Duchin (2007) for the regional A matrices, y vectors, and factor data for capital, labor, and pastureland. This dataset was chosen as the primary dataset as it distinguishes three agricultural sectors: cereals, livestock, and other crops. Data on fossil fuels for F and f is taken from Strømman and Duchin (2006) since the additional factor constraints help create a more realistic division of global production.

4.2 Construction of irrigated and rainfed technologies

The scenarios described in Section 1.5 require including land and water as factors of production. Both Strømman and Duchin (2006) and Juliá and Duchin (2007) include land as a factor of production, but do not distinguish between rainfed and irrigated land. Only López-Morales and Duchin (2011) include water as a factor of production using the WTM, but only for Mexico and for blue water.

This study adds irrigated and rainfed land along with both blue water and green water as factors of production to the WTM database using a dataset provided by Siebert and Döll (2010). This dataset is generated by the Global Crop Water Management (GCWM) model, a biophysical hydrology model, and these global and regional totals compare well with estimates by other land and water experts (see Section 1.3). This dataset is the only water database to provide comprehensive global detail by region, crop, and technology (rainfed and irrigated), allowing straightforward aggregations of GCWM classification to the WTM classification while allowing for the disaggregation of the cereals and other crops sectors into two distinct crop technologies.

Rainfed and Irrigated Land

The GCWM data distinguishes both land area harvested and tonnes of crops produced on irrigated vs. rainfed land. Two technological options are distinguished in the factor requirements matrix (F), first distinguishing irrigated from rainfed agriculture technologies (resulting in two columns) and second by distinguishing two types of arable land (two rows). Land in the GCWM is measured in harvested land (i.e., the percentage of the land used that is actually harvested). Harvested land is converted to used land by means of harvest coefficients by region and land type taken from Bruinsma (2009) for rich and for developing countries; the latter are used for China, Rest of Asia, Latin

America, and Africa, and the former for all other regions. This step provided the necessary data on quantities of irrigated and rainfed land requirements in all regions. Rainfed and irrigated land endowments for the Baseline are assumed to be the amount available in 2000, not assuming full utilization of land due to land left fallow and crop losses (and since 1990 land use is lower than 2000). Finally, the data was converted from tonnes ha^{-1} to tonnes $\$^{-1}$ using data on regional production in 1990 from FAO (2010).

Irrigated land endowments for the Baseline are the total land equipped for irrigation in 1990. This data is taken from the Aquastat database (FAO 2011b), as shown in Table 1.4. Juliá and Duchin (2007) provide factor prices for arable land and pastureland, and it is assumed that the price of irrigated land is the same as rainfed land.

Green and blue water

Three alternative sources are used to calculate water requirements per unit of sectoral output. First, the GCWM dataset provides data on blue and green water consumption for agriculture and on tonnes of crop harvested on irrigated and rainfed land. The Aquastat database (FAO 2011b) provides estimates of total regional water withdrawals in three categories: agricultural, industrial, and municipal uses. Additional data from de Fraiture *et al.* (2007) is used to quantifying water withdrawals for the electric power sector as a percentage of the manufacturing sector. Other industrial withdrawals were distributed among the remaining sectors. Municipal withdrawals from the public water supply are delivered to industry and commerce as well as households and public sector us as follows: 40% to municipalities and other services, 20% to household consumption, and the remainder to industries (Solley, Merk, and Pierce 1988; López-Morales 2010).

A fourth source was required to translate the physical representation of the land and water requirements per unit of output into a monetary unit using world food production FAO (2010) for the Baseline year. These monetary representations of the land and water requirements per unit of output are used as the Baseline input-output coefficients.

Availability of blue water is the amount withdrawn in 1990 using data from the Aquastat database. No fee is imposed on the withdrawal of blue water. Green water use, which is free to the owner of the rainfed land, is not constrained by the amount of water but by the amount of rainfed land.

4.3 Other data additions and adjustments

The data from Juliá and Duchin (2007) is for 1990 but in 1970 prices and was adjusted for this study to reflect 1990 prices. Other changes were made after comparing the WTM database to control totals from other sources, particularly data from the FAO on physical and monetary measure of production and demand for certain crops and food groups and the EXIOPOL database. For instance, final demand for cereals was adjusted using data from the FAO (2010) and for the mining sector from the EXIOPOL dataset.

The pastureland coefficients were calculated using data on both the physical production of livestock and the value of production, obtained from the FAO (2010). Pastureland was distinguished from arable land in Juliá and Duchin (2007), yet they distinguish coefficients six different types of pastureland, and hence average pastureland coefficients for a single category of pastureland needed to be calculated. Ideally, while these six categories of land with their coefficients could have been adapted to fit the RCOT model, instead, the range provided by these coefficients were used as a control for each region. These values were use for the f-coefficients for seven of the ten regions. Three regions – Other Europe, Africa, and Oceania – were roughly adjusted further to better match the range provided by Juliá and Duchin (2007).

Although fossil fuel data was available from Strømman (2006) for F and f, it did not include prices. Extraction costs per tonnes of coal equivalent (TCE) were estimated from IEA (2010) data on the price of fossil fuels. For regions with low stocks of fossil fuel, extraction costs were simply the price of fossil fuels. For regions with large, high quality reserves of fossil fuels, however, extraction costs were lowered to represent the comparative advantage these regions have in the extraction of fossil fuels. This is the first attempt to price fossil fuels in the WTM database.

As explained in Section 3.3, labor payments were disaggregated into two categories: agricultural wages and other wages. EXIOPOL data was used to estimate the wage rate of agriculture, as this database provided labor payments disaggregated by sector. In addition to increasing capital endowments to reflect 1990 availability, capital is disaggregated into two types of capital: agricultural capital and other capital. This change imposes the non-substitutability of fixed agricultural capital with other types of capital.

Table 4.1 – Components and sources of the WTM Baseline

Parameter		Unit	Calculation
A		$\$ \$^{-1}$	Intermediate Production (1) / Total Production (1)
y		$10^9\$$	Domestic Final Demand (1)
F	-- Agricultural Capital	$10^9\$ \ 10^{-9}\$$	Capital Value Added (1) / Total Production (1)
	-- Other Capital	$10^9\$ \ 10^{-9}\$$	Captial Value Added (1) / Total Production (1)
	-- Labor	workers $10^{-3}\$$	Workers (1) / Total Production (1)
	-- Rainfed Land	ha $10^{-3}\$$	Rainfed Land Use (4,5) / Rainfed Production (4,6)
	-- Irrigated Land	ha $10^{-3}\$$	Irrigated Land Use (4,5) / Irrigated Production (4,6)
	-- Pasture Land	ha $10^{-3}\$$	Pasture Land Use (1) / Livestock Production (6)
	-- Rainwater	$m^3 \ \$^{-1}$	Rainwater Consumption (4) / Total Production (4,6)
	-- Blue water	$m^3 \ \$^{-1}$	Water Withdrawal (4,7,8) / Total Production (4,6)
	-- Fossil fuels	tce $10^{-3}\$$	Tonnes of Coal Equivalent (2) / Total Production (2)
f	-- Agricultural Capital	$10^9\$$	Agricultural capital stock (1,9)
	-- Other Capital	$10^9\$$	Other capital stock (1,9)
	-- Labor	10^6worker	Economically available population (1)
	-- Rainfed Land	10^6ha	Rainfed land used (4,5)
	-- Irrigated Land	10^6ha	Irrigated land used (4,5)
	-- Pastureland	10^6ha	Pastureland used (1)
	-- Blue Water	10^9m^3	Water Withdrawals (7)
	-- Green Water	10^9m^3	Rainwater - Runoff (7)
	-- Fossil Fuels	10^6tce	Tonnes of Coal Equivalent (2) / Total Production (2)
pi	-- Capital	$10^9\$ \ 10^{-9}\$$	Rate of return (1)
	-- Agricultural Labor	$10^3\$$ worker^{-1}	Wage (1)
	- Other Labor	$10^3\$$ worker^{-1}	Wage (1)
	-- Rainfed Land	$10^3\$$ ha^{-1}	Annual Land Rents (1)
	-- Irrigated Land	$10^3\$$ ha^{-1}	Annual Land Rents (1)
	-- Fossil Fuels	$10^3\$$ tce^{-1}	Fossil Fuel Price (10)

Source: (1) Juliá and Duchin 2007 (2) Strømman 2006 (3) Own calculations, see text 1 (4) Siebert and Döll 2010 (5) Bruinsma 2008 (6) FAO 2010 (7) FAO 2011b (8) de Fraiture et al. 2007 (9) EXIOPOL 2011 (10) IEA 2010.

Notes: Money is in 1990 dollars. Data from sources (1) and (2) was adjusted by the author to inflate $1970 prices to $1990 prices.

4.4 Results from the Baseline Scenario

The WTM Baseline Scenario was run using the RCOT model described in Section 3.2. The endogenous output from the model includes regional production by technology, net exports by sector, world commodity prices, and rents on factors of production for producers that fully utilize endowments. Production can also be used to calculate factor use and costs for different regions.

Table 4.2 shows global factor use in the Baseline compared to control totals from various sources. No factor is fully utilized and output is within 80% of total endowments for land and water resources. Table 4.3 shows the percentage of global agricultural production produced by region in the Baseline compared against these same percentages in the Baseline Scenario from Juliá and Duchin (2007) and in control totals from FAO (2010). Although agricultural production is lower than both Juliá and Duchin and the FAO for North America and Europe, production matches FAO control totals better for other regions such as China and Australia.

Table 4.2 – WTM Baseline factor use compared against control totals

	Units	Baseline	Control	Year	Source
Rainfed land use	10^6ha	1,074	1,271	2000	Bruinsma (2008)
Irrigated land use	10^6ha	269	273	2000	Siebert and Doll (2010)
Pastureland use	10^6ha	3,206	3,405	1990	FAO(2010)
Blue water withdrawals	10^9m^3	3,275	3,574	1990	Shiklomanov (2003)
Green water consumption	10^9m^3	4,960	5,505	2000	Siebert and Doll (2010)
Labor	10^6worker	1,795	2,359	1990	ILO (2010)
Capital	10^9\$	7,202	10,060	1990	Stromman and Duchin (2006)
Raw coal	10^6tce	3,063	4,857	1990	EIA (2010)
Crude oil	10^6tce	3,939	4,321	1990	EIA (2010)
Natural gas	10^6tce	2,107	2,738	1990	EIA (2010)

Source: Own computations for WTM Baseline. Sources for control totals listed under column labeled “Source.”

Additional results from the Baseline will be presented alongside the results from the scenario analysis in Chapter 6.

Table 4.3 – Percentage of total agricultural production produced regionally in the WTM Baseline compared against two control totals

	Baseline	Juliá and Duchin (2007)	FAO (2010)
North America	8	15	14
Western Europe	9	11	11
Other Europe	2	8	8
Former Soviet Union	6	12	11
Japan	0	1	1
China	16	3	17
Rest of Asia	26	19	19
Latin America	14	21	10
Africa	16	0	8
Australia & NZ	2	11	2
World	100	100	100

Source: Data from Juliá and Duchin (2007) calculated from Baseline Scenario. Control total calculated using data from FAO (2010).

Note: Estimate from Juliá and Duchin (2007) and this study may contain double counting since livestock and crops were summed**.**

4.5 The EXIOPOL database and baseline scenario

In recent years there has been a resurgence of interest in global questions involving tracking the paths of global material flows, the quantities of resources and pollution embedded in final products, and the structure of global production and trade. Due to the lack of global databases with transparent and explicit data description to facilitate the interpretation of results, a variety of alternative global input-output databases now exist or are currently in development (see Table 4.4).

The EXIOPOL database is one of the first of these global databases to be completed, and the scenario analysis in this study was one of the first applications of this database. As an environmentally-extended input-output database, EXIOPOL originally planned to provide all the necessary components to construct a Baseline scenario: the regional input-output tables; satellite accounts that included physical labor and capital inputs, endowments, wages, and capital gains; environmental extensions that include land, water, fossil fuels, and dozens of various ores and metals.

Table 4.4 – List of Global Input-Output Databases

Database	Source	Aggregation	Global Coverage	Example Studies
WTM Database	Duchin (2005)	10 regions, 10 sectors	Yes	Julia and Duchin (2007), Stromman and Duchin (2009)
GTAP	Narayanan and Walmsley (2008)	87 countries, 57 sectors	Yes	Darwin *et al.* (1995), Lee *et al.* (2009), Calzadilla *et al.* (2010)
OECD Bilateral Trade Database	OECD (2010)	52 regions, 57 sectors	No	Giljum et. al. 2009
Asian International IO Table	Kuroiwa (2011)	10 countries, 24 sectors	No	Shimoda et al. 2008
EORA	Kanimoto *et al*. (2011)	Flexible	Yes	None yet
EXIOPOL	EXIOPOL (2011)	41 regions, 129 sectors	Yes	Duchin, Springer, and Levine (2011)

The construction of such large and detailed databases is a relatively new undertaking, with dozens of institutional partners compiling different parts of the database over a four year time span. It is therefore not surprising that the project ran into a number of hurdles. Table 4.5 shows the method of calculation of the variables and parameters for the EXIOPOL baseline along with the sources used to calculate each entry. Although a good portion of the data came from the EXIOPOL database (sources 1, 2, and 3), a large amount of the data needed to be found from other sources. In addition, the data that did come from the EXIOPOL project had numerous problems in the end, including erroneous or missing entries from columns, water data that was incomplete and did not match with control totals, input-output tables in which columns did not match rows, and a very troublesome rest-of-world region that contained unrealistic production and final demand in both the agriculture and electricity sectors. The full extent of the database problems are outlined in Duchin *et al.* (2011) and will therefore not be discussed at length here.

Table 4.5 – Methods and sources for the calculation of exogenous variables and parameters for the EXIOPOL Baseline

Parameter		Unit	Calculation
A		€/€	Intermediate Production (9) / Total Production (9)
y		10^6 €	Domestic Final Demand (9)
F	-- Agricultural Capital	10^6 €/10^6 €	Agricultural capital stock (4) / Total Production (9)
	-- Other Capital	10^6 €/10^6 €	Other capital stock (4) / Total Production (9)
	-- Labor	workers / 10^3 €	Workers (4) / Total Production (9)
	-- Rainfed Land	ha/€	Rainfed Land Use (3,6,10) / Rainfed Production (9,6)
	-- Irrigated Land	ha/€	Irrigated Land Use (3,6,10) / Irrigated Production (9,6)
	-- Rainwater	10^3 m^3/ €	Rainwater consumption (6) / Total Production (9,6)
	-- Blue water	10^3 m^3/ €	Water Withdrawal (5,6,9) /Total Production (9,6)
	-- Fossil fuels	tce/€	Tonnes of Coal Equivalent (9,11) / Total Production (9)
f	-- Agricultural Capital	10^6 €	Agricultural capital stock (4)
	-- Other Capital	10^6 €	Other capital stock (4)
	-- Labor	10^6 worker	Economically available population (8)
	-- Rainfed Land	10^6 ha	Rainfed land used (9,6,10)
	-- Irrigated Land	10^6 ha	Irrigated land used (9,6,10)
	-- Blue water	10^9 m^3	Sustainable supply (4,5)
	-- Rainwater	10^9 m^3	Rainwater available (5)
	-- Fossil fuels	10^6 tonnes	Tonnes of coal equivalent extracted (4)
	-- Ores and minerals	10^6 tonnes	Tonnes extracted (4)
pi	-- Capital	10^6 €/10^6 €	Rate of return (4)
	-- Agricultural Labor	10^3 €/worker	Payments to agricultural labor (9) / agricultural workers (9)
	-- Mining Labor	10^3 €/worker	Payments to mining labor (9) / mining workers (9)
	-- Manufacturing Labor	10^3 €/worker	Payments to manufacturing labor (9) / manufacturing workers (9)
	-- Services Labor	10^3 €/worker	Payments to services labor (9) / services workers (9)
	-- Rainfed Land	€/ha	Payments to rainfed land (9,6) / rainfed land use (9,6,10)
	-- Irrigated Land	€/ha	Payments to irrigated land (9,6) / rainfed land use (9,6,10)

Source: (1) EXIOPOL Input-Output Tables (2) EXIOPOL satellite accounts (3) EXIOPOL environmental extensions (4) Own estimates, see text (5) FAO 2011b (6) Siebert and Döll 2010 (7) USGS 2010 (8) ILO 2009 (9) de Fraiture *et al.* 2007 (10) Bruinsma 2008 (11) IEA 2010.

The construction of EXIOPOL Baseline followed the same logic as the construction of the WTM Baseline. Yet once it was completed and run with the WTM, it became obvious that the results from this database did not follow the logic of the model. For example, analyzing the results of the Baseline aroused suspicions about the cattle sector. Table 4.6 shows what was found when the shares of intermediate demand for cattle in all regions were calculated: in most regions the vast majority of intermediate cattle output is delivered to the meat-processing sector, but in the rest-of-world region – which is the major producer of livestock under this scenario -- it is only 7%! More intermediate cattle output goes to pork and poultry production than beef. Unfortunately, this is only one example of the anomalies that were noted, and therefore detailed results of the EXIOPOL baseline and scenarios are not presented.

The EXIOPOL Baseline proved to have problems that precluded a full comparison of results with the other EXIOPOL scenarios or the WTM scenarios. Nonetheless, running the scenarios using an expanded database was informative. Indeed, the transparency of the WTM made it possible to identify the data problems. Some of the baseline EXIOPOL data was also useful for checking and disaggregating some of the data in the WTM database, particularly labor and final demand estimates.

Table 4.6 – Distribution of Cattle Output in EXIOPOL Input-Output Tables

	Cereals	Veg, fruit, nuts	Other Crops	Cattle	Pigs	Poultry	Meat animals nec	Animal products nec	Raw milk	Products of meat cattle	Products of meat pigs	Products of meat poultry	Other meat products	Dairy products	Other food products	Fish products	Other Sectors	Total
Australia	0	0	0	<0.1	0	0	0	0	<0.1	66.3	0.4	3.0	9.3	0	10.7	5.6	3.9	100
Brazil	<0.1	<0.1	0.3	6.0	<0.1	<0.1	<0.1	1.1	1.8	76.9	0.2	0.3	<0.1	0.2	8.9	0.2	3.4	100
Canada	20.2	<0.1	3.3	22.9	9.4	<0.1	0.2	2.7	<0.1	38.0	0.5	0.1	0.1	0.2	0.5	<0.1	1.3	100
China	2.9	<0.1	<0.1	27.6	2.6	<0.1	0.3	<0.1	<0.1	47.2	5.9	<0.1	<0.1	0	6.9	0	6.4	100
Germany	0	0	0	<0.1	<0.1	0	<0.1	<0.1	<0.1	89.2	0	0	0	2.4	4.3	0	4.0	100
Spain	0	0	0	<0.1	0.3	0	<0.1	0.1	<0.1	90.5	0	0	0	3.5	2.8	0	2.6	100
EU1	<0.1	<0.1	<0.1	2.7	0.5	<0.1	<0.1	0.2	0.2	84.8	<0.1	<0.1	<0.1	2.8	5.4	<0.1	3.1	100
EU2	<0.1	<0.1	<0.1	<0.1	0.5	<0.1	<0.1	<0.1	<0.1	93.5	<0.1	<0.1	<0.1	0.8	3.2	<0.1	1.8	100
France	0	0	0	0.2	0.4	0	<0.1	<0.1	<0.1	90.5	0	0	0	3.9	2.5	0	2.4	100
UK	<0.1	<0.1	<0.1	<0.1	0.3	<0.1	0.1	<0.1	0.1	86.7	<0.1	<0.1	<0.1	4.3	4.8	0.2	3.3	100
Indonesia	4.0	6.0	7.3	<0.1	0.2	0	<0.1	0.1	<0.1	32.4	<0.1	10.1	0.2	6.8	<0.1	27.7	2.6	100
India	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Italy	0	0	0	<0.1	0.3	0	<0.1	<0.1	<0.1	87.0	0	0	0	1.1	2.1	0	9.5	100
Japan	3.7	4.2	0.9	6.2	3.2	0	<0.1	2.7	3.0	63.1	2.6	2.9	1.2	0	0	0	6.5	100
Korea	0.6	0.5	0.1	1.0	0.7	0	<0.1	0.3	0.3	83.8	1.8	0.5	0.6	6.1	0.3	0	3.2	100
Mexico	3.3	3.9	3.5	8.8	5.4	0.3	0.8	3.8	6.4	58.3	1.0	0.8	0.5	<0.1	0.3	<0.1	1.7	100
Russia	18.8	16.4	6.4	9.9	8.8	0	0.7	3.4	11.5	16.4	1.9	4.2	1.3	0	0	0	0.2	100
Turkey	15.5	9.9	14.1	4.0	0	0.1	5.2	3.5	5.0	23.9	0	0.5	14.4	0.4	0.3	0.2	3.1	100
USA	0.7	1.0	0.9	31.2	0.5	0.1	0.1	0.1	1.2	61.7	<0.1	<0.1	<0.1	0.1	0.4	<0.1	1.6	100
Rest of World	<0.1	0.5	<0.1	0.2	0.8	<0.1	<0.1	<0.1	<0.1	7.0	40.8	13.2	33.0	<0.1	1.9	0.2	1.3	100
South Africa	3.3	1.8	2.8	1.1	0.2	<0.1	0.7	0.4	0.7	70.2	0	10.2	0	0	7.6	0	0.6	100

Sources: Own computations using intermediate production data from EXIOPOL IO tables.

Notes: Highlighted cells are greater than 5% of total intermediate cattle production in the region. "Other sectors" is a sum of the remaining sectors not individually identified. Regions are ordered alphabetically by their two letter EXIOPOL code.

5. Scenario 2050: Increasing pressure on global resources

This goal of this chapter is to describe the construction of a scenario that depicts increases in economic and environmental pressures due to changes in population, diets, and resource availability. The combination of these changes is anticipated to place more pressure on resources over the next several decades. The feasibility of this scenario will help test Hypothesis 1, which suggests these changes will prevent future demand for food from being met.

One of the challenges common to the construction of all scenarios is assuring consistency between physical units and money units. Typically production and consumption data are in money values. A simple approach is to ignore the physical relationships and estimate changes in the economic data directly; however, the scenario approach taken by this study first estimates changes in physical terms and second translates those changes into monetary terms.

Changes in food consumption are represented by changes in domestic final demand in vector **y**. Improving crop water management is represented by changes in the land and water requirements per unit of output in the regional F matrices. Allowing an endogenous choice between technologies is done by adding disaggregating an average technology for a sector – represented by a single column in both A and F - into multiple columns for A and F, each representing a different technological option. Finally, changes in the availability of factor inputs are represented by increasing or decreasing endowments in f.

5.1 Increasing regional consumption due to population and diets

Population

Domestic final demand in each region is increased by the percent of population change anticipated for 2050 using data from a medium-growth scenario from the UN (2010). Table 5.1 shows total population in 1990 and 2050 with the percentage increase by region. Most of this increase is experienced in developing countries, particularly Rest of Asia and Africa.

Table 5.1 – S2050: Percentage changes in final demand per region

	1990	2050	% Δ
North America	292,973	489,558	67.1
Western Europe	335,880	413,804	23.2
Eastern Europe	203,859	205,082	0.6
Former Soviet Union	287,386	285,374	-0.7
Japan	124,123	123,502	-0.5
China	1,224,429	1,481,559	21.0
Rest of Asia	1,795,427	3,653,694	103.5
Latin America	453,550	804,598	77.4
Africa	611,305	2,123,674	247.4
Oceania	21,023	40,343	91.9
World	5,349,955	9,621,188	79.8

Source: Medium-growth scenario from UN (2010).

Note: Columns for 1990 and 2050 are 10^3 persons.

Diets

Diets are improved in two steps to the level of food availability necessary to eliminate undernourishment in each developing region (Seckler and Amarasinghe 2003; Rockström *et al.* 2005; Rockström *et al.* 2009). First, following the common approach from the literature (Alexandratos 2006, de Fraiture *et al*. 2007, Tukker *et al.* 2008, Falkenmark *et al.* 2009), caloric consumption for primary food products –cereals, animal products, and other food crops – are taken from the FAO (2010). This database provides country level data on "food availability for final demand consumption," defined as the average supply of food available in either calories or kilograms for different food types. The baseline physical diets for each region are constructed by taking food availability per capita and food type for each country and aggregating these to match the regional and sector classification of the WTM database. Overall consumption of food products is then increased until the total caloric availability equals 3000 kcal/capita/day. Second, the composition of the diet is shifted to assure that 20% of the calories come from animal products.

To translate these physical caloric changes into monetary changes, it is assumed that a percentage change in calories or kg is equivalent to the same percentage change in monetary units, implicitly assuming that the price per calorie of a particular food category in the new and old diets is the same. This is not problematic since this study keeps the structure of diets within a category the same between scenarios. In other words, as long as a region maintains the same percentage consumption of meat and dairy, a percentage change in the sum of these two food types is the same as a percentage change in each of them individually. For each region, the percentage change in caloric intake is applied to the three agricultural sectors in the WTM database, although the classification of grains, livestock, and other crops in the WTM database may be slightly different from that used by the FAO.

Table 5.2 – S2050: Percentage increase in domestic final demand for food products

Region	Crops	Livestock	Manufacturing
china	8	79	17
roa	26	100	31
la	8	27	12
africa	18	99	27

Source: Own calculations using data from FAO (2010), see text for methodology.

Processed food products account for a significant portion of diets, particularly in rich regions. Since percentage of processed food in manufacturing is not explicit, it is deduced from estimates of total domestic demand for food products, which varies between regions by 61 – 85 % (ERS 2009). The percentage of processed food in final demand from EXIOPOL was used as a control total since this database explicitly distinguishes between the primary and secondary sectors. The percentage of diets that come from processed foods varies between 57% - 87%, except for China (38%) and

India (28%) (EXIOPOL 2011). This dissertation may therefore be overestimating diet increases from these regions and more detailed attention to the difference between primary and secondary products may be useful in future studies. In fact, distinguishing between primary and secondary agricultural products was one of the main goals of constructing the scenarios with the EXIOPOL dataset. Future demand for processed food is estimated using the percent change in total caloric intake since processed food is not distinguished between crops and animal products.

5.2 Increasing regional factor endowments

The third change from the Baseline to S2050 is estimated factor endowments, including endowments of future rainfed and irrigated land. The endowments assumed for 2050 are presented in Table 5.3. Irrigated land endowments for S2050 are taken from the Aquastat database (FAO 2011b). This global dataset includes country-level estimates of land potentially available for irrigation, although unfortunately not for all regions; and several countries are shown to have less potential irrigated land in 2050 than in 2000, decreasing in some cases to zero. For such regions the endowment of potentially irrigated land was conservatively kept at 1990 levels.

Table 5.3 – S2050: Irrigated land endowments (10^6 ha)

	1990 avaialble	2050 equipped	% Δ
North America	22	28	27
Western Europe	11	13	20
Other Europe	11	12	6
Former Soviet Union	21	53	152
Japan	3	3	-2
China	49	67	37
Rest of Asia	98	185	88
Latin America	17	62	267
Africa	11	38	252
Australia and NZ	2	4	70
World	244	463	90

Source: Aquastat (FAO 2011b).

The region with the largest increase in endowments is by far Rest of Asia. Since the percentage of irrigated land used is about 80-90% of land equipped (Bruinsma 2009), the estimates of irrigated land equipped from Aquastat are conservative since they allow more arable land to be used for irrigated agriculture than other experts predict.

Rainfed land endowments for S2050 are defined as potentially available arable land minus forestland, protected land, and potentially equipped irrigated land. As discussed in Chapter 1, this definition allows expansion of agriculture onto additional arable land without unsustainably using forestland, particularly in Africa and Latin America. Potential arable land are taken from FAO (2000) are presented in Table 5.4.

Table 5.4 – S2050: Rainfed land endowments (10^6 ha)

	Baseline	S2050	% Δ
North America	202	292	44
Western Europe	81	110	36
Other Europe	91	107	18
Former Soviet Union	183	183	0
Japan	3	7	139
China	101	150	48
Rest of Asia	265	285	8
Latin America	135	421	213
Africa	184	766	317
Australia and NZ	30	48	59
World	1,274	2,370	86

Source: Own estimates using data from FAO (2000).

Blue water endowments are increased to 40% of the renewable supply. According to the Water Efficiency Index described in Chapter 1, this is the level at which blue water becomes critically scarce. Table 5.5 shows these increases for each region.

Table 5.5 – S2050: Blue water endowments (km^3)

	Baseline	S2050	% Δ
North America	520	1,554	199
Western Europe	190	194	2
Other Europe	107	360	237
Former Soviet Union	261	1,294	395
Japan	88	110	24
China	656	707	8
Rest of Asia	1,332	3,107	133
Latin America	265	4,001	1408
Africa	213	1,593	647
Australia and NZ	26	236	806
World	3,660	13,157	259

Source: Own calculations from FAO (2011b).

Other endowment increases

Labor endowments for each region are increased by the projected percentage change in the economically active population (Table 5.6), defined as those of ages 20 – 60 and using data from the UN Population Division (2010). These were then adjusted slightly to reflect emigration from developing regions with large labor increases (where labor constraints would most likely be non-binding) to rich regions with anticipated labor shortages. Following this logic, 100 million workers from Rest of Asia and Africa emigrated to North America, Western Europe, Other Europe, Japan and Latin America. A more detailed treatment of potential immigration in the WTM framework between regions would be a fruitful avenue for future research.

Each region's capital availability was increased by at least the same percentage as its labor availability to maintain capital to labor ratios. Maintaining a non-declining capital/labor ratio assures that a moderate amount of additional built capital will be available for production.

Table 5.6 – S2050: Changes in capital and labor endowments from 1990 (10^3 persons)

	1990	2050	% Δ
North America	145	223	54
Western Europe	198	206	4
Other Europe	50	61	21
Former Soviet Union	147	132	-10
Japan	65	62	-5
China	822	864	5
Rest of Asia	459	1,042	127
Latin America	152	289	90
Africa	196	805	311
Australia and NZ	11	18	59
World	2,245	3,702	65

Source: UN (2010).

Fossil fuel endowments are increased using projections from the EIA (2010) for fossil fuel use in 2035. Conversion factors from the IEA (2010) are used to convert oil and natural gas into tonnes of coal equivalent (TCE). Projections of fossil fuel extraction in for 2050 are not available. To account for this difference – and to reflect the potential for expansion beyond predicted use - this study follows Strømman *et al.* (2009) and increases regional endowments an additional 50% beyond 2035 EIA estimates.

5.3 Introducing livestock expansion onto arable land

S2050 introduces an additional technological option that allows cattle production to use arable land as well as pastureland for grazing. Experts agree that the use of extensive pastureland has reached its peak: arable land is currently used to graze cattle in some regions (Steinfeld, 2006) and Gibbs *et al.* (2010) show that livestock production has expanded onto arable land in recent decades, particularly in Brazil. Since S2050 endowments include potential arable land, allowing livestock production to use this land endowment represents this potential expansion.

For each region, an additional column is added to both the A and F matrices to represent a new livestock technology that can utilize potential arable land. This new technology is identical to the original livestock sector except for one change: the coefficient in the pastureland row of the F matrix is moved to the arable land row. This forces the new technology to use rainfed land instead of pastureland, while the original livestock sector continues to use pastureland. Any combination of these two technologies can be used to produce livestock, determined by the comparative advantage of different technologies in different regions.

Table 5.7 summarizes the changes made to the different variables and parameters to construct S2050. As a whole, S2050 embodies changes in consumption, endowments, and technologies simultaneously.

5.4 Results: Scenario S2050 is infeasible

S2050 was run with the RCOT model and the solution was infeasible. Had this scenario been feasible, it could have been used as new baseline against which to compare the solution scenarios. Yet as hypothesized in Hypothesis 1, future global demand for food cannot be met without either the unsustainable expansion of land and water or a change in crop-water and livestock technologies. The feasibility of the remaining scenarios will determine whether or not the first hypothesis is rejected. This result is not only due to the increase in population and diets but the lack of the necessary factors to produce this increased agricultural requirement, even though availability of land and water has increased substantially from Baseline 1990.

Table 5.7 – Description of Scenario 2050

Consumption (y)	Population	All regions: scaled proportional to population change (1)
	Diets	Developing regions: increased caloric per capita availability to 3000 calories with 20% from animal products (2)
Technologies (A, F)	Cattle grazed on pastureland	Same livestock sector as Baseline
	Cattle grazed on arable land	Same sector as Baseline except cattle uses arable land instead of pastureland (4)
Endowments (f)	Labor	Scaled proportional to change in working-age population (1,7)
	Built capital	Scaled to at least maintain K/L availability ratio (7)
	Irrigated land	Estimate of potential irrigared land from (3)
	Rainfed land	Potential arable land minus forestland, protected land, and irrigated land (4,5)
	Fossil fuels	Estimate of future endowments (6,7)

Sources: (1) UN 2010 (2) FAOSTAT 2010 (3) FAO 2011b (4) FAO 2000 (5) Fischer *et al.* 2002 (6) EIA (7) Own calculations, see text for explanation.

Notes: All changes relative to Baseline. Money value of change in food consumption is assumed proportional to change in caloric content.

6. Solution scenarios: Reducing the pressure from S2050

This study considers four alternative ways to overcome the infeasibility of S2050: further expansion of land and water use, less resource-intensive diets in rich countries, water-saving irrigation technologies, and pastureland-saving livestock technologies in Africa and Latin America. As discussed in the literature review, to the knowledge of the author this is also the first study to consider all these scenarios comprehensively.

6.1 SRE: Resource expansion of land and water endowments

One solution to the increasing demand for land due to population and diet pressures would be to use additional regional endowments of land and water. In S2050, both arable land and water use were restricted due to the potential environmental impact of expanding crop and livestock production onto forestland and expanding blue water use beyond above the 40% critical water threshold. The solution is tested in SRE by increases arable land endowments in each region to include potentially arable forestland and blue water endowments to their renewable supply (Table 6.1).

Table 6.1 – SRE: Endowments of arable land (10^6 ha) and blue water (km^3)

	Arable Land			Blue Water	
	S2050	SRE	% Δ	S2050	SRE
North America	292	414	42	1,554	3,886
Western Europe	110	117	7	194	485
Other Europe	107	132	23	360	901
Former Soviet Union	183	259	42	1,294	3,235
Japan	7	10	39	110	275
China	150	159	6	707	1,767
Rest of Asia	285	308	8	3,107	7,768
Latin America	421	683	62	4,001	10,004
Africa	766	892	16	1,593	3,983
Australia and NZ	48	91	92	236	590
World	2,370	3,066	29	13,157	32,894

Source: Own calculations from FAO (2000; 2011b).

This inclusion increases global availability of rainfed land another 29% above S2050 endowments, with the largest additional increases coming from Australia, Latin America, and North America. Still, Latin America and Africa remain the regions with the largest amounts of potential arable land. Latin America and Rest of Asia remain the regions with the highest endowments of blue water.

6.1.1 SD: Low-resource diets in rich regions

Decreasing overall food availability and switching from animal products to plant products reduces both the direct and indirect use of factor inputs, lowering production, resource use, and food prices. All rich regions (except Japan) in this study have food availability above 3000 kcal/cap/day and consumption of animal products above 20%. This benchmark – the same benchmark that was used to improve developing country diets – is used here to construct "low-resource diets" for rich regions of North America, Europe, the Former Soviet Union, and Australia.

The same method that was applied to developing countries in S2050 is applied to these rich regions here. Overall caloric intake is reduced to 3000 kcal/capita/day and then availability of animal products is reduced until it comprises 20% of caloric availability. The same assumptions also hold for determining changes in availability of processed food. Table 5.2 shows the percent decrease in final demand in rich regions for cereals, livestock, other crops, and manufacturing (processed food).

Table 6.2 – SD: Percentage decrease in domestic final demand for food products

Region	Crops	Livestock	Manufacturing
nah	-4	-38	-13
oecd	2	-44	-12
eem	-5	-26	-10
fsu	9	-27	-1
japan	4	-2	3
anz	17	-44	-4

Source: Own calculations using data from FAO (2010), see text for methodology.

6.1.2 SW: Improved crop-water management in Africa and Latin America

Technologies that increase the efficiency of water application and utilization by crops can to some extent offset the increases in prices and resource use due to global increases in food consumption. SW considers improved water management for both rainfed and irrigated agriculture in Africa and Latin America. The changes considered in this scenario examine these prospects for cereals in Africa and Latin America, the first involving efficiency improvements in irrigation systems and the second involving improved management green water management for rainfed agriculture.

The assumptions for these water management improvements are presented first for irrigated agriculture and then irrigated agriculture. Changes to the land and water coefficients for this scenario are presented in Table 6.3.

Improved irrigation efficiency and yields in Africa and Latin America

Improvements to irrigated agriculture are represented by increasing the irrigation efficiency in these two regions. First, withdrawal estimates from Aquastat (FAO 2010b) and consumption estimates from Siebert and Döll (2010) are used to calculate current irrigation efficiencies of 0.33 for Latin America and 0.54 for Africa. This study then follows de Fraiture *et al.* (2007) and Calzadilla *et al.* (2008) who estimate that irrigation efficiency in these regions can be raised to 0.7 using a combination of sprinkler and drip irrigation systems. To reflect these assumptions the blue water coefficients are lowered in both Latin America and Africa (m^3 $tonne^{-1}$). This study ignores losses between withdrawal and application while assuming that a percentage change in yield in tonnes is equivalent to the same percentage change in money units.

Simultaneously, these improved irrigation technologies also create a vapor shift in the consumption of blue water. To reflect these yield improvements, the irrigated land coefficients (ha $tonne^{-1}$) are reduced for Latin America and Africa. Yield improvement estimates are taken from de Fraiture *et al.* (2007).

Improving crop water transpiration and rainfed yields in Latin America and Africa

This study follows Falkenmark and Rockström (2006), who estimate that a vapor shift in green water consumption from evaporated water to transpired water could achieve a doubling of cereal yields. Although green water consumption remains constant, these increases in yields improve water productivity from current levels around 2000 – 3000 m^3 $tonne^{-1}$ (such as Africa and Latin America) to 1500 m^3 $tonne^{-1}$. These improvements lower both green water coefficients and rainfed land coefficients.

Table 6.3 – SW: Land coefficients (10^3 ha $\$^{-1}$) and water coefficients (m^3 $\$^{-1}$) for cereals

	Latin America			Africa		
	S2050	SW	% Δ	S2050	SW	% Δ
Rainfed Land	4.54	3.07	-33	8.70	2.49	-71
Irrigated Land	2.05	1.14	-44	1.34	0.72	-47
Green Water	18.42	10.26	-44	30.25	11.05	-63
Blue Water	22.66	10.57	-53	17.26	13.27	-23

Source: Own computations, see text for methodology.

6.1.3 SL: Additional livestock production technologies

Increasing global demand for meat in S2050 requires increased production in the livestock sector, which is dependent on large amounts of pastureland. Different livestock production systems use different amounts of pastureland, allowing for a potential tradeoff between pastureland and other factor inputs.

With the largest tracts of potential arable land located in Latin America and Africa, and the most abundant pastureland in Africa, this scenario provides industrial systems in both these regions as a technological option for raising cattle. Two alternative livestock systems are distinguished: pastoral systems and mixed/industrial systems. S2050 introduced an additional livestock technology that uses arable land instead of pastureland, providing two livestock technologies per region. In SL, these two technologies further disaggregated in Latin America and Africa to include both pastoral and mixed industrial technologies, resulting in four technologies in these regions.

Whether livestock is being produced on pastureland or arable land, it now has the additional option to be produced in two ways in these regions.

To calculate differences in land use (ha) and production (tonnes) for the two industrial farming systems, this study uses data from Bouwman *et al.* (2006) on pastureland yield for the two livestock systems in developing countries. The data from Bouwman is only for ruminants and is supplemented by FAO (2010) data on ruminant versus non-ruminant production. Using the percentage of total pastureland use and total production for both pastoral systems and mixed/industrial systems for developing countries, the coefficients in A and F were disaggregated (Table 6.4).

Table 6.4 – Pastureland coefficients (10^3 ha $\$^{-1}$) and intermediate crop inputs ($\$ \$^{-1}$) for livestock technologies

			S2050	SL	
Region	Parameter		Livestock	Pastoral	Industrial
Africa	A	**grains**	0.016	0	0.022
		rest of ag	0.021	0	0.029
	F	**land**	16.140	25.000	1.493
Latin America	A	**grains**	0.054	0	0.086
		rest of ag	0.013	0	0.020
	F	**land**	11.710	12.881	1.181

Source: Calculated using data from Bouwman *et al.* 2006.

The goal behind the approach of the solution scenarios is to show the overlap of scenarios that are usually only considered individually within different literatures. Although doing so sacrifices the detail of certain aspects of the scenarios, a concerted effort has been made to utilize the specialized knowledge from experts in different areas. Constructing these multiple specialized scenarios simultaneously gives depth beyond a more piecemeal approach; yet by also considering each scenario individually in a stepwise approach, the intention is to provide results that are transparent and straightforward to interpret. Table 6.5 summarizes the variables and parameters that are changed for these solution scenarios.

Table 6.5 – Additional changes from S2050: Description of solution scenarios

Endowments (f)	**SRE**	Land and Water Expansion	Increase rainfed land endowments to include forests (4) and increase blue water endowments to the renewable supply (3)
Consumption (y)	**SD**	Low-Resource Diets	Developed regions: reduced caloric per capita availability to 3000 calories with 20% from animal products (2)
Water Technologies (F)	**SW**	Rainfed Agricultural Improvements	Improved green water productivity for rainfed cereals (8)
		Irrigated Agriculture Improvements	Improved irrigation efficiency (cubic km consumed/withdrawn) for irrigated cereals (8)
			Improved rainfed and irrigated cereal yields (t/ha) (9)
Livestock Technologies (A,F)	**SL**	Mixed/Industrial Livestock Technology	Reduced land requirements and uses all grain and processed feed inputs from livestock sector (10)
		Pastoral Livestock Technology	Increased land requirements and no grain or processed feed inputs from livestock sector (10)

Source: (2) FAO 2010 (3) FAO 2011b (4) FAO 2000 (8) Falkenmark *et al.* 2009 (9) de Fraiture *et al.* 2007 (10) Bouwman *et al.* 2006.

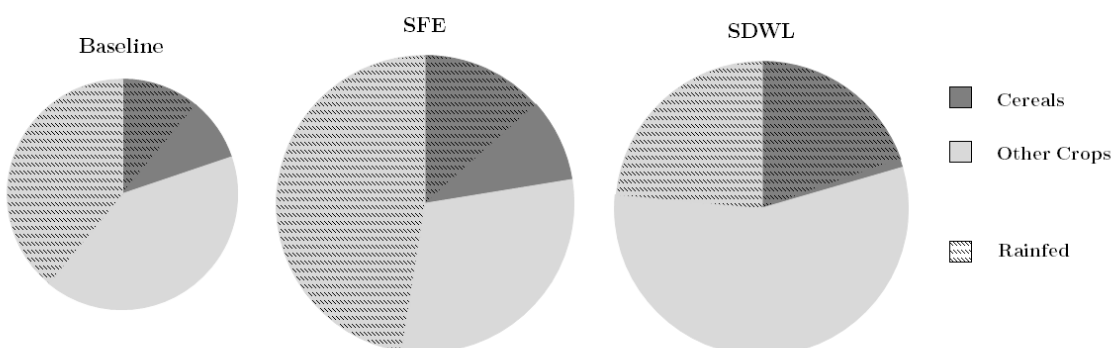
6.2 Results: SRE and SDWL

This chapter compares the results of SRE and SDWL relative to the Baseline and to each other, highlighting the pros and cons of each scenario. Section 6.2.1 presents the results of Hypothesis Test 1 and discusses the global structure of production and exports that allow each scenario to meet global demand. Section 6.2.2 presents the results of Hypothesis Test 2 and discusses the degree to which land use and water withdrawals are overexploited in both scenarios. Section presents the results from Hypothesis Test 3 and discusses the degree of reduction in food prices due to the scenario assumptions.

6.2.1 Future global food demand can be met with both land expansion or diet and technology changes

Both expanding forestland in SRE and adopting low-resource diets and technological changes in SDWL produce feasible solutions. Hypothesis 1 is therefore not rejected. Figure 6.1 shows that both SRE and SDWL meet final demand with about the same level of production, but using different mixes of technologies in each case.

Figure 6.1 – Global production of cereals and other crops (10^9 \$)



Source: Own computations.

Note: The shading represents the crop type and the hashes represent rainfed production of that crop type. Areas without hashes are irrigated production. Pie chart areas in columns (2) and (3) reflect changes in volumes relative to the baseline in column 1.

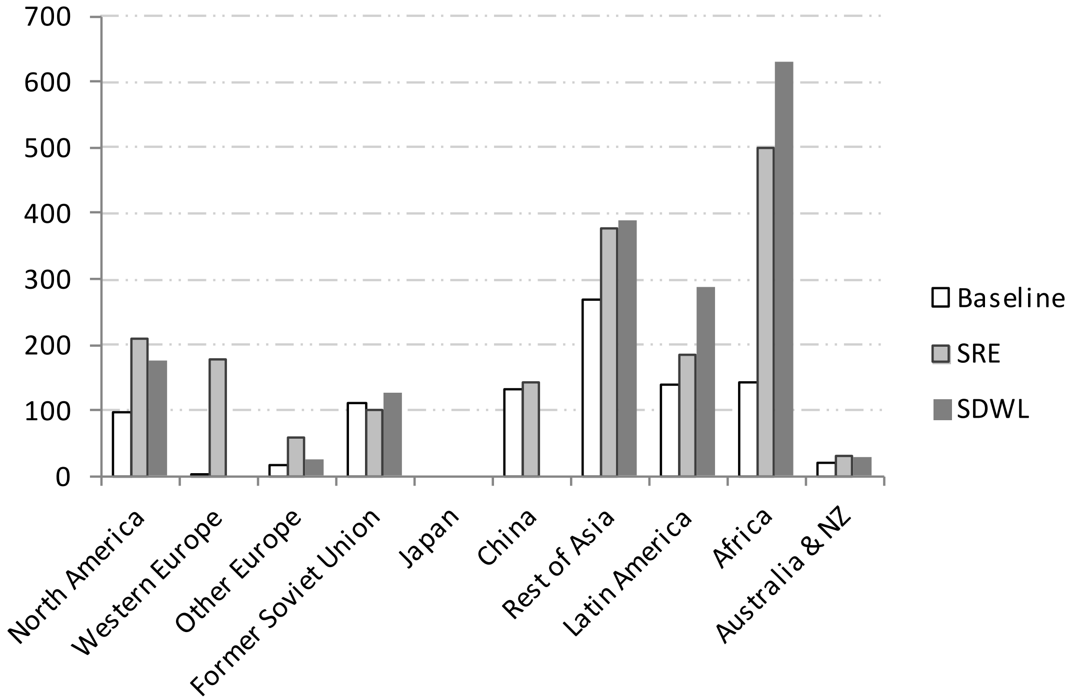
In SRE, both irrigated and rainfed technologies are used to produce the different crop types about evenly. Yet in SDWL, almost all cereal production comes from rainfed land while a larger percentage of irrigated production is reserved for other crops. With restrictions on the expansion of cheap rainfed land, farmers utilize more expensive but efficient irrigated land, using this more productive land to produce high-value crops instead of cheaper cereals. Increased rainfed cereal production in SDWL comes primarily from North America, Latin America, and Africa while increased irrigated production of other crops comes from Rest of Asia, Latin America, and Africa. With the availability of additional cheap rainfed land in SRE, production of both rainfed cereals and other crops increases as a percentage of total global production, with the largest increase in rainfed production coming from cereals in Latin America and Rest of Asia and other crops in Africa.

Figure 6.2 highlights the regions that benefit the most from increased agricultural production in each scenario. Africa clearly increases production the most in both scenarios, particularly in SDWL where it benefits from crop-water and livestock technological improvements. In fact, half of Africa's production is SDWL comes from industrial livestock production on pastoral land. Africa is also the low cost producer of irrigated other crops, and gains some of the highest land rents of any region.

Latin America surprisingly fairs better in SDWL then SRE. With one of the largest endowments of potential arable land, it seems odd that they would produce more when land use is restricted. However, in SRE, Latin America uses a portion of its irrigated land to produce cereals, which is much less productive. In SDWL, they use the majority of all of their irrigated land to produce other crops and produce more output.

Overall, more regions produce in SRE than in SDWL. This follows from the logic behind the scenarios, for expansion of agriculture onto additional land allows new producers to begin producing to meet the increased final demand. But this does not affect the productivity of the former producers, which continue producing the same amount. When these producers begin producing more efficiently, however, this reduces the amount of production needed to be produced by others. Hence, the most expensive producers drop out of production, which in the case of SDWL is Europe, and prices drop.

Figure 6.2 – Regional agricultural production (10^9 \$)

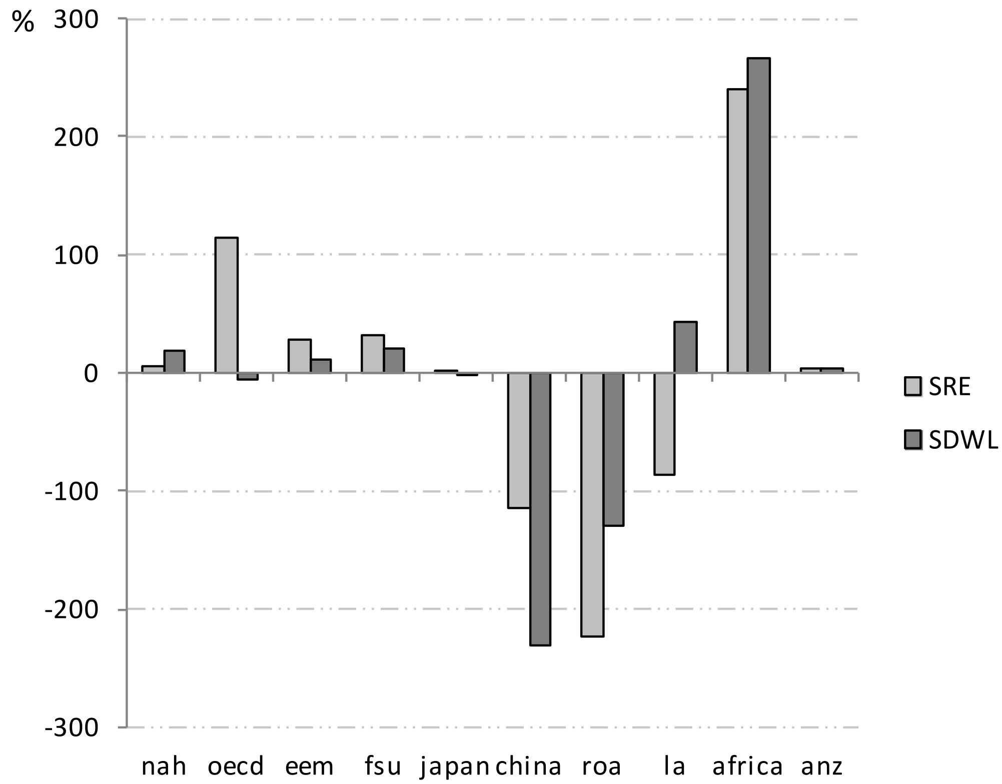


Source: Own computations.

Note: Total agriculture production data presented here may contain some double counting.

These changes in production are mirrored by changes exports and imports (Figure 6.3). As the largest producer, Africa increases exports the most in both scenarios. Europe also increases exports dramatically in the SRE scenario, but becomes increases net imports once again when production of domestic agriculture drops due to lower cost regions of Africa and Latin America becoming more efficient producers. Although Latin America has higher production in SRE compared to the Baseline, it still decreases exports due to their large population and diet increases to 2050. Both China and Rest of Asia become less food secure in both scenarios, increasing net imports by more than 100% in both scenarios. However, in SDWL, Rest of Asia increases exports at the expense of China, which becomes the largest food importing region.

Figure 6.3 – Changes in regional agricultural exports from the Baseline



Source: Own computations.

6.2.2 Land and water use: focus on pastureland expansion onto forests and trade-off between irrigated and rainfed agriculture

SDWL is successful at mediating increases in resource use – particularly pastureland use – compared to SRE, yet it does not reduce resource use to Baseline levels. Hypothesis 2 is therefore rejected. Table 6.6 shows the percentage change in land and water use for the three solution scenarios, and only land for livestock is lower than Baseline levels in SDWL (total land use is 14% above baseline levels).

Production in SRE relies to a much greater degree on rainfed land and therefore green water consumption increases much more than blue water. On the contrary, SDWL depends on to a greater degree on irrigated agriculture and blue water use increases from SRE to SDWL. Yet at the same time, irrigated land use falls. This result stems from a switch in irrigated land use from cereals to other crops. This switch results in the production of high-value crops that provide much higher output (in $) per unit of irrigated land. Irrigated production of other crops increases in regions with lower water coefficients (Rest of Asia and Latin America), which are 4 to 7 times lower than the irrigated cereal coefficients in other regions that reduce irrigated production of cereals. Therefore, even though irrigated production increases in SDWL, along with increasing blue water use, irrigated land use decreases.

Table 6.6 – Global land (10^6 ha) and water use (km^3) by scenario and type

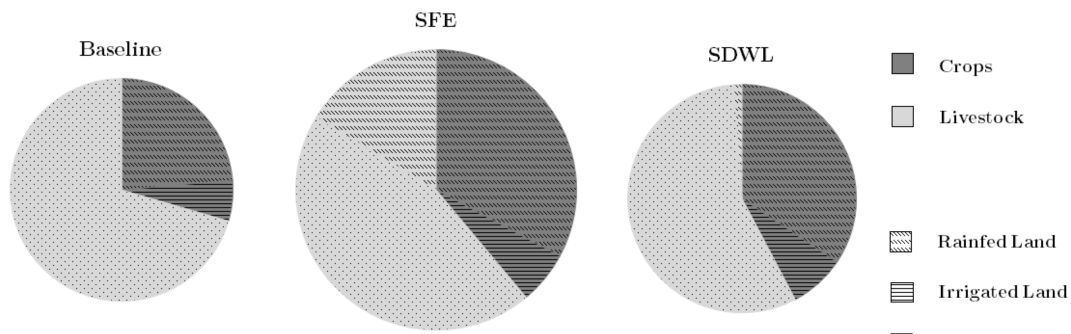
	Baseline	SFE		SDWL	
			% Δ		% Δ
Agricultural land	4,550	6,877	51	5,166	14
- Arable land for crops	1,343	2,753	105	2,059	53
-- Rainfed land	1,074	2,306	115	1,679	56
-- Irrigated land	269	447	66	380	41
- Land for livestock	3,206	4,124	29	3,107	-3
-- Arable land for pasture	0	721	-	424	-
-- Pastureland	3,206	3,402	6	2,684	-16
Blue water withdrawn	3,275	5,741	75	5,847	79
Green water consumed	4,960	10,393	110	8,383	69

Source: Own computations.

The large decline in land use for pasture in SDWL is due to the large amount of industrial agriculture taking place in Africa; yet this still does not prevent the expansion of livestock production onto arable land, which still expands 400 million hectares in North America and Latin America.

Figure 6.4 shows the change in the amount and percentage different land types used to produce crops and livestock. Rainfed arable land is used for livestock production when land use of forestland and protected land is not restricted. The expansion of livestock production onto potential arable land – along with the increases of irrigated and rainfed crop production – push land use into forested and protected areas in some regions.

Figure 6.4 – Global land use for crop and livestock production (10^6 ha)



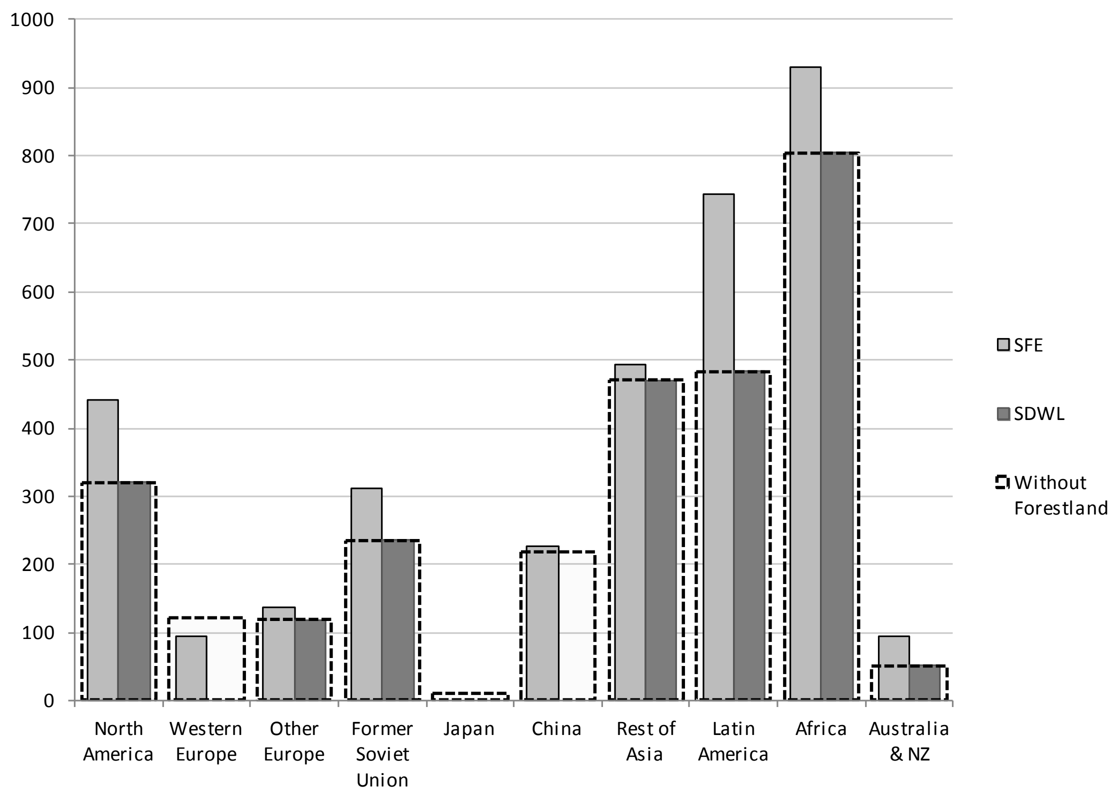
Source: Own computations.

Note: The shaded pies represent the type of production and the hashes represent the land category on which that type of production takes place. Pie chart areas in columns (2) and (3) reflect changes in volumes relative to the baseline in column 1.

Figure 6.5 shows total land use for each scenario compared to the level of land endowments in S2050. In other words, it shows how much land use expands onto forested land in SRE and which regions reach that constraint the Baseline and SDWL. Only Western Europe and Japan do not expand agricultural production onto forestland in SRE since they are the two highest cost regions. North America, Latin America, and Africa all expand the most into these additional land endowments. Almost all regions are bound by the forestland constraint in SDWL, again except for those regions that are high cost agricultural producers.

Figure 6.6 shows the WEI by region for in each scenario. No region reaches critical scarcity, but blue water resources are scarce in Baseline for China and slightly increase for SRE. Rest of Asia reaches water stress in both SRE and SDWL due to its high production of irrigated other crops, rising into the moderate stress region and approaching high stress in both SDWL. Africa also approaches moderate water stress in all both scenarios, and the Former Soviet Union does as well in SDWL.

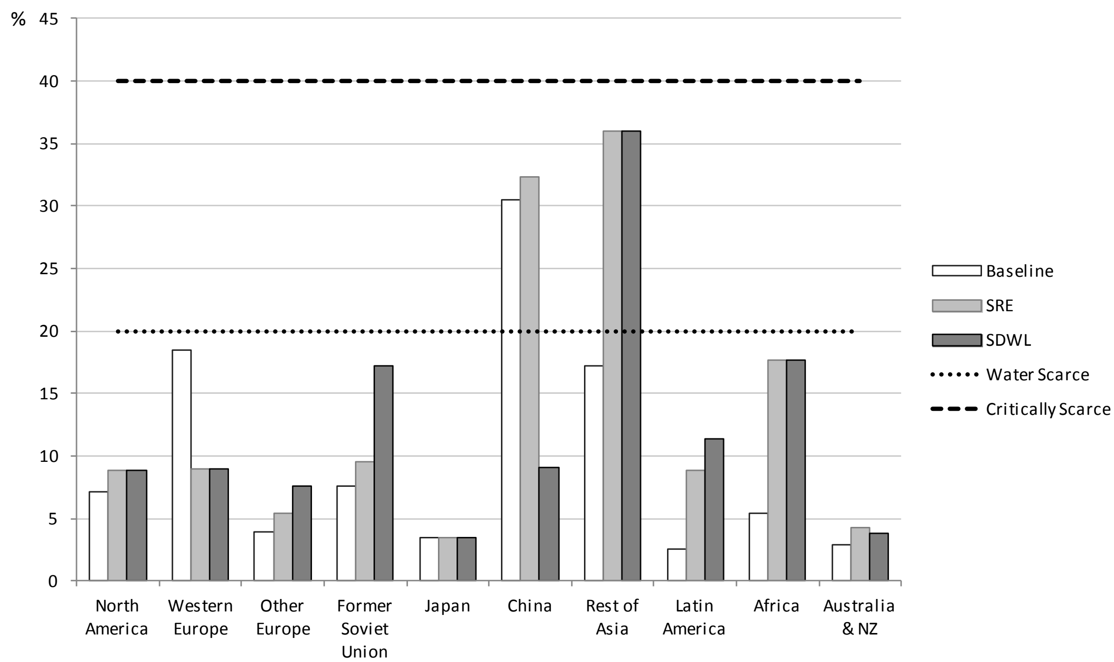
Figure 6.5 – Regional arable land use (10^6 ha) by scenario compared to the arable land endowment in S2050



Source: Own computations.

SRE increases water stress in China, but it subsequently decreases dramatically in SDWL, the scenario where its agricultural production declines precipitously. By becoming a large net importer of agricultural products, China is able to reduce its water stress. This highlights a tradeoff between food security and resource use, for China can improve its water scarcity situation by relying on other nations with larger renewable water endowments and less blue water scarcity.

Figure 6.6 – Water Exploitation Index by scenario

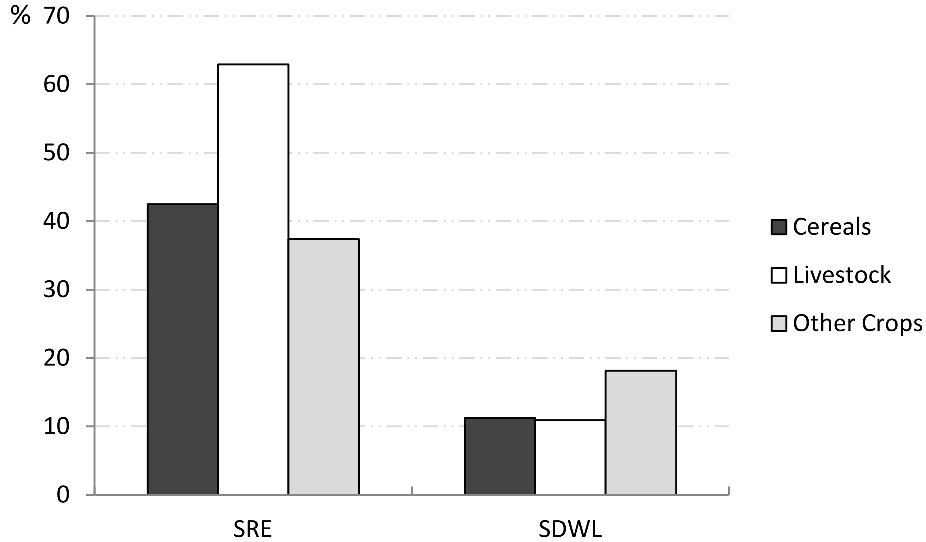


Source: Own computations.

6.2.3 Low-resource diets and technological changes decrease prices more than land expansion

Figure 6.7 shows the percentage change in agricultural commodity prices for the different scenarios. Prices for the three agricultural commodities are all higher for SRE. Therefore, Hypothesis 4 is rejected. The only way SRE can lower the price is if the expanded land produces higher yields than land currently used by other producers. This would make the most expensive producer drop out and the commodity price would decrease. As shown by the production results this is not the case. In SRE, almost all regions are producing, even high cost producers like Western Europe. This keeps the price high compared to SDWL, where increased land efficiency displaces some of the high cost producers and lowers the price. SDWL can therefore keep prices lower while simultaneously preventing the unsustainable solution of expanding forestland. This result makes SDWL a preferable path to SRE in two important ways.

Figure 6.7 – Percentage change in agricultural commodity prices



Source: Own computations.

7. Conclusions and continuing research

This section first discusses general conclusions from the results from Chapters 4 – 6 and compares them with the conclusions drawn from studies presented in the literature review. Other advantages of the model and scenario approach are also discussed briefly before closing with potential research avenues stemming from this dissertation.

7.1 Main findings and contribution to the literature

Some of the results from this study provide further insight into the conclusions drawn from other studies in the literature. Two main examples are explained here: explicitly testing the feasibility of meeting future food demand with current technologies and explicitly estimating future regional expansion of agricultural production onto forestland. Some main results suggest different conclusions from those found in similar studies from the literature (due to difference in assumptions behind the modeling framework and scenarios). Three examples are explained here: the world regions that are major exporters in the future, the amount of future global land use and water withdrawals, and the different contributions of rainfed and irrigated production that achieve a sustainable scenario of both land and water use.

Provides results about 2050 feasibility

One main objective of this dissertation was to determine the feasibility of meeting future food demand in the face of many potential problems, before considering a diverse set of potential solutions. A common approach in the literature is to estimate a "business-as-usual" 2050 baseline that considers problems – such as population growth or increasing meat consumption – alongside solutions – such as rates of land expansion or technological yield improvements. As a result, the 2050 "baselines" from many of the studies covered in the literature review are feasible (Bruinsma 2009; Calzadilla, Rehdanz, and Tol 2010; de Fraiture and Wichelns 2010). Such "business-as-usual" baselines for 2050 do not consider a scenario that first measures the extent of the problems separate from the solutions, allowing for ambiguous claims such as feeding future populations is "easily possible" (Anon 2010).

A separate scenario testing the feasibility of meeting future demand given current technologies goes deeper by addressing first part of this claim separately, testing whether feeding future population is “easily possible” because the problems are small. In fact, there is broad agreement that these problems are not small – both in terms of physically producing enough food to feed future populations and doing so without degrading the environment – and that overcoming such problems is not possible without dramatic solutions such as reducing the yield gap, expanding land, or reducing meat consumption (Godfray *et al.* 2010). This dissertation includes S2050 for this reason and finds that feeding future populations with current technologies and potentially available resources is not possible and that increasing population growth, diet change, and land and water scarcity are indeed very problematic.

Considers scenarios not often considered in literature

As shown in the literature review (Table 2.2), this dissertation incorporates and groups scenarios by bringing combining approaches and insights from different literatures and disciplines. For example, the trade-off of livestock production systems has rarely been considered in global economic scenario models, and never with a model that chooses among technologies based on the low-cost technology and the availability of different land types. Similarly, a scenario testing the implications of improvements to rainfed agriculture in developing regions has only been modeled using physical and partial equilibrium approaches, and never using a model with non-agricultural sectors that also endogenously considers the large amount of water withdrawn for industrial purposes. Also, separating diet improvements in developing regions from decreases in food demand in developed regions has never been considered in two separate scenarios (to the knowledge of the author).

This linking of scenarios provides additional insight, for instance adding the dimension of forestland expansion to the analysis of future increases in land use. Such estimates of future land expansion are rare in global scenario analyses. This study not only quantitatively shows the potential for expansion onto forestland but the regional distribution of this expansion - particularly Latin America, Africa, and North America – that takes place if other mitigating strategies are not pursued.

Developing countries do not depend on developed countries for food

One main conclusion from studies using general equilibrium approaches is that future food demand will be met in developing countries through exports from developed countries. For instance, de Fraiture and Wichelns (2010) find that both Africa and East Asia are importers of agricultural commodities, with large exports coming from OECD regions. Results from Hubert *et. al.* (2010) also suggest that feeding future food demand will require large amounts of exports from developed countries. This study comes to a different conclusion, that meeting future food demand is dependent on the ability of developing countries, particularly Africa, to increase production and export food. This is particularly true for the more sustainable solution of diet and technological change.

This result is especially important as general equilibrium approaches use trade elasticities and the Armington Assumption to determine trade between regions, calibrating trade parameters based on current trade patterns. Hence, the structure of future trade patterns tends toward the baseline calibration. However, it is possible in the future that the structure of these trade flows may be quite different than the present. The advantage of the modeling framework used in study is that regional comparative advantages endogenously determine trade flows, not trade elasticities or the Armington assumption. The results from this analysis show that Africa's comparative advantage in agricultural production is large enough to make it a global exporter in decades to come.

Land and water use may be higher than often suggested

Estimates of global changes in future land use and water withdrawals vary in the literature. Some studies conclude that increases land use – particularly rainfed arable land - will be relatively small or non-existent as a result of optimistic assumptions of improvements in yields (see Table 1.6). However, in SRE global land use expands by about 50%, about ~500 million hectares, suggesting that without these yield improvements land expansion will remain a large component of meeting future agricultural demand. Similar large increases are suggested in a couple studies that make estimates without changes in yield technologies. de Fraiture and Wichelns (2010) estimate increases of ~450 million hectares in their rainfed technology scenario and Rockström *et al.* (2007) increases of ~500 million hectares. The results from dissertation show additional detail in by presenting rainfed, irrigated, and pastureland use separately.

Future irrigated land use as estimated by this study is similar to estimates from the literature, and yet blue water withdrawals are ~1000 km^3 higher than estimates Table 1.9. This is true in both SDWL and SRE, even with assumptions of improvements in crop-water consumption. This suggests that additional potential improvements in water productivity are considered in other studies, particularly in regions such as Asia where irrigated production is the high.

Increasing irrigated production as a sustainable solution

The comparison of future rainfed and irrigated production – with representation of both blue and green water inputs – is only considered in a few studies. The most relevant and comparable study from the literature (Calzadilla, Rehdanz, and Tol 2010) finds that higher rainfed production and green water use is more sustainable since it reduces water withdrawals in water-scarce regions such as North Africa and Asia. On the contrary, the results from this study suggest that global increases in irrigated production and blue water withdrawals are more sustainable. This difference is due to the consideration of both land and water sustainability simultaneously, since increasing irrigated production decreases expansion of rainfed land onto forestland while simultaneously shifting production away from water-scarce China to more water-abundant regions. Although expanding rainfed production may improve the sustainability of water use, this study shows that a broader inclusion of other sustainability criteria can change the interpretation of the results.

Contributions of the model and database

A number of studies take an "integrated approach" to their modeling framework by linking biophysical databases and models with economic databases and models (Lotze-Campen *et al.* 2008). Unfortunately, the "bridge" between these different components is not always made explicit. A good example is the Hubert *et al.* (2010), which use a number of biophysical and economic components including IMPACT (PE), GTEP (CGE), and IMAGE (biophysical). Yet it is not clear how the authors use each component: as exogenous parameters from a database, as endogenous output from a model, or as endogenously linked models using separate databases. This dissertation provides an explicitly separate and transparent database, model, and scenario analysis, uniting the exogenous physical and economic data used to construct the scenarios with the modeling approach of the WTM that uses both the physical and economic data to endogenously model future production, trade, resource use, and factor rents.

7.2 Continuing research opportunities

A number of additional research avenues build upon the scenario analysis presented in this dissertation. Some of these avenues require no additional data or scenarios, but instead provide a more in-depth analysis in specific areas, using results that were not central to the broader analysis presented in this dissertation. For instance, each scenario provided results on fossil fuel use and fertilizer application rates in different regions that have not yet been considered in detail. As another example, a more detailed examination of the changes in production and land use for different livestock production technologies in Africa or Latin America could prove useful for understanding which systems can better prevent agricultural expansion onto forestland.

Constructing additional scenarios or running similar scenarios with additional detailed data opens up yet more avenues. The opportunities presented here are intended show the potential a broader research program using the WTM and global, environmentally-extended input-output databases to look at the future of world agriculture.

Additional scenarios about changes in population and diets

The population scenario in this study was using the average population projection from the UN (2010). Different population and demographic change assumptions may give further insight into the importance of these parameters. More dramatic diet scenarios could also be constructed, considering even lower-meat and higher vegetable diets, or even global vegetarian diets. Such diet scenarios could be particularly improved by utilizing a database with additional detail in the agricultural and food processing sectors (similar in scale to the EXIOPOL database) and with an even more detailed translation of the FAO food balance sheet data into monetary demand for different types of foods. Representing food consumption demand in physical units is also possible and potentially desirable, especially in the WTM framework, and the author is not aware of any global input-output studies that have done this.

Bilateral trade model to look at issues such as food security and regional subsidies

This study does not analyze the possible policy goals of food security. Latin America is a net importer of agricultural products when forestland is allowed to expand but a net exporter when land use is restricted and instead diet and technological solutions are promoted. This has policy implications, for although allowing additional expansion of land on to forestland may appear to be a plausible way to increase food security, this result suggests that it may not. A more detailed analysis of imports and exports using the WTM with Bilateral Trade, (Strømman and Duchin 2006) would provide further insight into how trade flows change between scenarios and which regions are highly dependent on others. This analysis could also include an additional scenario that shows the policy implications of land grabs in particular nations, for instance requiring that a certain endowment of land in Africa be used to produce food for China. This scenario would follow upon the results of this study, which in SDWL suggest that China is a large net importer of food.

Using Absorbing Markov Chains (AMC) to calculate embodied land and water in diets

The scenario results can be used to perform an AMC analysis (Duchin and Levine 2010) to calculate embodied resource use for each region in each scenario. For instance, this approach could be used to compare the embodied blue and green water content before and after diet changes, with the "after" encompassing endogenous changes in trade flows due to these diet changes. The main barrier is running the RCOT model with the World Trade Model with Bilateral Trade. All the data is in place to run the WTMBT with RCOT, yet as these two frameworks have not been run together in an empirical study – or furthermore with an *ex-post* AMC analysis – such an analysis requires further development program adjustments to the WTM.

Different scales of water and land use

More detailed land and water data could be used to calculate factor inputs and endowments at a scale consistent with the physical boundaries of these resources, such as climes and watersheds, modeling the use and scarcity of these resources with greater precision (Duchin and López-Morales 2011). This same detail could provide additional detail in representing alternative farming technologies. For instance, Julia and Duchin (2007) consider the impact of future changes in climate on the productivity of land, which affects each regions endowment of different land types. Integrating this more detailed treatment of land endowments with the separation of irrigated and rainfed technologies (along with the inclusion of green and blue water) have the potential to provide unique insights into the effect of climate change on both endowments and resource use.

This does not necessarily mean representation of dozens of different crops on minute-by-minute grid cells, which tends to be the approach of many other modeling research programs. The problems that were encountered when applying the EXIOPOL database to the scenarios in this study highlight the many pitfalls that can arise. A more precise approach identifies level of conceptual detail necessary to represent the physical concepts more accurately and determine how to integrate them with national account data from input-output databases.

Adding additional farming systems using RCOT

This study was the first attempt to model alternative farming systems at the global level utilizing the RCOT framework, and there remains much untapped potential to further utilize this method. For research about the future of agriculture, this potential could be used to represent regional farming systems with more detail by further disaggregating the crop and livestock technologies into any number of alternatives. This effort could particularly enhanced by the literature on global farming systems that strives to categorize world agricultural technologies based upon physical, economic, social, and institutional factors (Dixon, Gulliver, and Gibbon 2001; Norman 2002). A scenario considering multiple different farming systems could test the comparative advantages of these different technologies; however, this would also require the classification of these systems using direct factor inputs and indirect intermediate inputs, which to the knowledge of the author does not exist at the global scale.

Consideration of pollution and emission component of sustainability

Lastly, this study defines sustainability as land and water scarcity and doesn't consider additional sustainability metrics such as emissions or pollution from production. Including data on such negative outputs using global databases such as EXIOPOL adds another dimension to the question regarding the sustainability of each scenario. For instance, it is possible that SDWL results in more nitrogen runoff or carbon emissions than SRE. Coupled with an analysis of different farming technologies, some of which are low fertilizer and hence lower yield, one could analyze the tradeoffs between decreasing pollution and increasing land and water use. This pairing of resource input scarcities with negative emissions output would allow a more comprehensive picture of the sustainability of future agriculture.

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Appendices

A. Database Classification

Table A.1 – Classification of regions, sectors, and factors for WTM database

Regions	**Sectors**	**Factors**
North America	Coal	Rainfed land
Western Europe	Oil	Irrigated land
Other Europe	Gas	Pasture
Former Soviet Union	Electricity	Blue water
Japan	Mining	Green water
China	Manufacturing	Agricultural labor
Rest of Asia	Services	Other labor
Latin America	Grains	Agricultural capital
Africa	Livestock	Other captial
Australia/NZ	Rest of Agriculture	Coal
		Crude oil
		Natural gas

Table A.2 – Classification of regions for the EXIOPOL database

EU Developed	Other Developed	Developing	Rest of World
France	Australia	Brazil	Africa (except S. Africa)
Germany	Canada	China	Asia (except Japan, S. Korea, China,
Italy	Japan	India	India, Indonesia, and Turkey)
Spain	South Korea	Indonesia	Middle East
United Kingdom	United States	Mexico	Other Eastern Europe
Other Western EU		Russia	Latin America (except Brazil)
Eastern EU		South Africa	Oceania (except Australia)
		Turkey	

Note: Other Western EU also included Norway and Switzerland.

Table A.3 – Classification of factors for the EXIOPOL database

Land and Water	Capital and Labor	Fossil Fuels and Ores
Rainfed land	Agricultural labor	Coal
Irrigated land	Mining labor	Crude oil
Pastureland	Manufacturing labor	Natural gas
Blue water	Services labor	Uranium
Green water	Agricultural capital	Iron Ore
	Other captial	Copper
		Nickel
		Bauxite
		Precious Ores
		Lead, Tin, and Zinc
		Other Ores
		Stone
		Sand and Clay
		Chemicals and Fertilizers

Table A.4 – Classification of factors for the EXIOPOL database

Primary Crops	Primary Animal	Processed Food
Cereals	Cattle	Products of meat cattle
Vegetables, fruit, nuts	Pigs	Products of meat pigs
Other crops	Poultry	Products of meat poultry
	Meat animals nec	Other meat products
	Animal products nec	Products of vegetable oils
	Raw milk	Dairy products
	Fish	Other food products
		Sugar
		Beverages
		Fish products

Other Manufacturing	Services	Mining
Tobacco products	Water collection and distribution	Coal, lignite, and peat
Textiles	Construction work	Crude petroleum and natural gas
Wearing apparel and furs	Sale, maintenance, repair of motor vehicles	Uranium and thorium ores
Leather and leather products	Wholesale and commission trade services	Iron ores
Wood and cork products	Retail trade services	Copper ores and concentrates
Pulp, paper and paper products	Hotel and restaurant services	Nickel ores and concentrates
Printed matter and recorded media	Transportation services	Aluminium ores
Coke, petroleum, and nuclear fuel products	Post and telecommunication services	Precious metal ores
Chemical products and man-made fibres	Financial intermediation services	Lead, zinc and tin ores
Rubber and plastic products	Insurance and pension funding services	Other non-ferrous metal ores
Other non-metallic mineral products	Services auxiliary to financial intermediation	Stone
Basic metals	Real estate services	Sand and clay
Fabricated metal products	Renting services of machinery and equipment	Chemical and fertilizer minerals
Office machinery and computers	Computer and related services	
Electrical machinery and apparatus	Research and development services	
Media and communication equipment	Other business services	**Other Sectors**
Medical, precision and optical instruments	Public administration and social services	Forestry
Motor vehicles, trailers and semi-trailers	Education services	Electrical energy, gas,
Other transport equipment	Health and social work services	steam and hot water
Furniture and other manufactured goods	Sewage and refuse disposal services	
	Membership organisation services	
	Recreational, cultural and sporting services	
	Other services	

B. Acronyms and Initials

Table B.1 – List of acronyms and initials

AMC	Absorbing Markov Chains
CGE	Computable General Equilibrium
EWR	Environmental Water Requirements
ELR	Environmental Land Requirements
EXIOPOL	A New Environmental Accounting Framework Using Externality Data and Input-Output Tools for Policy Analysis
FAO	Food and Agriculture Organization
GCWM	Global Crop Water Management
GTAP	Global Trade Analysis Project
IIASA	International Institute for Applied Systems Analysis
IFPRI	International Food Policy Research Institute
IMPACT	International Model for Policy Analysis of Agricultural Commodities and Trade
IO	Input-Output
IWMI	International Water Management Institute
LPJmL	Lunds-Postdam-Jena managed Land Dynamic Global Vegetation and Water Balance Model
PE	Partial Equilibrium
RCOT	Rectangular Choice-of-Technology
S2050	Scenario 2050
SDWL	Scenario Diets Water and Livestock
SRE	Scenario Resource Expansion
TCE	Tonnes of Coal Equivalent
UNEP	United Nations Environment Programme
USGS	United States Geological Survey
WEI	Water Exploitation Index
WTM	World Trade Model