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Feeding Nine Billion People Sustainably: Conserving Land and Water through Shifting Diets and Changes in Technologies

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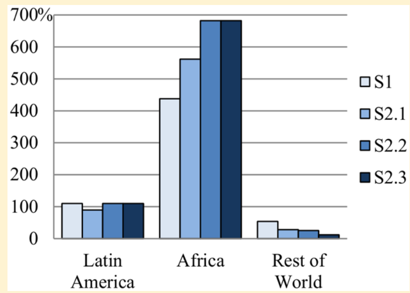
ABSTRACT: In the early 21st century the extensive clearing of forestland, fresh water scarcity, and sharp rises in the price of food have become causes for concern. These concerns may be substantially exacerbated over the next few decades by the need to provide improved diets for a growing global population. This study applies an inter-regional input-output model of the world economy, the World Trade Model, for analysis of alternative scenarios about satisfying future food requirements by midcentury. The scenario analysis indicates that relying only on more extensive use of arable land and fresh water would require clearing forests and exacerbating regional water scarcities. However, a combination of less resource-intensive diets and improved agricultural productivity, the latter especially in Africa, could make it possible to use these resources sustainably while also constraining increases in food prices. Unlike the scenario outcomes from other kinds of economic models, our framework reveals the potential for a decisive shift of production and export of agricultural products away from developed countries toward Africa and Latin America. Although the assumed changes in diets and technologies may not be realizable without incentives, our results suggest that these regions exhibit comparative advantages in agricultural production due to their large remaining resource endowments and their potential for higher yields.



1. INTRODUCTION

The world population in 2050 will exceed the present number of people by at least two billion,[1] with most of the increase in regions that currently experience relatively low agricultural yields and low per capita availability of food with only a small percentage of caloric intake from animal products. International efforts to reduce hunger, malnutrition, and poverty in sub-Saharan Africa and other poor regions by 2050 aim at achieving universal per capita food availability of 3000 kcal/day, of which 20% is derived from animal products.[2,3] These ambitious goals would help improve public health and reduce poverty but, at the same time, higher calorie, more meat-intensive diets in these fast-growing regions would require much more food to be produced, putting additional pressure on food prices and resource scarcity.

One way to expand production to meet this potential increase in demand is to devote additional stocks of land and water to agricultural activities. The amount of available arable land not now cultivated is more than twice as great as the amount currently used for crop production, with over half of this available land in Latin America and Africa.[4] Water requirements could be met by appropriating additional soil moisture on rainfed land and increasing withdrawals from surface and groundwater sources on irrigated land. This proposition appears plausible since at the global level only 7% of the renewable supply of water is withdrawn for irrigation—which accounts for over 70% of global water withdrawals—and all other economic purposes combined.[5]

However, expanding production through an increase in factor inputs poses various challenges for sustainable usage.[6] Over half of the remaining available arable land is forested or protected. Four million hectares of forestland are already converted to other uses each year,[7] and at this rate all remaining forestland with agricultural potential could be cleared by 2050. Yet the magnitude of foreign investment in African land with the intent of cultivation,[8] and revisions relaxing Brazil's Forest Code,[9] are evidence of planning for substantial expansion of agricultural land. Not all renewable water is available for use due to environmental requirements and infrastructure constraints. On average, water scarcity becomes a problem for a region withdrawing more than 20% of its renewable water supply, and scarcity becomes critical when the rate of withdrawal reaches 40%.[10−12] Many regions already experience scarcity, and population growth will increase competition over water among agriculture and other human activities.

The alternative to relying on more extensive provision of inputs is to reduce the demand for food or for the resources required for producing it. Per capita food availability in regions such as North America and Europe today exceed levels necessary to meet the dietary needs of the population.[2,3] Reductions in caloric intake, dietary shifts to less meat-intensive diets in these regions, and reduced food waste have the potential to improve public health and mitigate increases in land and water use.[13−15] Production efficiency—in terms of land and water requirements per metric ton of a given crop—varies substantially even among regions with similar quality soils and climatic conditions. Some ways to achieve greater

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productivity of water or land include improved management of soil moisture, irrigation, and industrial livestock production, reducing land and water requirements to produce the same amount of output. Africa and Latin America, the regions with the largest endowments of arable land, also have the greatest potential to reduce the gap between their currently low yields and those considered readily attainable through these specific technologies.[16,17]

The study reported in this paper tests the proposition that it is possible to produce enough food for the global population in 2050 while making sustainable use of land and water resources. Scenarios are constructed to examine the consequences of satisfying future global demand for food by appropriating additional land and water for agriculture, through diet change, and by intensifying farming technologies. The comparison of scenario outcomes reveals the assumptions consistent with producing enough food while using resources sustainably and the associated trade-offs regarding the international division of labor in food production, food prices, and land and water use. The scenarios are analyzed using the World Trade Model (WTM),[18] an input-output model of the world economy based on comparative advantage that takes account both of quantities of factors and goods and of money costs and prices.

2. LITERATURE REVIEW

Given the importance of the challenges, it is not surprising that the scholarly literature includes numerous studies rooted in a variety of disciplines that investigate the future of global agricultural production by analyzing alternative scenarios about the future. Such studies—in both the natural and social sciences—use scenarios not to make forecasts or predictions but to explore the likely implications of, instead using scenarios to suggest plausible assumptions both to gain insights about unanticipated consequences and as a basis for decision-making. A subset of this research focuses on requirements to ensure the sustainable use of land and water (Alexandros et al.;[19] Alcamo, Flörke, and Märker;[20] Rockström, Lannerstad, and Falkenmark;[21] Lotze-Campen et al.;[22] Bruinsma;[23] Foresight;[24] Paillard, Treyer, and Dorin).[25] The analyses of de Fraiture and Wichelns[26] and Hubert et al.[27] develop scenarios that, similar to ours, embody assumptions about population growth, land and water availability, dietary changes, and technological intensification, distinguishing between irrigated and rainfed production technologies. They explore the implications of these changes in the major determinants of both demand for food and its supply using a model of the global economy to quantify the trade-offs among scenario outcomes.

De Fraiture and Wichelns[26] use a partial equilibrium (PE) model to analyze six scenarios for 2050 and conclude that enough food to satisfy future demand can be produced under varying assumptions about rainfed and irrigated crop yields and water productivity. Under all scenarios Africa, the Middle East, and Asia are net food importers in 2050 while Europe, the Americas, and other OECD countries are net exporters.

Hubert et al.[27] analyze four scenarios for the year 2050 using the same PE model and also make use of a computable general equilibrium (CGE) model to provide some account of the interactions of the agricultural sector with the rest of the economy. These scenarios make alternative assumptions about yields and land availability and the rates of expansion onto irrigated and rainfed land. Demand for food is satisfied under all scenarios but with substantial differences in food prices, which are up to three to four times as high as in 2000; either intensification of production or extensification of land and water use is able to substantially contain price increases. Under all scenarios the developed regions remain the net exporters of cereals and meat in 2050, with China, Middle East, and Africa the largest net importers. Trade in other categories of food is not reported.

Calzadilla, Rehdanz, and Tol[28] perform the only global economic study of water scarcity using a CGE model and making explicit, as we will, the distinction between water sources for rainfed and irrigated production. They analyze a water crisis scenario with regional withdrawals above sustainable levels and a sustainable scenario that limits withdrawals in all regions, relying more heavily on rainfed agriculture. The authors conclude that sustainable production can be achieved through the expansion of rainfed agriculture at the cost of only slightly lower global household incomes, with the largest income reductions in those regions that now rely most heavily on irrigation. Sub-Saharan Africa, with its paucity of irrigated agriculture, is one of the few regions with a higher household income under the sustainable scenario, increasing its share of global production, but from 6% in 2000 to only 8% by 2025.

A handful of studies to date have used the WTM to analyze agricultural scenarios. Juliá and Duchin[29,30] use the WTM to analyze prospects for global agriculture under climate change and find that production shifts, responding to changes in comparative advantage, ensure a feasible solution but at higher prices. The WTM has also been applied to inter-regional exchanges among hydro-economic subregions of Mexico to investigate the magnitude of water fees or caps on withdrawals that would be required to shift agricultural production out of low-cost but water-scarce regions of the country.[12,31,32]

3. THE WORLD TRADE MODEL WITH THE RECTANGULAR CHOICE OF TECHNOLOGY

The World Trade Model is formulated as a multiregional linear program that minimizes the global use of factors required to satisfy consumption demand. Under the optimal solution each good is produced in the relatively lowest-cost regions in quantities limited by each one's resource endowments. The model also solves for world prices and for the scarcity rents earned in the lowest-cost producing regions. The world price for each good is set by the cost of the highest-cost among these regions that actually produce, and the even lower-cost regions, which are prevented from expanding production by running out of resources, earn scarcity rents on these scarce resources.

The distinctive transparency of the model's logic is achieved by generalizing to m regions, n goods, and k resources the economic theory of comparative advantage, which is usually considered implementable for only two regions, two goods, and two resources (the $2 \times 2 \times 2$ case). The WTM makes direct comparisons among input cost structures for all goods and all regions simultaneously; see Duchin[18] for details and proofs. The model can be written as a small number of matrix equations, shown below, and variables and parameters for each region can be fully accommodated by two matrices of parameters, two vectors of exogenous variables, and two vectors of endogenous variables. For region i the parameters include the standard input-output coefficient matrices A_i and F_i, for intermediate and factor requirements, respectively, per unit of output. The j^{th} columns of these matrices quantify the input requirements corresponding to the average technology employed to produce the j^{th} good.

Table 1. Land and Water Use in 2000 and Endowments in 2050 by Region[a]

	rainfed arable land (10^6 ha)			irrigated land (10^6 ha)		renewable water supply (10^9 m^3)		
	2000 Baseline	2050 S1	2050 S2	2000 Baseline	2050 S1, S2	2000 Baseline	2050 S1	2050 S2
North America	202	414	292	28	28	520	5978	1196
EU-15	81	118	110	12	13	190	1055	211
Other Europe	91	136	107	8	12	107	1959	392
Former Soviet Union	183	292	183	20	52	261	5218	1044
Japan	3	10	7	3	3	88	430	86
China	101	159	150	67	67	656	2945	589
Rest of Asia	265	385	285	107	185	1 332	11 950	2390
Latin America	135	732	421	13	62	265	18 525	3705
Africa	184	919	766	12	38	213	5665	1133
Australia and NZ	30	91	48	4	4	26	819	164
World	1274	3256	1982	272	463	3660	54 545	10 909

[a]Source: Own computations, see text for sources. Note: S1 is the extensive scenario with all land and water endowments available for use, and S2 is the sustainable scenario that excludes forestland and 80% of the renewable water supply. The columns labeled S2 quantify the endowments that are assumed for scenarios S2.1, S2.2, and S2.3. Endowments are exogenous (f_i); resource use for 2050 is endogenous. See text for details.

Exogenous variables are consumption demand, y_i, factor endowments, f_i (i.e., resource availability), and factor prices, π_i (the price may be zero). This exogenous price will be augmented by an endogenous, nonzero scarcity rent if and only if that factor in that region is fully utilized. (Higher-cost regions will import the good.) The solution for a scenario consists of x_i, the vectors of goods produced in each region; p, the vector of world prices of goods; and r_i, the region-specific scarcity rents.

To allow multiple technologies to operate in the same sector, we implement the Rectangular Choice of Technology (RCOT) within the WTM by adding a column to A and F for each technological option and denoting the resulting rectangular matrices A^* and F^* (Duchin and Levine).[33] If a region that produces a good has no shortage of factors, only the lowest-cost of the options will operate. But if it runs out of a factor, the next lowest-cost technology may become active. Thus two or more technologies may operate simultaneously within a region, say rainfed and irrigated cereal production. If there are t possible technologies for the n sectors combined, then the cost structures for all technologies are readily accommodated in the A_i^* and F_i^* matrices.

The resulting primal model, with variables measured in mixed units, can be written as follows:

$$\min z = \sum_i \pi_i' F_i^* x_i^* \quad (1)$$

$$\sum_i (I^* - A_i^*) x_i^* = \sum_i y_i \quad (2)$$

$$\sum_i F_i^* x_i^* \le f_i \quad (3)$$

$$x_i \ge 0 \quad (4)$$

The so-called dual of this model involves money costs and prices. While it is redundant to write the dual, we do so to make explicit the logic behind the determination of world prices and scarcity rents:

$$\max z = p' \sum_i y_i - \sum_i r_i' f_i \quad (5)$$

$$(I^* - A_i^*)' p - F_i^{*'} r_i \le F_i^{*'} \pi_i \quad (6)$$

$$p \ge 0 \quad (7)$$

The inequality of eq 6 shows that the price, p, must be less than or equal to the cost of production in any region. The world price is in fact set to the cost of the highest-cost producer, who earns no scarcity rents. Other producers also sell at the world price, earning rents on limiting factors to comprise the difference between the price and their costs. Nonproducing regions benefit from being able to import the good at a price that is strictly lower than that for which they could have produced it.

4. DATA SOURCES FOR THE 2000 BASELINE SCENARIO

The baseline WTM database establishes numerical values for A_i^*, F_i^*, y_i, f_i, and π_i in 2000 for the 10 × 10 × 9 case. The point of departure is the database of Juliá and Duchin,[29] extended by Strømman, Hertwich, and Duchin,[34] for 10 regions: North America, EU-15, Other Europe, Japan, the former Soviet Union, Australia plus New Zealand, Latin America, Africa, China, and the Rest of Asia; 10 economic sectors, of which three produce agricultural products: cereals, other crops, and livestock; and seven factors of production: capital, labor, two categories of land (cropland and pasture-land), and three categories of fossil fuels. These data are updated to 2000 for prices, final demand and capital (World Bank);[35] labor force by region (ILO);[36] fossil fuels (U.S. Energy Information Administration);[37] and agricultural subsidies for North America, Europe, and Japan (OECD estimates)[38] that are treated like factor inputs (in negative money values).

From this starting point, we disaggregate cropland to distinguish irrigated from rainfed and add water as a distinct factor of production, for a total of nine factors. We add columns to A_i^* and F_i^* to distinguish rainfed from irrigated agricultural technologies for each crop sector. Data for rainfed technologies and irrigated technologies for the production of cereals and of other crops are derived from Siebert and Döll's Global Crop Water Management database,[39] and water withdrawal requirements (m^3 per unit of output) for the agricultural sectors, industrial sectors, and municipal water supply are from FAO AQUASTAT.[5] Electric power cooling requirements are disaggregated from other industrial withdrawals based on de Fraiture et al.,[17] and municipal water withdrawals are allocated among industrial, services, and household demand using estimates from Solley et al.[40]

Finally, data are compiled for factor endowments (f_i) of rainfed arable land, land equipped for irrigation, and pastureland (FAOSTAT)[41] and endowments of water (FAO AQUASTAT),[5] as shown for 2000 in the corresponding columns of Table 1.

5. SCENARIOS FOR 2050 AND DATA SOURCES

Scenario Descriptions. We define five scenarios for 2050, all assuming the UN medium population projection[1] of 9.7 billion people. Regional demand for goods and services is increased proportional to regional change in population. These scenarios all also assume dietary improvements in developing countries: total caloric demand is set at 3000 kcal/capita/day and the share of animal products increases to 20% of total calories, with offsetting adjustments to demand of both cereals and other crops.[2,3] (3000 kilocalories are defined as *available* for consumption; this figure includes calories lost between purchase and ingestion as well as those actually ingested, which are difficult to distinguish). Changes in demand for processed foods are estimated from Tukker et al.[42] These data comprise the starting point for final demand (y_i) for all scenarios for 2050. Like the 2000 baseline, the 2050 scenarios offer the choice between rainfed and irrigated agriculture. The 2050 labor force in each region is set at the projected working-age population,[1] and capital is increased at the same rate to maintain the capital to labor ratio. No agricultural subsidies are assumed for 2050.

The Extensive scenario, S1, makes available all arable land and the entire renewable supply of water. These figures, shown in Table 1, are based on the FAO World Soil Resources report[4] less protected land from the IUCN World Database on Protected Areas.[43] The table also distinguishes potentially available irrigated land (FAOSTAT).[5] Regional pastureland endowments are kept at the baseline 2000 levels, and we add a technological option permitting the livestock sector to use available cropland in addition to pastureland (which Steinfeld et al.[44] and Gibbs et al.[45] note is already the case). Endowments of water are regional renewable water resources from FAO AQUASTAT.[5]

The Sustainable scenario, S2, shares all the other assumptions of S1 except that land endowments are reduced to preclude the clearing of arable forested land, in amounts estimated using data from Fischer et al.,[46] and its water endowment is limited to 20% of the renewable supply.[10−12] Both factor endowments (f_i) are shown in Table 1.

Dietary Moderation in Developed Countries Under S2.1. S2.1 is the first variation on S2, the scenario limited to sustainable use of land and water for agriculture, and is intended to relax pressure on these resources by moderating food demand. In developed regions, demand is reduced to 3000 kcal/capita/day with no more than 20% of the available calories from animal products.

Technological Change in Africa and Latin America under S2.2. Scenario S2.2 is the second variation of S2 and assumes improved crop-water management and the availability of mixed pastoral and industrial livestock technologies in Africa and Latin America, regions with particularly high capacity to improve agricultural productivity.

In rainfed systems, land leveling, terracing, soil fertility management, and tillage can improve soil moisture productivity by reducing the loss to evaporation for a given amount of rainfall. Based on Siebert and Döll's GCWM database,[39] de Fraiture et al.,[17] and Falkenmark and Rockström,[16] we estimate such techniques can lower land requirements per metric ton of rainfed cereal from 0.37 to 0.25 ha in Latin America and from 1.00 to 0.33 ha in Africa. These figures are used to reduce the rainfed land coefficients for cereals in F_i* for Latin America and Africa.

In irrigated systems, microirrigation technology can reduce water withdrawals per unit of effective consumption. We estimate irrigation efficiency in 2000 at 33% for Latin America and 54% for Africa based on Siebert and Döll's GCWM database[39] and FAO AQUASTAT.[5] Following de Fraiture et al.[17] we assume an improvement to 70% in both regions as well as a related improvement in land yields of 80% (reducing the land requirement by nearly half) due to the attendant vapor shift. These figures are used to reduce the irrigated land and water coefficients for cereals in F_i* for Latin America and Africa.

In livestock systems, different production technologies can both directly and indirectly reduce of land and water use. Bouwman et al.[47] distinguish pastoral grazing of ruminants, which rely almost solely on pastureland, from mixed pastoral and industrial production, where, in addition to grazing, livestock are fed a mix of food crops, fodder, and grass; they give estimates of land use and productivity for these two ruminant systems in three groups of countries (developed, transition, and developing). We supplement this source with detail at the country level and for nonruminant production (pigs, chicken, etc.) using data from FAOSTAT[41] and assume intermediate crop purchases are negligible for the pastoral system. This information is used to disaggregate the single, average technology for the production of livestock into two technologies in A_i* and F_i*: pastoral production and a blend of pastoral with industrial techniques.

Combining Diet and Technological Changes under S2.3. Scenario S2.3 combines the assumptions of S2.1 and S2.2 to represent the combined impact of less rich diets and technological improvements in agricultural production. This scenario should make it possible to satisfy future food demand at both lower cost and lower requirements for agricultural land and water than S2, S2.1, or S2.2.

6. RESULTS

The Extensive scenario, S1, turns out to be feasible but results in the clearing of forestland in virtually all regions, particularly in Africa and Latin America (and also in North America). The withdrawal of water for agriculture also increases substantially and exceeds 20% of the renewable supply in the EU-15 and in Japan, China, and the rest of Asia.

The S2 scenario was formulated to preclude both the conversion of forestland to agricultural use and the withdrawal of water beyond sustainable levels. Unfortunately, this scenario turns out to have no feasible solution. So we turn to S2.1−S2.3 to examine the potential for changes in diets and technologies to make a sustainable scenario for 2050 more realistic.

Scenarios S2.1 and S2.2 are both feasible. Table 2 shows that global livestock production under S2.1 indeed falls compared to S1, but by only about 20% (from 128% to 108% of the baseline 2000 value). Both S2.1 and S2.2 require at least 70% more water for irrigation and 50% more land than the 2000 baseline scenario (see Table 3). Still, the changes in technology under S2.2 reduce land requirements appreciably, utilizing only 48%

Table 2. Global Agricultural Production by Product and Technology in 2050 (% Change from Baseline 2000)[a]

product and technology	S1 (%)	S2.1 (%)	S2.2 (%)	S2.3 (%)
crops	50	51	51	48
rainfed cereals	88	56	87	96
irrigated cereals	86	136	32	4
other rainfed crops	−18	23	24	−4
other irrigated crops	115	66	73	95
livestock	128	108	130	108

[a]Source: WTM computations. Note: S1 is the extensive scenario with all land and water endowments available for use. The other scenarios assume sustainable levels of endowments with dietary moderation (S2.1), technological change (S2.2), and both dietary moderation and technological change (S2.3). S2, with sustainable levels of endowments but no offsetting changes in diets or technologies, proves to be infeasible. See text for further details.

Table 3. Agricultural Land Use, Water Withdrawals, And Commodity Prices in 2050 (% Change from Baseline 2000)[a]

factor and technology	S1 (%)	S2.1 (%)	S2.2 (%)	S2.3 (%)
water withdrawals	93	79	73	77
agricultural land used	87	73	49	46
crops rainfed	80	59	40	37
crops irrigated	70	68	37	41
land for livestock	93	80	55	50
cereals prices	44	242	14	14
other crops prices	11	69	17	16
livestock prices	62	334	23	22

[a]Source: WTM computations. Note: S1 is the extensive scenario with all land and water endowments available for use. The other scenarios assume sustainable levels of endowments with dietary moderation (S2.1), technological change (S2.2), and both dietary moderation and technological change (S2.3). S2, with sustainable levels of endowments but no offsetting changes in diets or technologies, proves to be infeasible. See text for further details.

more land to produce 51% more crops and 130% more livestock in 2050 than the baseline in 2000.

Considering the growth in factor use, it is not surprising that food prices rise under both scenarios (see Table 3). The dietary moderation in rich countries under S2.1 cannot offset the resource limits imposed by sustainability criteria, and prices of cereals and livestock products rise two to three times relative to the 2000 baseline. However, S2.2 holds the price increases for 2050 over the baseline scenario to no more than 23%. Without the technological improvements under S2.2, sustainable land and water constraints require higher-cost regions to produce, even under the assumptions of S2.1.

S2.2 requires less water, much less land, and much lower costs than S1 or S2.1 for an additional reason: its increased reliance on rainfed production for cereals and irrigated production for other crops. Globally, virtually all the irrigation capacity is now reserved for higher-value other crops rather than cereals (Table 2). Irrigated other crops use less land and water per unit output compared to irrigated cereals, and much less land (but more water) per unit output compared to rainfed cereals (Siebert and Döll).[39] The result − that a decrease in water withdrawals under S2.2 relative to S1 or the 2000 baseline can coincide with a large decline in land utilized − is due to a shift in comparative advantage to regions and for crops experiencing improvements (relative to other regions) in land yields and water productivities, prominently rainfed cereal production in Africa. Under S2.1, it is higher-cost regions (such as North America and Europe) that produce irrigated cereals to conserve land, but improved rainfed technologies in Africa allow it meet a large fraction of global cereal demand at relatively low cost, and now Rest of Asia and Latin America produce irrigated other crops. Although rainfed cereal production uses more land than irrigated cereal production, this increase is compensated by the much larger savings in land because these last regions have low land coefficients. The same is true for water: rainfed cereals by definition use no irrigation water, and irrigated other crops use less water per unit of output (in money values) than irrigated cereals.

In terms of the international division of labor, there is a striking shift in comparative advantage in agricultural production from the developed economies of North America and Europe to Latin America and Africa under all scenarios (see Figure 1). Given the vast stocks of available arable land and of

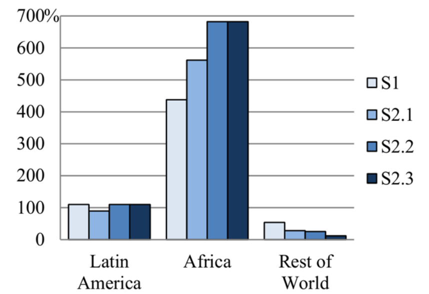

Figure 1. Agricultural production by region in 2050 scenarios (% change from Baseline 2000). Source: WTM computations. Note: S1 is the extensive scenario with all land and water endowments available for use. The other scenarios assume sustainable levels of endowments with dietary moderation (S2.1), technological change (S2.2), and both dietary moderation and technological change (S2.3). S2, with sustainable levels of endowments but no offsetting changes in diets or technologies, proves to be infeasible. See text for further details.

water assumed for Latin America and Africa, it is not surprising that most additional production (and exports) take place in these regions. In the baseline for 2000, North America and Europe account for 38% of global agricultural production while Latin America and Africa produce 19%; in scenarios S1, S2.1, and S2.2, North America and Europe jointly produce only 27%, 15%, and 11% of cereals, other crops, and livestock, respectively, in 2050 while Latin America and Africa jointly produce 35%, 40%, and 44%. Africa is already a large net exporter under S1, but even more so under S2.1 and 2.2.

The final scenario, S2.3, which combines diet moderation and increases in productivity, shows improvements over both S2.1 and S2.2, but has only slightly better outcomes than S2.2 alone. Livestock production is naturally lower under S2.3 than S2.2 alone, but production and exports from Africa are comparable and food prices barely change. The shift in irrigation from cereals to other crops, however, is even more marked. We gain more insight into this result by exploring the sensitivity of the outcomes to scenario assumptions.

Sensitivity Analysis. We calculate five variations of each scenario, including the infeasible scenario, S2, to examine the sensitivity of the results to assumptions about resource availability, food demand as related to population size and diets, and productivity improvements in agricultural technologies.

For the first two sensitivity experiments, we replace the U.N. medium population projection for 2050 by the low estimate of 8.5 billion people and then the high estimate of 11 billion. For the third, we lower food demand from 3000 to 2700 kcal/capita/day (retaining 20% from animal products), which would represent some combination of reduction in waste or lower ingestion (2700 kcal/capita/day availability with 20% from animal products describes the average Japanese diet in 2000). For the fourth, to explore Africa's potential as a major food producer and exporter, we reduce by half the sustainable land endowments in Africa, on the grounds that some of this land will be unavailable to agriculture due to unsuitability, institutional impasses including armed conflict, or competing land-use claims. Our final sensitivity experiment reduces by half the land and water productivity gains and extent of industrialization of livestock agriculture in Africa and Latin America under S2.2 and S2.3.

Under the high population assumptions (an increase of 13% globally relatively to the UN medium projection), both S1 and S2.1 become infeasible. Conversely, under either the low population projection (a reduction of 12%) or the reduction of 10% in caloric content of diets globally, S2 for the first time becomes feasible and, furthermore, the high prices of the original S2.1 scenario are substantially reduced. (These assumptions have little effect on prices under the S2.2 scenario.) We conclude that in the absence of productivity improvements, it takes a 10−15% decrease (or increase) in demand for agricultural products to eliminate (or require) production in high-cost regions.

If we reduce by half the endowments of agricultural lands in Africa, both S1 and S2.1 fail to produce a feasible outcome. However, the technology assumptions of S2.2 and S2.3 are able to compensate for reduced access to land in Africa to yield a feasible solution. Moreover, the money value of African agricultural output hardly changes with restricted land availability although land use and water withdrawals are 24% and 47% lower, respectively, than under scenario assumptions with the much larger land and water endowments.

Assuming less optimistic yield improvements in Africa than under the original assumptions for S2.2 and S2.3 allows other regions to improve their comparative advantages relative to Africa. Agricultural prices increase by about 4%, and agricultural production in Africa falls by 13% and 18%, respectively, and net exports by 23% and 36%, respectively, compared to the outcomes for the original S2.2 and S2.3 scenarios. Still, both production and net exports of Africa are much higher than under the baseline for 2000.

Closer inspection of these latter two variations reveals that Africa is still able to maintain a very substantial level of agricultural output under S2.2 and S2.3 by reducing production of cereals (both rainfed and irrigated) and increasing production of higher value crops and industrial livestock, the former being more efficient than cereals in both land and water use per dollar of output, and industrialized livestock requiring minimal direct use of land. These assumptions raise world agricultural prices by less than 4% relative to the original assumptions for the S2.2 and 2.3 scenarios. This result suggests that even if land expansion or technological improvements in Africa are quite modest, it can still realize its potential as a major sustainable agricultural player and contain future food prices by precluding other highest-cost regions from producing.

7. DISCUSSION

Our scenarios show that feeding the population anticipated for 2050 while improving diets in developing countries would require either exploiting land or water beyond sustainable limits or moderating resource-rich diets and improving agricultural technologies at least in low-yield regions, in particular in Africa. Furthermore, if the UN's highest population projections for 2050 are realized, it would be much more difficult to ensure that the global population can be adequately fed. Conversely, the UN's low population growth projection coupled with a less rich diet could markedly reduce the pressure for agricultural expansion onto forestland and overexploitation of water for irrigation while incurring only relatively small increases in food prices. These results are broadly consistent with scenario results from other studies. Without productivity improvements in developing countries, such as those assumed under S2.2, we can anticipate dramatically higher prices, as Hubert et al.[27] point out; in fact, it may simply not be possible to supply adequate diets sustainably, an outcome suggested by the infeasibility of the S2 scenario.

Our second conclusion is that developing countries have the potential to play an increasing role in global agricultural production and in fact become the principal producers and exporters. Some of these regions are potentially low-cost producers relative to Europe and the U.S, and under the assumptions of the Diet and Technology scenario, S2.3, Africa and Latin America improve their cost advantages. The likelihood of actually achieving this potential is corroborated by the sensitivity analysis: even with quite modest assumptions about future land availability and yield improvements in Africa, there still remain enough resources and sufficiently favorable cost structures in Africa to produce and export large quantities of food. This possibility is at odds with the conclusions of other studies, which use partial equilibrium or CGE models (such as those described earlier)[26,27] to suggest that increased production and exports will most likely continue to come from developed countries, particularly Europe. Their conclusion that the United States and Europe will continue to be major producers and exporters, and developing countries net importers, in our opinion reflects the reliance on exogenous trade parameters, the so-called Armington elasticities, to govern changes in trade flows. If a region did not produce and export a particular good in the base year, it would take a huge Armington elasticity for that region to produce and export that good in subsequent years. Such an extreme value could not be inferred from past values, nor assumed a priori. By contrast our scenarios make transparent explicit assumptions about changes in region-specific demand, input structures, and resource endowments, and using these data the World Trade Model is able to reveal the associated relative cost advantages that can emerge for Latin America and Africa under the 2050 scenarios.

Third, we show that increasing rainfed cereal and irrigated other crop production in regions with adequate land and water endowments can simultaneously deter expansion of production onto forestland and overuse of irrigation water, either in the same or other regions. In a study that focuses on water use alone, Calzadilla et al.[28] observe that increased reliance on rainfed crop production may be necessary in the future to reduce the pressure on water for irrigation in water-scarce regions. Our results suggest, however, that a number of trade-offs need to be considered regarding the use of both scarce land and scarce water. Under the Diet and Technology scenario, S2.3, operating with sustainable endowments of land and water, both global land use and global withdrawals of water are lower than under the Extensive scenario, S1. One systematic shift that makes this possible is that water for irrigation is devoted to higher-value crops under S2.3 while grains are now grown rainfed.

By applying the Rectangular Choice of Technology framework, we are able to allow a region the choice among alternative technologies including the option of operating them simultaneously. The full integration of RCOT into the World Trade Model allows for both intraregional and inter-regional substitutions among technologies, that is, among multiple factors and intermediate inputs considered simultaneously, subject to their utilization in physically plausible combinations (quantified in the columns of coefficients in A^* and F^*). The RCOT approach is equally suited for representing, say, technologies for generating the homogeneous output of electric power in kWh using nuclear, fossil fuel, or renewable sources subject to production capacity constraints, and it should prove valuable for studying the implications of limited availability of other factors of production besides land and water.

The input-output database for this study has been expanded by the representation of alternative technologies and resource endowments compiled from diverse sources. Our quantitative representation of technological options is highly simplified; hopefully the insights provided by the results can justify devoting substantial effort to building a library of alternative farming technologies directly based on expertise in this area. Particularly vital is the development of standardized, operational definitions of what constitutes the "stock" for individual resources. Resource endowments should figure into every economic analysis of future resource constraints, but the necessary data are scarce. Fortunately, several new input-output databases of the world economy of unprecedented comparability and scope, including detailed environmental data, are in the process of becoming available (Dietzenbacher et al.,[48] Lenzen et al.,[49] and Tukker et al.).[42]

The productivity improvements offered by new technologies, and restrictions imposed by formal legislation on access to scarce resources, will have to be accompanied by the willingness of citizens of affluent societies to embrace less resource-intensive lifestyles, which then have the chance of being emulated in the aspirations of people in other places. The most resource-intensive personal activities surround diet, housing arrangements, and motorized transport (Hertwich et al.,[50] Jungbluth et al.,[51] and Nijdam et al.).[52] We have begun to address the potential impact of shifts in the composition of diet in this study. This is the easiest starting point, as individual households are in a position to initiate dietary changes simply by making different purchasing decisions at the supermarket. Changes related to housing and mobility, by contrast, depend not only on household willingness but also on the nature of the existing housing stock and transportation infrastructure and many other aspects of the built environment. We recognize that policy initiatives may be necessary to incentivize such changes in lifestyles and technologies, and geopolitical realities may override economic considerations regarding future resource use. Nonetheless, we believe that the empirical results of this study are sufficiently informative as to suggest that the modeling approach utilized can be fruitfully applied to the analysis of many other kinds of scenarios as well.

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Notes

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