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Water and Land Resources and Global Food Supply

INTRODUCTION

The world population is expected to grow to 7.7 billion in 2020, from 5.3 billion in 1993 (UN, 1996). Although the latest population projections represent a slowdown from past estimates, the large absolute increase in population raises serious concerns about how food demand will be met in the next decades, especially in the context of a possibly stagnant or even decreasing stock of natural resources. These concerns have escalated sharply in recent years, in the face of dramatic increases in world cereal prices in 1996, combined with declining cereal stocks, and the simultaneous appearance of several widely read publications presenting the possibility of a starving world in the next century, unable to meet growing food demands from a deteriorating natural resource base (Brown, 1995; Tyler, 1995; Brown and Kane, 1994).

In this paper, we examine the prospects for global food supply and demand for the year 2020, in the light of the two most often identified natural resource constraints, land and water. We first briefly summarize recent trends in area, yield and production for cereal crops, the key staple crops for most of the world, describe the IMPACT global food projections model and present an overview of food demand and supply projections. We then ask whether land and water constraints will pose serious threats to long-term cereal production growth. In particular, we assess the effects of land degradation and land conversion to urban uses on agricultural production and the effect of increasing water scarcity on future global food supply. For the latter assessment, we develop projections of global water demand until 2020 that are consistent with the underlying assumptions in the global food projections. We conclude with implications for land and water policy.

GLOBAL FOOD DEMAND AND SUPPLY

Table 1 summarizes recent trends in area, production and yield for cereals for the periods 1967–82 and 1982–94, which roughly divide the period 1967–94

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TABLE 1 *Crop area, production and yield growth rates, 1967–94 (per cent per year)*[1]

	1967–82			1982–94		
	Area	Prod.	Yield	Area	Prod.	Yield
Wheat						
Developing	1.45	5.39	3.88	0.42	2.94	2.52
Developed	–0.12	1.73	1.87	–1.38	–0.03	1.35 USA
World	0.48	2.88	2.40	–0.59	1.20	1.80
Maize						
Developing	0.65	3.46	2.80	1.36	3.66	2.27
Developed	0.64	3.05	2.33	–0.26	0.69	1.01 USA
World	0.64	3.20	2.52	0.77	1.93	1.16
Rice						
Developing	0.81	3.21	2.38	0.21	2.03	1.81
Developed	–0.23	–0.14	0.09	–0.28	0.34	0.61 USA
World	0.78	2.96	2.17	0.20	1.94	1.74
Other grains						
Developing	–0.87	1.20	2.08	0.12	0.03	–0.09
Developed	0.52	1.32	0.79	–1.63	–0.78	0.85 USA
World	–0.15	1.28	1.43	–0.79	–0.52	0.26
All cereals						
Developing	0.48	3.36	2.87	0.46	2.34	1.87
Developed	0.23	1.92	1.69	–1.27	0.01	1.30 USA
World	0.37	2.61	2.24	–0.24	1.27	1.51

Note: [1] Based on three-year moving averages.

Source: Basic data, FAO (1997).

into a peak 'green revolution' period and a post 'green revolution' period. Global growth rates of cereal production declined substantially, from 2.6 per cent per year in 1967–82 to 1.3 per cent per year after 1982, mainly owing to a contraction of area harvested in the developed world and to a slowdown in growth of crop yields in both developing and developed countries. The pattern of global cereal yield growth also shows a significant slowdown, from 2.2 per cent per year in 1967–82 to 1.5 per cent per year in 1982–94. In the developed countries, the slowdown in crop area, yield and production growth was primarily policy-induced, with European and North American governments scaling back farm-price support programmes and cutting down on cereal stocks. In addition, the economic collapse and subsequent struggles with economic reform in the former Soviet Union and Eastern Europe further depressed production during the 1990s. In the developing countries, declining cereal prices have led to a direct shift of land out of cereals into more profitable crops and to a slowdown in growth in input use and in investment in research and irrigation infrastructure, with consequent detrimental effects on yield growth (Rosegrant and Pingali, 1994). At the same time, the achievement of relatively high cereal yields in parts of Asia, high input levels and increased land intensity slowed further increases in yields (ibid.; Byerlee, 1994).

The global food projections model

Projections of global food supply and demand have been made using an updated model of IFPRI's International Model for Policy Analysis of Commodities and Trade (IMPACT) (see Rosegrant *et al.*, 1995, for details of the original work). The model covers 37 countries and regions, and 17 commodities, including all cereals, roots and tubers, soybeans and meats. The model is specified as a set of country-level supply and demand equations, where each country model is linked to the rest of the world through trade. Demand depends on prices, elasticities, income and population growth, and incorporates the dynamic adjustment of income elasticities with respect to income growth. Prices and the rate of productivity growth determine growth in commodity production in each country, while it is also influenced by advances in public and private agricultural research and development, extension and education, markets, infrastructure and irrigation. The crop supply side now incorporates the effect of irrigation expansion as a separate variable that directly affects area harvested and yields. In this model, we have updated population data with the most recent United Nations projections (UN, 1996) and the baseline production and consumption data, on which projections are being made, have been updated to 1993.

Projected world food prices

The baseline results of IMPACT suggest that world prices of cereals will fall, but at a slower rate than in recent years. Cereal prices on average are projected to drop by 11 per cent by 2020. The slow decline in prices will be accompanied by rapidly increasing world trade in cereals, with the developing countries as a group increasing imports from the developing countries. Net cereal imports of developing countries will more than double by 2020, reaching 228 million metric tons (mt.).

Projected demand for cereals

Changing patterns of demand are apparent in the projected growth rates in food and feed demand shown in Table 2. In many developing countries, strong income growth, rapid urbanization and changing tastes and preferences will cause a shift to more diversified diets, with higher per capita consumption of meat, dairy products, fruits and vegetables. Growth rates in total cereal

TABLE 2 *Increase in total demand for cereals, by region, 1993–2020 (million metric tonnes)*

	Wheat	Maize	Rice	Other grains	All cereals
China	40.3	79.3	21.0	5.1	145.7
India	39.2	3.2	35.4	6.8	84.6
Other East Asia	3.4	11.0	1.2	0.7	16.3
Other South Asia	27.4	2.1	15.8	0.8	46.2
Southeast Asia	7.5	18.0	28.2	0.5	54.2
Latin America	12.8	40.5	7.8	9.4	70.5
WANA	51.2	9.9	6.5	20.9	88.4
Sub-Saharan Africa	10.3	28.1	11.9	34.2	84.5
USA	7.8	43.0	1.1	5.8	57.7
Western Europe	5.2	3.9	0.3	7.3	16.7
Eastern Europe & CIS	10.8	3.9	0.1	17.9	32.7
Other developed	6.7	5.3	–0.04	7.6	19.6
Developing	192.4	192.3	128.0	78.3	591.1
Developed	30.5	56.1	1.5	38.6	126.7
World	222.9	248.4	129.5	116.9	717.8

Source: IFPRI, IMPACT simulations.

demand will decline, owing to both changes in the diet structure and a continued gradual slowdown in population growth. Global per capita consumption will be virtually constant, with declining consumption of cereals at higher income levels balancing the increasing demands of lower-income countries. Total cereal demand will increase by about 718 million mt., from 1773 million mt. in 1993 to 2491 million mt. in 2020. More than 80 per cent of this change will come from the developing world, where increases in population and income will be more pronounced than in the developed world. China and India together will account for more than 30 per cent of the increase in global food demand. Additional demand for meat will lead to a strong expansion in the use of maize and other cereals for animal feeds, especially in the more rapidly growing developing economies, which will experience rapid growth of their livestock industries.

Projected area and yield growth for cereals

How will the expanding cereal demand be met? Expansion in area will almost cease to contribute to future production growth, with a total increase in cereal area of only 39 million hectares (ha) by 2020, from 700 million ha in 1993 (Table 3). Of this growth, 88 per cent will originate in developing countries, in particular sub-Saharan Africa, which accounts for almost 60 per cent of expan-

TABLE 3 *Crop area harvested, cereal crops, by region, 1993–2020 (million hectares)*

	1993	2020	Increase, 1993–2020
China	88.6	89.1	0.5
India	99.4	101.2	1.8
Other East Asia	3.7	3.3	–0.4
Other South Asia	26.7	27.5	0.8
Southeast Asia	47.2	48.2	1.0
Latin America	47.9	54.0	6.1
WANA	55.6	57.4	1.8
Sub-Saharan Africa	62.4	85.4	23.0
USA	63.3	65.3	2.0
Western Europe	36.8	37.2	0.4
Eastern Europe & CIS	127.3	129.0	1.7
Other developed	41.0	41.6	0.6
Developing	431.6	466.2	34.6
Developed	268.5	273.1	4.6
World	700.0	739.3	39.2

Source: IFPRI, IMPACT simulations.

sion in area harvested. The projected slow growth in area places the burden of meeting future cereal demand on crop yield growth. Although that will vary considerably by commodity and country, a further decline is projected compared with the already reduced rates of the 1982–94 period. The global yield growth rate for all cereals is expected to decline from 1.5 per cent annually in 1982–94 to 1.1 per cent in 1993–2020. For developing countries, wheat yield growth will drop from 2.5 per cent to 1.3 per cent per year, maize yield growth will decrease from 2.3 per cent to 1.4 per cent, and rice yield growth will decline from 1.8 per cent to 1.1 per cent per year. In developed countries, average crop yield growth is projected to slow from 1.3 per cent to 0.9 per cent per year (Table 4).

Can the crop area, yield and production growth rates projected here be attained? To what extent will land and water quality and availability limit the ability to attain the necessary production to meet the demands of rising populations and incomes? The following sections of the paper examine these possible constraints and discuss their implications for global food supply and land and water policy.

TABLE 4 *Projected annual cereal yield growth rate, 1993–2020 (per cent per year)*

	Wheat	Maize	Rice	Other grains	All cereals
China	0.88	1.40	0.69	0.39	0.98
India	1.53	1.75	1.43	0.80	1.42
Other East Asia	1.38	1.88	0.47	0.51	0.84
Other South Asia	1.45	1.84	1.50	0.62	1.50
Southeast Asia	0.29	1.79	1.19	0.50	1.30
Latin America	1.64	1.25	1.94	0.98	1.37
WANA	1.70	1.39	1.81	2.20	1.85
Sub-Saharan Africa	1.29	1.80	1.88	1.52	1.67
USA	1.24	0.87	1.13	0.75	0.96
Western Europe	0.35	0.67	0.94	0.40	0.42
Eastern Europe & CIS	1.24	1.22	0.45	0.99	0.75
Other developed	1.60	0.98	0.06	0.74	1.37
Developing	1.30	1.36	1.08	1.24	1.20
Developed	1.06	0.84	0.53	0.78	0.94
World	1.17	1.03	1.05	0.85	1.06

Source: IFPRI, IMPACT simulations.

LAND AND WATER AS LIMITING FACTORS TO GLOBAL FOOD SUPPLY

Cropland potential and land loss to urbanization

Total crop area harvested was 1593 million ha in 1993, of which 1077 million ha were in the developing world, and 516 million ha in developed countries (FAO, 1997). Cereal crop area harvested was 700 million ha in 1993: 269 million ha in the developed world, and 432 million ha in the developing world. It is expected to increase by 39 million ha by 2020, almost all of which will be accounted for by developing countries (see Table 3). Can the existing land base support this increase in cereal crop area harvested?

In order to estimate cropland potential, the entire land area that could be converted to agricultural uses must be taken into account. According to FAO (1997), in 1994, total land resources were 13 044 million ha, of which 1353 million ha were classified as arable land, 114 million ha as having permanent crops, 3399 million ha as pasture, 4172 million ha as forest and woodland and 4003 million ha as other land, including built-on areas, roads and barren land. Out of this area, Buringh and Dudal (1987) identified 700 million ha as prime agricultural land and 2600 million ha with low or medium capability for crop production. This would yield a potential land area suitable for crop production of at least 3300 million ha, and an additional crop area potential of 1833 million ha.

As most of the currently cultivated land is relatively good or prime agricultural land, the productivity of other land forms converted into cropland is expected to be lower than the existing land stock. Conversion may also eliminate forest and rangelands with important functions in their present uses. According to Kendall and Pimentel (1994), the world's arable land might be expanded at most by 500 million ha, at a productivity below present levels. Most of the potential cropland (about 87 per cent) is located in developing countries, mainly in sub-Saharan Africa and Latin America. In Asia, on the other hand, nearly 80 per cent of the potentially arable land is already under cultivation, and local cases of land scarcity for agricultural production have been reported from China, Indonesia and elsewhere in Asia (Plucknett, 1995). Although global per capita arable land has been decreasing steadily, from 0.35 ha in 1970 to 0.24 ha in 1994, per capita area harvested has declined much more slowly, from 0.23 ha to 0.20 ha in the same period. It is rarely noticed that the ratio of crop area harvested to arable land, which represents an aggregate cropping intensity index, has improved steadily over the past three decades, from 1.05 in 1970 to 1.20 in 1994 for the world, and from 1.28 to 1.56 for developing countries during the same period, making it less necessary to bring new land under cultivation (computed from FAO, 1997).

The world's urban population is expected to be more than 5 million by 2025, implying an overall urban growth rate of 2.3 per cent from 1995, and 61 per cent of the population in urban areas, up from 38 per cent in 1975. With the urban population being nearly stable in Europe and North America, about 90 per cent of the urban population growth will occur in developing countries, where roughly 200 000 people will be added to the urban population every day between 1995 and 2025. In China, the share of urban population is expected to triple between 1995 and 2025 and, in much of the rest of Asia, it is projected to double. Sub-Saharan Africa is expected to have more than half of its population living in urban areas by 2025, Latin America 85 per cent, and West Asia and North Africa (WANA) 75 per cent (WRI, 1996).

There is no doubt that this rapid urbanization will remove some agricultural land from production. Indeed, the conversion of land from agricultural uses to higher-value uses on the fringes of urban areas is part of the process of economic development, generating in most cases significant economic benefits (Crosson, 1986; Moya *et al.*, 1994). Biased urban and industrial growth strategies, together with the neglect of the agricultural sector, have also led to significant damage to prime agricultural land (Bhadra and Brandão, 1993). However, there is little evidence that the process of land conversion to urban uses poses a serious threat to future global food production. For developing countries, urbanization is expected to lead to the conversion of 476 000 ha of arable land annually, amounting to a loss of 14 million ha between 1990 and 2020 (USAID, 1988).

The projected increase in crop area of 39 million ha necessary to meet global food demand by 2020 is much lower than both the theoretical maximum additional potential crop area of 1833 million ha and the more realistic potential for economically feasible conversion of land resources to agricultural uses of 500 million ha. A possible loss of 14 million ha of agricultural land to urban uses in the developing countries appears small compared to potential expansions in crop area, and the continued increases in cropping intensity on existing cultivated area. Thus the lack of potential crop area *per se* cannot be considered a major constraint to future agricultural production growth.

Physical limits to crop productivity

Global food production can be increased through expansion of areas and increases in cropping intensity (extensification), or through increases in agricultural productivity (intensification). Crop area harvested, as projected in IMPACT simulations, is expected to grow only slowly. Thus increases in agricultural productivity will have to come from improved yields. Will agricultural productivity as the main engine of agricultural production growth be able to keep up with global food requirements in the face of current and future challenges? Are the projected 1993–2020 yield growth rates biologically achievable?

The earth's biophysical limit of food production is reached when all agricultural land is cultivated and irrigated, maximum potential yields are attained and the remaining suitable grazing land is grazed. The specific upper limit to crop yield is determined by soil type, climate, crop properties and available irrigation water; it is reached when the farmer selects the optimal combination of crop species and management practices (Penning de Vries *et al.*, 1995). Maximum theoretical yields are calculated for specific crops as the highest limit of biological potential for a given location on the basis of photosynthetic potential, land quality, length of the growing season and water availability. Maximum theoretical yields in grain equivalents have been calculated by Linneman *et al.* (1979) and Luyten (1995), and range from about 7.6 mt. per hectare per season in the former Soviet Union to just over 8 mt. per hectare per season for China, India and the rest of South Asia, and in excess of 9 mt. per hectare per season in Southeast Asia, sub-Saharan Africa, North America and Western Europe. Yield levels simulated by IMPACT for 2020 are all well below the maximum theoretical yields. Thus, despite the slowdown in yield growth over the past 15 years, overall trends by country and region indicate ample room for yield improvement for most crops and regions (Plucknett, 1995). However, continuing investment in agricultural research will be essential for maintaining current trends in yield growth and to further increase the yield potential.

Land degradation

The most comprehensive assessment of global land degradation, Oldeman *et al.* (1990), classifies the main types of land degradation as soil erosion from wind and water, chemical degradation (loss of nutrients, soil salinization, urban–industrial pollution and acidification) and physical degradation (compaction, waterlogging and subsidence of organic soils). Out of the total land resource base, Oldeman *et al.* estimated that 1964 million ha suffered from some degree of degradation. Water erosion accounted for 56 per cent of land degradation, wind erosion for 28 per cent, chemical degradation for 12 per cent and physical degradation for 4 per cent. However, for the estimated 562 million ha of degraded agricultural land, chemical degradation was much more important, accounting for 40 per cent of degraded land. Degradation leads to reductions in crop yields, may reduce total factor productivity by requiring the use of higher input levels to maintain yields, may lead to the conversion of land to lower-value uses and may cause temporary or permanent abandonment of plots.

Estimates of the crop production impacts of land degradation are rare. Comprehensive country-level studies have only been undertaken for the United States (Alt *et al.*, 1989; Crosson, 1986). These studies found very small long-term yield effects due to soil erosion: if erosion rates continued at the same rate as in 1982 for 100 years, national average yields in the United States would be 3–10 per cent lower than in the absence of erosion (Crosson and Anderson, 1992).

Crosson (1995), based on the Oldeman *et al.* analysis, estimated the 1945–90 cumulative crop productivity loss due to land degradation to be about 5 per cent, which is equivalent to a decline of 0.11 per cent per year. While this is not an insignificant loss, the impact of degradation was dwarfed by crop yield growth of 1.9 per cent annually during 1967–94. Crop yield losses due to past erosion show cumulative crop yield reductions that range from 2 per cent to 40 per cent across African countries, with a mean of 8.2 per cent for the continent and 6.2 per cent for sub-Saharan Africa (Lal, 1995, as cited in Scherr and Yadav, 1996). These national-level estimates confirm that land degradation can be devastating in some countries, especially in fragile environments within sub-regions of countries. However, estimated rates of land degradation and estimations of subsequent yield losses are relatively small and do not in general imply a threat to global food production. Furthermore, even these relatively small losses may considerably overstate the net impact of soil erosion, as eroded soil is often not lost to agricultural production, but rather deposited elsewhere on productive cropland or pasture (Crosson and Anderson, 1992). Thus, in many cases, soil erosion is a redistribution of crop production rather than a production loss.

Policies to counteract degradation should be aimed towards the zones of high risk and could include public investments in research, technology development, extension services and rural infrastructure, in order to stabilize or reverse degradation. Land degradation can also be mitigated through broader policy reforms, such as the establishment of property rights to land, market and price reforms, and the elimination of subsidies to agricultural inputs.

Water as a constraint to global food supply

In the following sections we examine whether water scarcity could limit the needed expansion in food production. The available annual renewable freshwater supply is estimated to be 9000–14 000 billion cubic metres (BCM)

(Rosegrant, 1997). Given the current global use of water of around 3700 BCM, the freshwater supply would be adequate to meet growth in demand for the foreseeable future, if supplies were distributed equally across the world's population. Freshwater, however, is distributed unevenly across the globe. While per capita water availability is highest in Latin America and North America, and lower in Africa, Asia and Europe, these regional figures also hide the huge variability in water availability. Freshwater is poorly distributed across countries (Canada has 120 000 cubic metres per capita per year of renewable water resources; Kenya has 600 cubic metres; and Jordan, 300 cubic metres), within countries (although India has adequate average water availability of 2500 cubic metres per capita, the state of Rajasthan has access to only 550 cubic metres per person annually), and across seasons (Bangladesh suffers from monsoon flooding followed by severe dry season water shortages) (ibid.). Moreover, with a fixed amount of renewable water resources supplying an increasing population, per capita water availability has declined steadily. Between 1950 and 1980, per capita water availability declined from 9600 cubic metres to 5100 cubic metres in Asia, and from 20 000 cubic metres to 9400 cubic metres in Africa (Ayibotele, 1992).

Water demand

Tightening water supplies have been accompanied by rapid growth in demand for water. Between 1950 and 1990, water use increased by more than 100 per cent in North and Latin America, by more than 300 per cent in Africa and by almost 500 per cent in Europe (Clarke, 1993). Global demand for water has grown by 2.4 per cent per year since 1970. Some key characteristics of water demand are presented in Table 5. Annual per capita domestic withdrawals in 1995 ranged from a high of 240 cubic metres in the United States to only 11 cubic metres in sub-Saharan Africa, a level that is just over one-half of the 20 cubic metres per capita estimated by Gleick (1996) to be required to meet the most basic human needs. China, India and other South Asian countries are all at or just above this basic human needs level. Southeast Asia, Latin America and WANA cluster at 56 cubic metres to 65 cubic metres per capita. For developing countries as a group, per capita water demand was 33 cubic metres in 1995, less than one-fourth the amount in developed countries.

The industrial water use (or withdrawal) intensity is defined as the amount of water used per one thousand US dollars of total GDP (cubic metres per US$1000). Intensity is affected by the share of industry within the economy, the proportion of different types of activity in industrial production and the efficiency of water use in individual industries. Among the developing countries, in general, the higher the per capita income, the lower the industrial water use intensity. Developed countries averaged 27 cubic metres per US$1000, compared to developing countries at 40 cubic metres per US$1000 (Table 5).

TABLE 5 *Irrigated area, per capita domestic water withdrawal, income elasticity for domestic withdrawal, and industrial water withdrawal intensity, 1995 and projected 2020*

Country/region	Irrigated area (million ha)		Income elasticity for domestic withdrawal	Industrial withdrawal intensity (m^3 per US$1000)		Per capita domestic withdrawal (m^3 per capita)	
	1995	2020		1995	2020	1995	2020
China	50.1	53.1	0.8	74	71	25	71
India	51.3	68.6	1.0	88	86	20	54
Other East Asia	2.9	2.9	0.2	25	23	77	98
Other South Asia	25.0	29.3	1.0	64	64	21	41
Southeast Asia	14.4	16.2	*a*	60	49	56	87
Latin America	17.3	18.7	0.6	23	23	65	82
WANA	24.3	31.2	0.6	28	27	56	70
Sub-Saharan Africa	5.0	7.4	1.2	38	38	11	15
USA	21.5	22.4	0.0	34	27	240	240
Western Europe	11.9	12.3	0.0	17	15	94	94
Eastern Europe & CIS	24.8	26.3	*b*	177	170	89	103
Other developed	7.4	7.6	*c*	12	10	169	180
Developing	190.2	227.4		40	43	33	59
Developed	65.6	68.6		27	22	135	147
World	255.8	296.0		29	28	56	75

Notes:
[a] Malaysia: 0.1, Indonesia, Philippines, Thailand: 0.4, Vietnam: 0.5, Myanmar, Others: 0.8.
[b] Eastern Europe: 0.2, former Soviet Union: 0.4.
[c] Japan: 0.0, others: 0.1.

Sources: 1995 estimates of per capita domestic withdrawal, WRI (1994) and Raskin *et al.* (1997); income elasticity for domestic water withdrawal, IFPRI estimates; industrial water withdrawal intensity, WRI (1994) and Raskin *et al.* (1997); irrigated area, 1995 value interpolated from FAO (1997).

Projections of water demand to 2020

To understand the critical importance of water as a possible constraint to future agricultural growth, this section examines the future growth in water demand, and presents projections of water demand to 2020 that are consistent with the 2020 food supply and demand projections from IMPACT. Key underlying assumptions on growth in population, income and irrigated area are taken directly from the food supply and demand projections. Although water demand would ideally be defined as consumptive use of water, it is approximated here by water withdrawals, owing to a lack of consistent data on consumptive use at the national or regional level.

Irrigated area growth is based on recent past trends, including rates of changes in these trends, and on our assessment of planned investment in irrigation. Projected growth rates in irrigated area are significantly lower than in the recent past. Irrigated area in developed countries is projected to increase by only 3 million ha between 1995 and 2020, at an annual growth rate of only 0.2 per cent, compared with one of 0.8 per cent between 1982 and 1993. In developing countries, an additional 37.2 million ha of irrigated area is projected by 2020, at an annual rate of increase of 0.7 per cent, compared to 1.7 per cent per year from 1982 to 1993. For the world as a whole, irrigated area is projected to grow at 0.6 per cent per year, compared with 1.5 per cent during 1982–93. The largest increase is expected in India, with 17.3 million ha, as public investment in irrigation has remained relatively strong and public investment in tubewells has been very rapid. However, even in India, the projected 1995 to 2020 rate of growth in irrigated area of 1.2 per cent per year is well below the rate of 2.0 per cent per year during 1982–93 (Table 5).

Per capita demand for domestic water is a function of income growth and the income elasticity. The elasticities (Table 5) are synthesized from available information, which is sparse both at the aggregate, cross-country level (see Rock, 1996) and within countries. The available evidence indicates that water demand is highly elastic at low income and low water use levels, and that the elasticities for domestic water decline gradually as income and water use rise (see Table 5). Particularly strong growth in per capita domestic demand is projected for China and India, spurred by high income growth and supported by strong income elasticities: demand will nearly triple in China, to 71 cubic metres, while in India a 270 per cent increase will bring demand to 54 cubic metres per capita. In other South Asian countries, per capita domestic demand will almost double to 42 cubic metres. Sub-Saharan Africa, on the other hand, will experience the smallest increase in per capita domestic water demand in the developing world, as GDP growth will barely outpace population growth, resulting in slow growth in per capita income. For developing countries as a group, per capita domestic water demand is projected to increase by 79 per cent, to 59 cubic metres. The increase is much lower in developed countries, from 135 cubic metres to 147 cubic metres per capita (Table 5).

To project industrial water needs to 2020, it was assumed that the United States and other developed countries (except Japan) will reduce intensities by 20 per cent by 2020, reflecting continued long-term improvements in efficiency of industrial water use. Western Europe and Japan, which have already reached low industrial water use intensities, are assumed to achieve an additional 10 per cent reduction. Water use intensities for Eastern Europe, the former Soviet Union and the developing countries are projected using a 'convergence' algorithm developed by Raskin *et al.* (1995). Intensities in these countries converge towards the 2020 levels of the OECD countries in proportion to the rate at which their 2020 per capita GDP approaches the 1990 per capita GDP of the OECD countries. By postulating convergence towards the 2020 OECD water use intensities, rather than 1990 levels, the algorithm allows for 'leapfrogging'; that is, the developing countries can take advantage of improved water use and industrial processing technologies that were not available to OECD countries during their earlier development stages (ibid.).

As can be seen in Table 5, the actual degree of convergence achieved during the 1995–2020 period is limited. Because of the very low 1995 income levels in most of the developing countries, only a relatively small portion of the income gap is closed by 2020, even with fast growth rates in income. The biggest improvement (and degree of convergence) in industrial withdrawal intensity will be in Southeast Asia, where the initial per capita income level is fairly high, and per capita income growth is fast: industrial water withdrawal intensity is expected to improve by 18 per cent, from 60 cubic metres to 49 cubic metres per US$1000. Even though all of the developing countries and regions will have equal, or improved, intensities by 2020, the figure for developing countries as a whole will be increasing from 40 to 43 cubic metres per US$1000, because the most rapid growth in industrial demand occurs in countries with high water use intensities, in particular China and India.

Global average water withdrawal for irrigation (computed by dividing agricultural withdrawal by irrigated area) was estimated to be 10 259 cubic metres per hectare, with slightly higher figures in developing than in developed countries. Although there is a fairly wide range of experience across regions, it is difficult to know whether such cross-country variation corresponds to differences in irrigation practices, or technology, or the cropping pattern used on irrigated areas. The domestic and industrial water withdrawals shown in Table 5 conform broadly to the expected cross-country pattern relative to levels of economic and technological development. However, it is not even clear what the expected cross-country pattern of irrigation withdrawals should be, since cross-section and time-series data are virtually non-existent.

There is technological potential for improved irrigation practices that would reduce water withdrawals per irrigated area, but there is little evidence that this is actually occurring. In the United States, where data are available, water withdrawals per hectare of irrigated area increased by 35 per cent between 1960 and 1975, declined by about 15 per cent from 1975 to 1980, increased again, and in 1990 was still higher than the 1975 level (Raskin *et al.*, 1995). Given limited and mixed evidence, irrigation withdrawals were assumed constant for the projections period. Globally, water withdrawals are projected to increase by 35 per cent by 2020, to 5060 billion cubic metres (BCM) (Table 6), with growth in developing countries much faster than in developed countries. Developed countries as a group will increase water demand by 22 per cent to 1710 BCM, more than 80 per cent of which will be for industrial uses. The serious pressure on water resources, however, will be in the developing world, where withdrawals are projected to increase dramatically, by 43 per cent, from 2347 BCM in 1995 to 3350 BCM in 2020. In sharp contrast to past growth patterns in developing countries, the absolute increase in domestic and industrial water demand will be greater than the increase in agricultural water demand, projected at 589 BCM and 415 BCM, respectively, from 1995 to 2020 (Table 6). The combined share of domestic and industrial use in total demand in developing countries will hence more than double, from 13 per cent to 27 per cent, representing a significant structural change in their patterns of water use.

China and Southeast Asia show the most dramatic transformation in water demand structure, driven by rapid economic growth and slower growth in

TABLE 6 *Global water withdrawals for domestic, industrial and agricultural uses, 1995 and projected 2020 (billion cubic metres)*

Country/region	1995				2020			
	Dom.	Ind.	Agr.	Tot.	Dom.	Ind.	Agr.	Tot.
China	30	35	439	504	101	146	465	712
India	18	24	564	607	69	91	755	916
Other East Asia	8	13	26	47	12	28	26	66
Other South Asia	6	6	308	321	20	21	364	405
Southeast Asia	27	29	169	225	57	112	189	358
Latin America	31	33	193	257	54	67	209	330
WANA	22	22	266	309	45	52	341	438
Sub-Saharan Africa	6	6	65	77	16	15	95	126
USA	64	221	207	492	78	305	215	598
Western Europe	36	125	95	256	36	195	98	329
Eastern Europe & CIS	37	146	270	453	43	208	284	535
Other developed	38	67	92	197	47	105	95	248
Developing	147	170	2 030	2 347	375	531	2 445	3 350
Developed	174	560	664	1 398	204	813	693	1 710
World	322	730	2 694	3 745	579	1 344	3 138	5 060

Sources: 1995 estimates from Raskin *et al.* (1997) and WRI (1994).

irrigated agriculture. China is projected to more than triple domestic use, and to increase industrial withdrawals fourfold. As a result, the combined share of domestic and industrial water demand in total demand will increase from 13 per cent in 1995 to 35 per cent in 2020 (Table 7). In Southeast Asia, a doubling of domestic water withdrawals and a 290 per cent increase in industrial demand will boost the combined share of these sectors in total water demand from 25 per cent in 1995 to 47 per cent in 2020. India is projected to have the largest absolute increase in water withdrawals in the world, at 309 BCM (virtually the same demand increment as for the developed world), owing to a combination of strong growth in domestic and industrial demand and relatively rapid expansion of use for irrigation. Total withdrawals in India will be up by 50 per cent from the 1995 levels, including a 34 per cent increase in those for agriculture, and a 280 per cent increase in the domestic and industrial sectors.

Meeting future water demands

Can the rapid growth in water demand, particularly in the domestic and industrial sectors, be met without massive transfers of water out of agriculture that could derail the projected growth in crop yield and area described? Development

TABLE 7 *Sectoral water withdrawals as a percentage of total withdrawals, 1995 and projected to 2020*

Country/region	1995			2020		
	Dom.	Ind.	Agr.	Dom.	Ind.	Agr.
China	6	7	87	14	21	65
India	3	4	93	8	10	82
Other East Asia	16	28	56	8	42	40
Other South Asia	2	2	96	5	5	90
Southeast Asia	12	13	75	16	31	53
Latin America	12	13	75	16	20	63
WANA	7	7	86	10	12	78
Sub-Saharan Africa	8	8	84	13	11	76
USA	13	45	42	13	51	36
Western Europe	14	49	37	11	59	30
Eastern Europe & CIS	8	32	60	8	39	53
Other developed	21	35	44	19	43	38
Developing	6	7	87	11	16	73
Developed	13	40	47	12	48	40
World	9	19	72	11	27	62

Source: 1995 estimates from WRI (1994).

of irrigation and water supplies has become increasingly expensive. In India and Indonesia, for example, the real costs of new irrigation have more than doubled since the late 1960s and early 1970s; costs have increased by more than 50 per cent in the Philippines; they have tripled in Sri Lanka and increased by 40 per cent in Thailand (Rosegrant and Svendsen, 1993). The cost of supplying water for household and industrial uses is also increasing rapidly. In Amman, Jordan, the average incremental cost of water from groundwater has been US$0.41 per cubic metre. However, with shortages of groundwater, the city has begun to rely on surface water, pumped with a lift of 1200 metres from a site 40km from the city, at an average incremental cost of US$1.33 per cubic metre. In Shenyang, China, the cost of new water supplies will nearly triple, from US$0.04 to US$0.11 per cubic metre between 1988 and 2000, because pollution of the current groundwater source will require a shift to water conveyed by gravity from a surface source 51km from the city. In Mexico City, water is currently being pumped over an elevation of 1000 metres into the Mexico Valley from the Cutzamala River through a pipeline about 180km long, at an average incremental water cost of US$0.82 per cubic metre. That is almost 55 per cent more than the previous source, the Mexico Valley aquifer (World Bank, 1993). Non-traditional sources of water are unlikely to be a major component of new water supplies. Desalination offers an infinite supply of freshwater, but at a high price, and will not be a significant factor in most regions. The reuse of waste water will similarly make an important contribution only in arid regions such as the Middle East, where the cost of new supplies is very high. Water harvesting (the capture and diversion of rainfall or floodwater to fields to irrigate crops) will be important in some local and regional ecosystems, but will not have a significant impact on global food production and water scarcity (Rosegrant, 1997).

If high costs of development choke off new sources of water, the rapidly growing household and industrial demand will need to be met increasingly from water savings from irrigated agriculture. A particularly difficult challenge will be to improve the efficiency of agricultural water use to maintain crop yields and output growth, while at the same time allowing reallocation of water from agriculture to rapidly growing urban and industrial uses. How this will be managed could determine the world's ability to feed itself.

To meet this enormous challenge, it will be necessary to generate physical savings of water and economic savings by increasing crop output per unit of evaporative loss, by increasing the utilization before it is lost to water 'sinks' and by reducing salinization and other pollution that diminishes crop yield per unit of water. It is unclear how large each of these potential water savings might be. Water use efficiency in irrigation in much of the developing world is typically in the range of 25 to 40 per cent, while in urban supply systems 'water unaccounted for' (much of which is direct loss to the oceans) is often 50 per cent or more in major metropolitan areas in developing countries (Rosegrant, 1997). These inefficiencies seem to imply the potential for huge savings from existing uses of water. However, the potential savings in many river basins are not as dramatic, nor as easy to achieve, as implied by these efficiency figures, because much of the water 'lost' from irrigation systems is reused elsewhere (Seckler, 1996). In these basins, efficiency gains from existing systems may prove to be limited, because whole-basin water use efficiencies are quite high as a result of recycling of drainage water, even though individual users are inefficient. For example, estimates of overall water use efficiencies for individual irrigation systems in the Nile Basin are as low as 30 per cent, but the overall efficiency for the entire Nile river basin is estimated at 80 per cent (Keller, 1992).

Important research remains to be done on the issue of physical and economic water savings. Definitive estimates of the potential for improving crop yields per unit of water applied, and the potential for maintaining crop productivity growth while transferring water out of agriculture, require basin-specific analysis, with aggregation to the global level to assess the likely effects on food security. Can significant real water savings be achieved through improved water management policies? What would be the impact on food production and food security of transfers of saved water out of agriculture?

Implications for water policy

Although important questions must still be answered, a clear place to start in seeking water savings, improving water use efficiency and boosting crop output per unit of water is the reforming of existing water policies that have contributed to the current predicament: both urban and rural water users are provided with massive subsidies on water use; irrigation water is essentially unpriced; in urban areas the price of water does not cover the cost of delivery; and capital investment decisions in all sectors are divorced from management of the resource. These water-wasting policies can be attacked through comprehensive reforms to improve the incentives at each level of the allocation process. Institutional and legal environment reforms must empower water users to make their own decisions regarding resource use, while at the same time providing a structure that reveals the real scarcity value of water. Key elements for reform include establishment of secure water rights to uses; decentralization and privatization of water management functions; and utilization of incentives including markets in tradable property rights, pricing reform and reduction in subsidies, and effluent or pollution charges. Non-market instruments, such as licensing and regulation, and direct interventions, such as conservation programmes, can also play an important role. Failure to address the increasing demand for water could significantly slow the growth in crop production in developing countries.

CONCLUSIONS

In this paper, projections of future global food demand and supply were confronted by possible future limitations on land and water resources. Cropland availability is not a significant impediment to future global food supply. The primary constraint to further crop area expansion is not a physical limit, but the anticipated continued decline of real cereal prices, which makes further expansion of cropland unprofitable. On a global basis, the impact of land degradation on yields is small compared to projections of crop yield growth due to technological change and increased efficiency of input use. Degradation should be attacked by correcting policy and institutional failures, especially the failure to establish secure rights to land, which leads to overuse or overextraction, and the lack of investment in efficient use and conservation of the resource; market and pricing failures, including inappropriate subsidies that fail to account for the external costs of different activities and decisions; and government failures, in terms of poorly managed bureaucracies, excessively extractive policies and inability to regulate environmental damage.

The rapid growth in water demand, particularly for domestic and industrial purposes, coupled with the escalating cost of development of new water sources, could be a more serious threat to future growth in food production. If high costs of new water resources require household and industrial demand to be met primarily through water savings from irrigated agriculture, projected growth in agricultural production could be threatened. Policy reforms will be urgently required to improve water use efficiency to maintain crop yields and output growth with less water. Key elements of these reforms closely parallel the necessary changes in land policy, such as the establishment of secure water rights to users; decentralization and privatization of water management functions; and utilization of incentives for water conservation, including markets in tradable water rights, pricing reform and reduction in subsidies, and effluent or pollution charges.

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