Global changes in diets and the consequences for land requirements for food

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Edited by B. L. Turner, Arizona State University, Tempe, AZ, and approved March 8, 2012 (received for review October 15, 2011)

Provision of food is a prerequisite for the functioning of human society. Cropland where food and feed are grown is the central, limiting resource for food production. The amount of cropland needed depends on population numbers, average food consumption patterns, and output per unit of land. Around the globe, these factors show large differences. We use data from the Food and Agriculture Organization to consistently assess subcontinental dynamics of how much land was needed to supply the prevailing diets during a span of 46 y, from 1961 to 2007. We find that, in most regions, diets became richer while the land needed to feed one person decreased. A decomposition approach is used to quantify the contributions of the main drivers of cropland requirements for food: changes in population, agricultural technology, and diet. We compare the impact of these drivers for different subcontinents and find that potential land savings through yield increases were offset by a combination of population growth and dietary change. The dynamics of the three factors were the largest in developing regions and emerging economies. The results indicate an inverse relationship between the two main drivers behind increased land requirements for food: with socioeconomic development, population growth decreases and, at the same time, diets become richer. In many regions, dietary change may override population growth as major driver behind land requirements for food in the near future.

global analysis | land use | historical trends | decomposition analysis

Throughout the world, agriculture provides human society with food. Since the emergence of large-scale agriculture, this crucial activity has been responsible for the largest environmental impacts of humans on natural systems: presently, the largest shares of human land and freshwater use (1, 2), biomass appropriation (3), and the alteration of the global nitrogen and phosphorus cycles (4, 5), and a significant contribution to energy use and greenhouse gas emissions (6), are associated with the provision of food. Within agriculture, croplands take a central and often limiting role. These lands are usually of high quality and, by generating food and feed crops, they provide the lion's share of the global food supply: in 2005, more than 90% of all food calories and approximately 80% of all food protein and fats available in the world were derived from croplands [Food and Agriculture Organization (FAO) of the United Nations, http://faostat.fao.org/].

The amount of cropland needed to supply a society with food depends on population numbers, the type of diet, and the food output per unit of land. Population, diets, and production techniques change over time and show large spatial variation. With socioeconomic development, population growth rates decrease (7) and diets change: typically, consumption of animal protein, vegetable oils, fruits and vegetables increases, while starchy staples become less important (8). These changes from staples toward richer diets imply that cropland demand of average diets will in general increase (9). By contrast, the introduction of new technologies leads to improvements in agricultural area productivity throughout time (10).

In this study, we assess the integrated effect of these changes on the amount of cropland needed to feed a person in different parts of the world during the a period of 46 y. We first describe recent changes in diets, yields, and population numbers, highlighting differences in these drivers across subcontinents and time and their influence on developments in land demand. This is followed by a structural decomposition analysis performed to quantify the impact of the three drivers individually. Our results provide insights into how projected changes in these drivers are likely to affect future demand for cropland globally and on subcontinental levels.

Results

Global Trends in Food Supply and Land Requirements for Food. The upper rows in Fig. 1 depict developments in food supply per capita (in kcal per person and day) throughout the world from 1961 to 2007, according to FAOSTAT food balance sheet data (http://faostat.fao.org/). The center rows in Fig. 1 show how much cropland was needed to provide for this food supply, i.e., the land required to feed one person in a given setting (in m^2 area harvested per person and year). The lower rows in Fig. 1 depict total cropland requirements for food of the respective regions (in Mha), thus accounting for population numbers.

With regard to food supply, at the global level, the most striking development was a continuous increase in the average availability of food calories per person during recent decades (from approximately 2,250 to approximately 2,750 kcal/person/d). The rates of change were different for the various food categories: in absolute terms, the strongest increases occurred in cereals, followed by vegetable oils and animal products. In relative terms, food categories linked to rich diets show higher rates of increase (e.g., stimulants, vegetable oils, vegetables, fruits, and animal products), compared with more basic food items that show slower relative increases (e.g., cereals) or even a decrease (e.g., roots and tubers and pulses). The global picture indicates relative gradual and continuous changes.

Increases in the total per capita food supply were not observed everywhere around the world: in some rich, developed regions such as Northern Europe and Oceania, levels remained virtually constant. At the other end of the development spectrum, the poor regions of Sub-Saharan Africa saw only modest increases in their prevailing low levels of available food, with Middle Africa experiencing a pronounced decrease. The highest rate of increase was observed in Eastern Asia; this was largely driven by rapid changes in China. This region exhibited by far the most drastic changes, with, above all, a more than fivefold increase in the supply of animal food calories per capita. The relative composition of average diets still differs markedly between regions. In most developing regions, cereals represent the staple of the

Author contributions: T.K. and S.N. designed research; T.K., M.J.I.R., and W.K. performed research; T.K., M.J.I.R., and S.N. analyzed data; and T.K. and S.N. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

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This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1117054109/-/DCSupplemental.

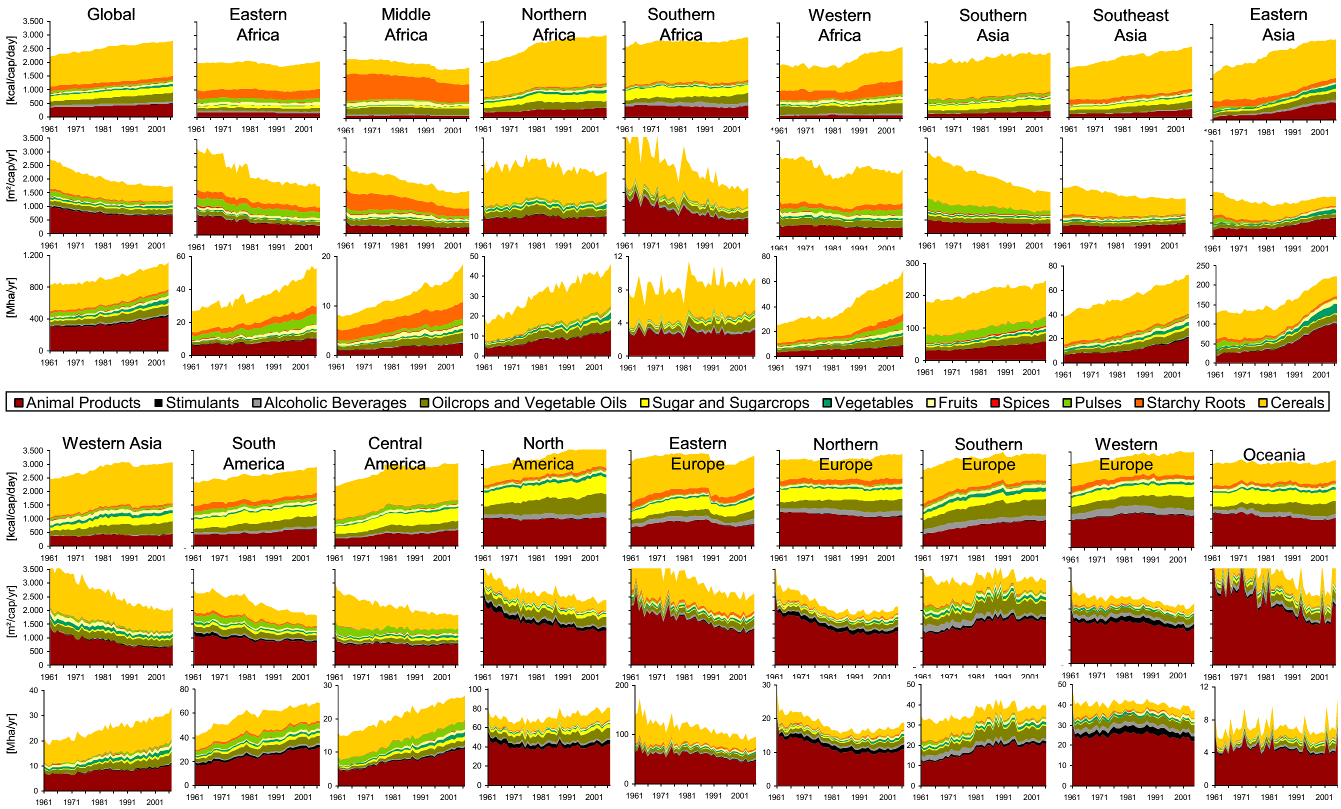

Fig. 1. Developments in per capita food supply (*Upper*), per capita cropland requirements for food (*Middle*), and total cropland requirements for food (*Lower*) at global and subcontinental levels for the period from 1961 to 2007; the values are presented according to 11 food categories; exact numbers can be found in Dataset S1.

diet, reaching shares of more than 60% in the food supply in Southern Asia. However, the share of cereals in the food supply was decreasing throughout the developing world, again with the fastest decrease in Eastern Asia. In most developed regions, the share of animal products was very high: throughout the entire period, they constituted approximately one third of the available calories, compared with values of 10% or less in many of the poorer regions. The one category that saw (mostly rapid) increases in all regions was vegetable oils and oilcrops.

The middle rows of Fig. 1 show how much land was needed to provide for the food supply depicted in the upper rows. At the global level, the average land area needed to feed a person in 2005 was two thirds of the corresponding value in 1963, decreasing from approximately 2,650 to just more than 1,700 m^2/person/y. The food categories contributing most strongly to this decrease were cereals, followed by animal products, pulses and root and tubers, and the categories of fruits and vegetables showed slight increases. During the study period, the category accounting for the largest share of land use shifted from cereals to animal products. Whereas the former category accounted for 40% of land requirements in 1963 and 31% in 2005, these values were 35% and 38% for the latter. The strongest relative increase occurred in vegetable oils: from 6% of the total in 1963 to 10% in 2005. Across the regions, per capita cropland requirements for food in 2005 were lowest in much of Asia, with approximately 1,300 m^2/person/y in Southeast Asia, followed by 1,450 m^2/person/y in East Asia and 1,550 m^2/person/y in Southern Asia. The highest values, with more than 3,000 m^2/person/y, were found in Oceania and Southern Europe, two dry regions with a large annual variability. Western Africa and Northern Europe, two regions at very different ends of the global spectrum in terms of per capita food supply, show the same per capita values in 2005, at approximately 2,350 m^2/person/y.

When looking at developments during the study period, decreasing per capita land requirements were a common feature throughout almost all subcontinents. This indicates that food production became more area-efficient around the globe. However, rates of decrease were different and developments were often nonlinear. The strongest relative decrease occurred in Southern Asia and Eastern Europe, two regions with high values at the beginning of the time series and limited dietary change. By contrast, hardly any decline occurred in Southern Europe and Eastern Asia, regions characterized by rapid dietary change. Cropland demand was dominated by food categories associated with rich diets in developed regions. For instance, the sum of animal products, stimulants, alcoholic beverages, and vegetable oils accounted for approximately 75% to 80% of land requirements throughout Europe and North America. For the poorest regions of Eastern, Middle, and Western Africa, the corresponding value for these four categories was 25%.

Finally, the lower rows of Fig. 1 put average per capita values into a global perspective by showing total cropland requirements for food, accounting for population numbers of the respective regions. At the global level between 1963 and 2005, a 30% increase, from approximately 840 to 1,100 Mha of cropland harvested, could be observed. This was mostly driven by growing land demand for animal products, which accounted for almost 50% of the total increase. Vegetable oils, vegetables, and fruits follow, contributing 20%, 12%, and 9%, respectively. These three categories also exhibited the largest relative increase during the study period, with 2005 levels more than twice as high as those in 1963. Although pulses were the only category showing a decrease in absolute numbers, cereals as well as roots and tubers increased only slightly. Looking at the different subcontinents, in 2005, Southern Asia had the highest total land demand for food, followed closely by Eastern Asia. Eastern Europe, which includes the states of the former Soviet Union, and North America follow at positions three and four. There are large differences in temporal trends: the highest relative increases occurred in Africa, with total land requirements more than doubling in some regions. The developed regions showed only limited increases or even decreases; this was the most pronounced in Eastern Europe, where, in 2005, values were less than two thirds of those in 1963. These trends also manifest in the fact that the share of Europe, North America, and Oceania in global cropland requirements for food decreased from 40% in 1963 to 25% by 2005.

Contributions of Population, Technology, and Diet to Changes in Land Requirements. Fig. 1 shows the added effects of dietary change (upper rows), technological change (middle rows), and population growth (lower rows) on cropland requirements for food. The structure of our calculation allows us to quantify the contributions of these three major drivers. We used the Logarithmic Mean Divisia Index (LMDI) decomposition method (11) to assess these contributions for all regions and three time periods (1963–2005, 1963–1984, and 1984–2005; *Methods*). Table 1 shows the result of the analysis for the global total and the different world regions arranged from the region with the largest absolute increase (Eastern Asia) to the region with the largest decrease (Eastern Europe); to allow for statements on relative changes, total cropland requirements for food in 2005 are displayed in Table 1.

At the global scale, the technology improvements were not sufficient to compensate for increases in population and changes in diets: global cropland requirements for food increased by approximately 270 Mha, or one fourth of the 2005 value, from 1963 to 2005. Population growth was the major driver behind the growing land demand. However, regional level results show large deviations from the global average. In many regions, land demand grew much faster, with values more than doubling during just four decades, with African regions seeing the largest relative increases. In large parts of Europe, cropland requirements for food remained constant or even decreased as technological improvements enabled compensation for the relatively slow population growth and minor changes in diets. In Eastern Asia and Southern Europe, regions with fast economic development (12), impacts of dietary change exceeded the population growth impacts. Comparing the first and second half of the study period reveals that, at the global level, the contribution of population declined while the impact of dietary change increased: dietary change contributed 24.6% to the sum of the impacts of diet and population change from 1963 to 1984; this value increased to 28.1% from 1984 to 2005. Additionally, Table 1 reveals that, compared with the first half of the study period, technological change contributed less to mitigate increasing land demand during the second half.

Discussion

The method used in this analysis enables consistent comparisons of land requirements for food in different subcontinents at different points in time and reveals the impact changes in drivers have had in this context. The numbers we present show marked similarities and differences between regions. Although a decrease in the area needed to feed an average person, with increasing food availability, seems a common feature, differences between diets remain large especially qualitatively. These variations in per capita food supply have been linked to differences in income levels (13, 14). By contrast, differences in per capita land requirements are less pronounced and not clearly linked to income levels. For instance, cropland demand for food per capita in much of Africa was in the same range as in Western Europe (approximately 2,000 m^2/person/y). These similarities in land requirements can be explained by large differences in output per unit land, while, at the same time, the diets of these two regions represent two extremes of the global spectrum. The high input agriculture in Western Europe is more area-efficient than cultivation methods in large parts of Africa. Although variability in climate and land quality may explain part of the difference, the findings indicate ample space for improvements in the average nutritional situation without increasing (per capita) land demand. However, there is no indication that the present rich Western diets with the most efficient production techniques will lead to land savings. Supplying the projected global population of more than 9 billion people in 2050 (15) with the present diet and agricultural technology of Northern America would mean that

Table 1. Additive decomposition according to contributions of changes in population, diet, and technology to overall changes in cropland requirements for food

Region	Cropland requirements for food in 2005	1963–2005				1963–1984				1984–2005			
		Δp	Δd	Δt	Δtot	Δp	Δd	Δt	Δtot	Δp	Δd	Δt	Δtot
World	1,105	682	239	−654	267	345	112	−391	66	314	123	−236	201
Eastern Asia	219	97	130	−139	88	53	52	−96	9	37	75	−33	79
Southern Asia	240	188	36	−164	60	97	14	−74	37	95	23	−96	23
Western Africa	63	46	11	−19	37	16	−2	−6	8	26	23	−20	29
Southeastern Asia	70	44	23	−37	30	23	10	−20	13	21	13	−17	17
Eastern Africa	53	45	−1	−19	25	18	−1	−12	6	24	−0	−4	19
South America	67	45	14	−34	25	25	4	−12	16	22	12	−25	9
Northern Africa	42	28	12	−15	25	14	8	−6	15	16	4	−10	9
Central America	26	19	7	−15	11	10	5	−9	6	9	2	−5	5
Western Asia	31	25	4	−19	11	13	4	−11	5	12	0	−7	6
Middle Africa	17	14	−1	−4	9	5	−1	−2	3	9	−1	−2	6
Southern Europe	39	7	13	−15	6	5	9	−9	6	2	4	−7	−0
Northern America	78	34	13	−42	5	15	4	−24	−4	17	8	−17	9
Oceania	8	4	−0	−3	1	2	−0	−1	1	2	−0	−1	1
Southern Africa	9	8	1	−7	1	5	0	−3	2	4	1	−5	−1
Western Europe	39	7	6	−16	−3	4	7	−12	−1	3	−1	−5	−2
Northern Europe	18	3	1	−9	−5	1	−1	−8	−7	1	1	−1	2
Eastern Europe	94	22	5	−81	−54	24	13	−70	−32	0	−6	−16	−22

Overall changes in cropland requirements for food (Δtot), according to the contributions of changes in population (Δp), diet (Δd), and technology (Δt). Values derived based on data presented in Fig. 1 using the LMDI decomposition method; following the totals of cropland requirements for food in 2005, the results are presented for three time periods: 1963–2005, 1963–1984, and 1984–2005. All values are presented in Mha of cropland area harvested per year.

cropland area had to be almost doubled; using Western Europe as a reference would still lead to an area expansion by more than 70%. Compared with an actual increase of approximately 30% during the past four and a half decades, this would imply tremendous additional pressures on the planet's resources.

Among the food categories accounting for increasing land demand, animal products are the most important ones, representing almost half the additional cropland requirements since the 1960s. Considering the vast areas of pastures and grasslands used for livestock grazing, their actual land requirements are even larger. These lands are typically of lower quality than cropland but large in quantity (1, 16). Consequently, meat and other animal products have been at the center of discussions on resource use for food and potentials for lowering this use (17, 18). However, our numbers also show that other food categories account for considerable increases in cropland requirements. Vegetable oils take the first place here, contributing one fifth of the increase during the study period. The category of stimulants, i.e., coffee, tea, and cocoa, also merits a closer look. These items are not consumed for their energy content but for their cultural role, and they contribute virtually nothing to caloric food supply. However, their claim on the land is considerable within consumption patterns of Western nations, reaching as much as 7% of total cropland requirements for food. Generally, the crops required for this consumption category are not grown within these regions themselves. This fact points to another issue: the growing importance of international trade in food products. The results presented indicate how much land was needed to provide the population of the respective regions with the prevailing diets. This is not necessarily equal to the amount of land under cultivation within a region. For instance, South America saw a striking expansion of agricultural lands during recent decades (FAOSTAT, http://faostat.fao.org). However, the total cropland requirements for food for this region did not increase greatly since 1980 (Fig. 1). Much of the expansion was indeed export-driven and used to provide for part of the increases in land demand elsewhere, e.g., in Eastern Asia (19, 20).

The results of the decomposition exercise highlight the very strong impact dietary change had on land demand in Eastern Asia, a region dominated by the dynamics in China. China's economic development has been rapid in the recent past, with average per capita income levels increasing more than tenfold from 1961 to 2007 (12). Many studies (13, 21) have focused on the rapid changes in food consumption patterns in this growing economy. A general pattern has been observed: as population growth rates decrease with socioeconomic development, per capita availability of food increases, and consequently average consumption patterns change markedly (13, 14). A closer look at Table 1 reveals that this pattern can also be recognized in the other developing regions, albeit at a slower pace. In most regions, during the second half of the study period, the contribution of the population growth to changing land requirements declined while the contribution of the dietary change increased. Our results also show developments in the opposite direction. In Eastern Europe, after the fall of communism, per capita income levels declined (12) and dietary change contributed to lower overall land requirements.

Our findings have far reaching implications for assessments of future land demand. The largest part of the global population lives in the developing regions, which are likely to exhibit high dynamics in the drivers behind land requirements within the coming decades. Until now, increasing global population numbers were the major driver behind increasing land use for food. However, projections on the stabilization of global population levels in the near future cannot be translated directly into prognoses on the stabilization of pressures on land resources needed for the provision of food. Ongoing dietary change will put considerable additional claims on these resources. To give an example, feeding 9 billion people with current Western diets produced with current Western technologies implies the need for almost twice the presently used cropland area.

Conclusion

The prospect of stabilizing population levels within the 21st century could also hold the promise of more stable patterns of future global land use. However, our analysis of past dynamics of land requirements shows that the socioeconomic development that helps to slow population growth is also linked to rapid dietary change. It suggests that pressures on land resources linked to the provision of food are likely to remain high in the coming decades, as these dietary changes affect a large share of the global population. Finally, recent increases in land use efficiency of food production, as highlighted in this study, were largely realized by steep increases in the use of external inputs, such as fertilizers, pesticides, fossil fuels, and irrigation infrastructure, all of which have substantial environmental impacts. Follow-up research should enhance our framework by consistently adding temporal trends in these inputs.

Methods

Our assessment of global and regional cropland requirements for food started with FAOSTAT data on food supply available as national/regional totals and per capita values (http://faostat.fao.org). These data indicate the amount of food available for human consumption at the household level for more than 90 food items. The values are assessed through a commodity balance model and include household level and retail wastes (22). They are, therefore, not equal to actual food intake but are commonly used and well suited for cross-country comparisons from a nutritional perspective (14). For all vegetal food items, we linked these data on food supply to land requirements through crop yields, i.e., the average amount output of a unit of land for the respective crop. To establish this link, where necessary, food items such as sugar and vegetable oils were converted to crop equivalents such as sugarcane and the respective oilcrop (details and factors used are provided in ref. 23). In this study, cropland requirements for food are defined as the area harvested in a given year to provide for the prevailing diet in the same year. As there are no data to consider multicropping practices consistently at the global level, we had to adopt this definition to allow for straightforward comparisons.

We used region-specific yields to assess cropland requirements for food in a given subcontinent. However, international trade poses a limit to this approach: food consumed in one area can originate from land within the region or from imports from outside the same region. To account for this, we split the amount of a crop available within a region into shares of domestic production and imports. This was done by considering the subcontinent's production of the crop and its imports of the same crop as well as products derived from it, for instance, soy oil imports for soybeans. The share from domestic soils was linked to the respective regional crop yield. For the import share, we performed a computation to assess the average world market yield: we calculated a weighted average of all exports of the respective crop by using the exporting countries' yields. For this purpose, we considered exports of crops as well as products processed from them. However, to exclude reexports from elsewhere, we include only exports originating from domestic production via the shares calculated as described earlier. These world market yields will be different from global average yields if the national yields of the main exporting nations differ from those of nonexporting major producers. To give an idea about the relevance of international trade flows, our calculations show that, in 2005, approximately 16% of global cropland requirements for food were met by imports from outside the country where the food was consumed; in 1963, this value was at 10%.

Compared with land requirements of plant-based products, calculating cropland demand of animal products introduces another level of complexity: these land requirements primarily depend on the yields of the feed crops (24), but also, among others, conversion efficiency and livestock species. FAOSTAT provides data on the feed use of crops, but these are not livestock species-specific. To be able to provide reproducible and comparable results, we followed a straightforward approach. We assumed that one animal source calorie requires three times the amount of cropland needed for an average calorie of vegetal origin in the same region and year. This assumption is based on a calculation comparing total feed input from cropland into the livestock sector to total livestock output (in calories; http://faostat.fao.org). This calculation showed that, on average, approximately three calories input were needed for one calorie of output and yielded no clear trend over time.

In 1963, 1984, and 2005, respectively, 2.8, 3.3, and 2.9 calories of feed inputs from cropland were required for one calorie of animal product output.

FAOSTAT data allowed for performing the calculations for 70 food items, which can be linked to 49 crops. The results were summarized into 11 categories: cereals, roots and tubers, pulses, spices, fruits, vegetables, sugar and sugarcrops, vegetable oils and oilcrops, alcoholic beverages, stimulants, and animal products. Developments are presented for 17 world regions (25). As the Soviet Union split into many different nations in 1991, official data allocate some of the area and population of the region Eastern Europe to other regions after this year. To enable consistent time series, we corrected for this change based on the respective population shares. The states of the former Soviet Union are therefore exclusively included within Eastern Europe in this study. Values for 1963, 1984, and 2005 in the text refer to 5-y averages for 1961 to 1965, 1982 to 1984, and 2003 to 2007, respectively. The exact numbers, on which Fig. 1 is based, are provided in Dataset S1 for reference, along with detailed information on how food items and countries were clustered into categories and regions.

The decomposition analysis performed to quantify the contributions of population, technology, and diet in the developments of total cropland requirements for food uses the additive version of the LMDI approach (11). This decomposition method allows for perfect decomposition (i.e., the contributions of the considered factors will add up to the total overall change) and is commonly used in energy studies to assess drivers of changes in energy consumption. The analogous application to changes in land demand was straightforward; we used the following identity as input for the method:

$$\text{Land requirements for food} = \text{capita} * \text{hectares}/\text{kcal} * \text{kcal}/\text{capita} \qquad [1]$$

This implies that we assessed land requirements as the product of population numbers, the amount of land needed per output in calories (i.e., the technology factor) and per capita consumption levels (i.e., the diet factor). The latter two terms were broken down into the 11 food categories used in this study. This accounted for the fact that yield changes were different in the various categories, and that, for instance, higher consumption levels of animal products have a different effect on land requirements compared with a similar change in cereals.

Limitations and Uncertainties. The values for cropland requirements for food presented in this study can be considered low estimates because we do not include seed use and processing losses in our calculation. This choice was made because the quality of estimates for these items is, in general, low, and we aimed to include only numbers for which consistent time series data are available. However, the FAOSTAT food supply data cover retail and household level losses. In developed nations, these can be as large as one third of total supply (26). The available data allowed for assessing land requirements as area harvested in a consistent manner. Actual land requirements are likely to be different, depending on prevailing cropping frequencies: they will be lower in intensive tropical systems, where more than one harvest per year is common. This implies that many systems in much of tropical Asia are even more area-efficient than found here. Land requirements will be higher in systems in which fallow periods constitute a vital element of the prevailing agricultural systems. As a crosscheck, we compared our global totals for cropland requirements with area harvested as reported by the FAO and observed a very good fit: throughout the 46-y study period, our values ranged from approximately 85% to 90% of those reported by the FAO. As expected our results are slightly lower, as seed use and processing losses were not included. With respect to the developments over time, our values show a somewhat steeper increase: a 32% increase from 1963 to 2005 compared with 28% in the reported area harvested. The main reason for this difference could be identified: in our treatment of animal products, we assumed constant conversion ratios throughout time. This choice was made because the introduction of time-dependent conversion ratios would have added another level of complexity and uncertainty to the assessment. When looking at the results, one should keep in mind that differences in the efficiency of feed production are included but those in feed to food conversion are not.

ACKNOWLEDGMENTS. We thank Michael Kastner for help with the decomposition analysis and acknowledge the insightful comments of Ton Schoot Uiterkamp, two anonymous referees, and the editor on earlier versions of this study.

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